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 2

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Issue Resolution Status Report, KTI: Total System Performance Assessment and Integration

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)

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	July 1999	General editorial changes.
Rev. 2	1.0	July 1999	Updated text on issue resolution.
Rev. 2	2.0	July 1999	Updated to reflect new subissues.
Rev. 2	3.2	July 1999	Updated to reflect new subissues.
Rev. 2	4.1	July 1999	Updated to new subissue; added acceptance criteria and review methods for transparency and traceability added.
Rev. 2	4.2	July 1999	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)

Rev. 2	4.3	July 1999	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	July 1999	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	July 1999	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	July 1999	Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation.
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Rev. 2	4.3.2.1.1	July 1999	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	July 1999	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	July 1999	Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation.
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Change History of "Issue Resolution Status Report (IRSR), Key Technical Issue: Total System Performance Assessment and Integration (TSPAI)" (cont'd)

Rev. 2	4.3.2.2.2	July 1999	Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation.
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Rev. 2	4.3.2.3.2	July 1999	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	July 1999	Updated technical basis to reflect TSPA-VA design and new data; modified Criterion T1 and Review Method to discuss expert elicitation.
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Rev. 2	4.3.3.1.3	July 1999	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	July 1999	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	July 1999	Moved to Section 4.1.
Rev. 2	5.0	July 1999	Updated status of Open Items and discussion points.
Rev. 2	Appendix B	July 1999	Updated to reflect new subissues.
Rev. 2	Appendix C	July 1999	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	July 1999	Moved from Appendix C. Updated to reflect changes to NRC total system performance assessment models.

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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 informal, pre-licensing consultation with the U.S. Department of Energy (DOE). These consultations, required by law, 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. The issue resolution approach attempts to reduce the number of, and to better define, issues that may be in dispute during the NRC licensing review.

Thus, consistent with NRC's regulations and a 1993 agreement with DOE, staff-level issue resolution can be achieved during the prelicensing consultation period; however, such resolution at the staff level would not preclude the issue being raised and considered during licensing proceedings. Issue resolution at the staff level during prelicensing is achieved when the staff has no further questions or comments (i.e., Open Items), at a point in time, regarding how DOE program is addressing an issue. There may be some cases where resolution at the staff level may be limited to documenting a common understanding regarding differences in the NRC and DOE technical positions. Pertinent, additional information could raise new questions or comments regarding a previously-resolved issue.

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 pre-licensing 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 post-closure repository performance help ensure that regulatory attention is focused where technical uncertainties will have the greatest affect on the assessment of repository safety, and that 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 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: (i) acceptance criteria for issue resolution and (ii) the status of resolution, including areas of agreement or when the staff has comments or questions. Feedback was also contained in the staff's Annual Progress Report (e.g., Sagar, 1997), which summarized the significant technical work toward resolution of all KTIs during the preceding FY. Finally, 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. In addition, the staff is currently integrating the IRSRs to develop a risk-informed and performance-based YM Review Plan for a potential YM repository LA.

This IRSR contains six sections, including this introductory section. Section 2.0 defines the KTI, related subissues, and scope of the subissues addressed in the IRSR. Section 3.0 discusses the importance of the subissue to evaluation of repository performance. Section 4.0 provides the acceptance criteria and review methods, which indicate the basis for resolution of the subissue and will be used by the staff in subsequent reviews of DOE submittals. These acceptance criteria are guidance for the staff and, indirectly, for DOE as well. The technical basis for the acceptance criteria is also included to further document the rationale for staff decisions. Section 5.0 concludes the report with the status of resolution indicating those items resolved at the staff level or those items remaining open. These Open Items will be tracked by the staff, and resolution will be documented in future IRSRs. Finally, Section 6.0 includes a list of pertinent references.

The IRSRs were the basis for the staff's review of information in DOE's Viability Assessment (VA) (U.S. Department of Energy, 1998b). 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 Total System Performance Assessment (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). Detailed comments on the TSPA-VA are provided in this revision of the IRSR. The rebaselined Open Items based on the review are documented in Section 5.0 of this IRSR.

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 on an assessment of performance of the repository system over the specified time of compliance. The objective of the Total System Performance Assessment and Integration (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 and related acceptance criteria identified herein will be used to review DOE's TSPAs and, eventually, resolve subissues associated with DOE's demonstration of compliance with proposed EPA standards.[1] Standards currently under development by EPA for the YM site are expected to require the proposed repository to meet an annual dose or risk limit to a clearly defined receptor group. In determining whether DOE has demonstrated compliance with such standards, the NRC, using acceptance criteria identified in this IRSR, will review DOE's TSPA. In addition, NRC staff will evaluate DOE's results by conducting an independent TSPA to evaluate the basis in DOE's TSPA for compliance with the overall system performance objective and to evaluate DOE's description of and technical basis for multiple barriers and the implementation of particular barriers in DOE's TSPA.

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 fully 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 and thermal effects to affect waste package (WP) corrosion and release; (ii) quantification of thermal (T), hydrologic (H), mechanical (M), and chemical (C) processes in the near-field of the 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; and (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 enter the biosphere by pathways such as well pumping to produce a 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 system and natural features, events and processes (FEPs). The need to adequately address this integration of technical disciplines in the development of a TSPA is specifically addressed in this IRSR. The incorporation of acceptance criteria addressing the integration issue in this IRSR is designed 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,

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[1] The NRC recognizes that pending legislation, if enacted, could affect the regulation and overall performance objective for HLW disposal at YM (*e.g.*, S.608 and H.R. 45). Irrespective of the level of protection, or the standards for YM, NRC expects that the same basic considerations for demonstrating compliance with such standards will apply.

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 on those key aspects of a TSPA methodology that should be addressed in TSPAs.

- 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; (ii) descriptions of the capability of barriers to isolate waste; and (iii) identification of degradation, deterioration, or alteration processes of engineered barriers that would adversely affect the performance of natural barriers. In addition, it addresses 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 under 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 is an update of the model abstraction acceptance criteria, review methods, and technical basis for the acceptance criteria, and adds acceptance criteria for scenario analysis. Revision 2 of the IRSR includes an update of the model abstraction and scenario analysis acceptance criteria, review methods, and technical basis for the acceptance criteria, and adds acceptance criteria for the demonstration of multiple barriers. Succeeding versions of this IRSR will add acceptance criteria and review methods related to use of PA to support demonstration of compliance with the overall performance objective. These upcoming revisions also will update the status of resolution at the staff level for all subissues in this IRSR.

Concurrent with development of this IRSR, the NRC initiated development of implementing regulations for the YM site with the expectation that, in the near future, EPA will issue standards for the YM site. One area of particular importance to the TSPA is the implementation of the Commission philosophy on defense-in-depth/multiple barriers. Based on current understanding of the YM site and the engineering designs, both the engineered and natural systems are expected to make a contribution to total system performance. As this rulemaking activity progresses, this IRSR will be revised and updated to ensure consistency with the implementing regulations.

3.0 IMPORTANCE OF ISSUE AND SUBISSUES TO EVALUATION OF REPOSITORY PERFORMANCE

The NAS recommended that the risk to the average member of a critical group be the performance measure for the proposed repository at the YM site (National Research Council, 1995). As noted in Section 2.0, DOE's demonstration of compliance with applicable standards for disposal of HLW in a geologic repository at YM will most likely need to meet the risk- or dose-based performance objectives in the implementing regulations. Because the proposed HLW repository at the YM site is a unique, one-of-a-kind facility with a long compliance period, demonstration of compliance with a dose/risk standard is expected to be a complex and difficult task. The TSPA, therefore, 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

It is expected that the implementing regulations for the YM site will require DOE to provide a comprehensive PA in its LA (U.S. Nuclear Regulatory Commission, 1999c). NRC is obligated to ensure in its review of a LA that the proposed repository will adequately protect public health and safety. As part of its review process, NRC staff will rely mostly on field, laboratory, and/or natural analog data collected by DOE, but will perform independent estimates of the repository performance. It will be necessary, therefore, for NRC to decide those portions of DOE's assessment requiring independent verification through more detailed quantitative analyses and limited laboratory studies.

NRC has used TSPA activities in pre-licensing 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 Nuclear Waste Policy Act of 1982, as amended (Public Law 97-425), 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 have also supported NRC staff interactions with EPA and NAS, as a part of the NAS re-evaluation of EPA's HLW standards, as they will 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 Site Recommendation (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 Section 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 that are considered important barriers to waste isolation, (ii) described the capability of the barriers important to waste isolation, and (iii) provided a technical basis for its description of the capability of the barriers. Furthermore, it 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 has appropriately executed the PA to demonstrate that repository performance under 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 ACCEPTANCE CRITERIA AND REVIEW METHODS

This section describes a process that NRC staff will follow in reviewing DOE's TSPAs and also provides a path to issue resolution. This section 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. Acceptance criteria and review methods are specified for each of the subissues identified in Section 2.0. Past independent research by the staff, information in open literature, review of previous DOE TSPAs; information learned during meetings with DOE; approaches used in staff's Total-system Performance Assessment (TPA) Version 3.2 code (Mohanty and McCartin, 1998); and acceptance criteria, review methods and technical bases contained in the IRSRs by other KTIs have been considered in formulating this section. 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 the subissues, but apply directly in the case of subissues two and three (scenario analysis and model abstraction). 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 for the PA—should satisfy the acceptance criterion on QA. Similarly, the use of expert elicitation should satisfy the appropriate acceptance criterion.

Criterion P1: The collection, documentation, and development of data, models, and/or computer codes have been performed under acceptable quality assurance procedures, or if the data, models and/or computer codes were not subject to an acceptable QA procedure, they have been appropriately qualified.

Review Method: Staff should ensure that as part of its site characterization programs, DOE has in place an acceptable, baselined QA program that meets NRC's requirements. Moreover, staff should confirm that DOE has qualified data, models, and/or computer codes supporting any potential LA to construct and operate a geologic repository. Additionally, staff should check that, As part of its TSPA, DOE has provided information to certify that the data, models, and/or computer codes used have been subject to an NRC-approved QA program. Guidance on an acceptable QA program can be found, as appropriate, in NUREG–0856 (Silling, 1983) and NUREG–1563 (Duncan et al., 1996).

For those data, models, and/or computer codes not collected/developed under an NRC-approved QA program, staff should ensure that DOE has demonstrated that they have been QA-qualified consistent with the guidance found in NUREG–1298 (Altman et al., 1988b).

Criterion P2: Formal expert elicitations can be used to support data synthesis and model development for DOE's TSPA, provided that the elicitations are conducted and documented under acceptable procedures.

Review Method: Should DOE rely on the use of formal expert judgment to collect, analyze, or interpret information in its TSPA, staff should ensure that DOE has demonstrated that the elicitation has been conducted consistent with the guidance found in NUREG–1563 (Kotra et al., 1996). If DOE chooses to follow alternative guidance than that described in this NUREG, staff should confirm that DOE has demonstrated that the alternative guidance is comparable to that of NRC's and provides a sufficient basis for the requisite findings to be made by the staff.

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 this IRSR, will review DOE's TSPA. Transparency and traceability of the analysis requires a description that allows for an adequate understanding of DOE's approach and results of the TSPA.

Transparency has been defined by the Nuclear Energy Agency (NEA) as an attribute of a PA report that is "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 should provide the NRC staff with ways to test the veracity 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. In order 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, 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 address: (i) TSPA document style, structure, and organization; (ii) FEPs identification and screening; (iii) abstraction methodology; (iv) data use and validity; (v) assessment results; and (vi) code design, data flow, and supporting documentation.

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, 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 comprehend the information recorded in the many documents and data sources, traceability and transparency require that source documents be well structured and organized.

Acceptance Criteria with Review Method

DOE's approach to document structure and organization will be acceptable if the following acceptance criteria are met:

Criterion T1: Documents and reports are complete, clear, and consistent.

Review Method: The NRC staff will ascertain whether documentation is complete in that, all necessary sections are included, all necessary details are included in a section, and all referenced or implied sections exist.

The NRC staff will ascertain whether documentation is clear in that, the content is appropriately decomposed (neither too much nor too little), the relationships between sections within a document are clear, the terminology (e.g., technical jargon) is clear and appropriate, and the meaning of each section and the entire document is clear and unambiguous.

The NRC staff will ascertain that sufficient information is available to fully understand the application and use of various terms and phrases (e.g., probability of event, igneous event) throughout the TSPA and when terms and phrases are defined differently for various applications that usage and rationale is clearly described.

The NRC staff will verify consistency in naming in that, important terms and phrases (e.g., fracture zone, major features, and minor features) are unambiguous and linguistically precise (Swedish Nuclear Power Inspectorate, 1997a).

The NRC staff will ascertain whether documentation is consistent with its stated scope and objectives, with all related work products, with all applicable guidelines, and related components within a document (e.g., a balance in the level of detail in the descriptions).

Criterion T2: Information is amply cross-referenced.

Review Method: The staff will ascertain that sufficient documentation is available [e.g., road map diagrams, traceability matrices, and others], which describes the relationship within and between documents and draws attention to important assumptions.

Technical Basis

All stakeholders will scrutinize DOE documentation. Therefore, TSPA documentation must be structured to facilitate in-depth reviews. 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 are diagram-intensive. Documentation must balance the level of detail, clearly state assumptions and simplifications made, and refer the source of basis data (e.g., dose-conversion factors) in main volumes (Swedish Nuclear Power Inspectorate, 1997b).

4.1.1.2 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 DOE has adequately identified and addressed those FEPs that are sufficiently likely to occur within the compliance period.

Criterion T1: The screening process by which FEPs were included or excluded from the TSPA is fully described.

Review Method: The staff will ascertain that sufficient documentation is available to allow an adequate understanding of the methods and criteria used for the screening of FEPs including rationale for including or excluding selected FEPs from the assessment.

Criterion T2: Relationships between relevant FEPs are fully described.

Review Method: The staff will ascertain that sufficient documentation (e.g., an interaction matrix, interaction diagram or some other suitable representation) is available that allows an adequate understanding of the relationship between relevant FEPs and how the relationship is modeled.

Technical Basis

The staff will review categorization of FEPs during evaluation of DOE's scenario analysis process [see Section 4.2]. 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.

4.1.1.3 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.

Acceptance Criteria with Review Method

DOE's approach to model abstraction is acceptably transparent and traceable if the following acceptance criteria are met.

Criterion T1: The levels and method(s) of abstraction are described starting from assumptions defining the scope of the assessment down to assumptions concerning specific processes and the validity of given data.

Review Method: The staff will confirm that sufficient information is available to trace the abstraction process from fundamental information (field data, laboratory data, natural analog data, or expert elicitation results) to the source code (forward traceability) and back (backward traceability).

Criterion T2: A mapping (e.g., a road map diagram, a traceability matrix, a cross-reference matrix) to show what conceptual features (e.g., patterns of volcanic events) and processes are represented in the abstracted models, and by what algorithms.

Review Method: The staff will ascertain that sufficient basis for all information is available that allows an adequate understanding of the basis for all decisions and assumptions made during the abstraction process.

The staff will determine whether there is enough documentation to make clear the assumption that underlie the models, the consistency of the assumptions, and their impact on results.

Criterion T3: An explicit discussion of uncertainty is provided to identify which issues and factors are of most concern or are key sources of disagreement among experts or stakeholders.

Review Method: The staff will ascertain that sufficient information is available to allow an adequate understanding of how problems, limitations, and uncertainties are identified and isolated including the resolution of stakeholder concerns. Where expert elicitation is incorporated into the TSPA abstraction process, the staff will ascertain that the expert elicitation process is clearly defined and documented.

Technical Basis

The NRC staff will evaluate DOE's model and data justification and associated uncertainty to ensure that the degree of technical support for models and data abstractions is commensurate with contribution to risk (see Section 4.3). The entire abstraction process, from fundamental source information (e.g., FEPs, field data, laboratory results, and others) needs to be recorded, together with the uncertainties and biases accumulated and resolved at each stage of the process, and evidence used, for example expert elicitation.

4.1.1.4 Data Use and Validity

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.

Acceptance Criteria with Review Method

DOE's approach to transparency and traceability for data use and validity is satisfactory if the following criteria are met.

Criterion T1: The pedigree of data from laboratory tests, natural analogs, and the site is clearly identified.

Review Method: The staff will ascertain that an "audit trail" exists to allow a reviewer to assess the quality and validity of all significant data, including unqualified data, used in the assessment and data used to guide modeling assumptions and decisions.

The staff will ascertain that sufficient information is available to allow an adequate understanding of QA controls placed on the data used in the assessment including data collection procedures, use of standards, data reduction, and data analysis.

Criterion T2: Input parameter development and basis for their selection is described.

Review Method: The staff will ascertain that sufficient information is available that allows an adequate understanding of the relationship of the selected input parameters to the natural and engineered features that may affect the performance of the repository, which is part of the process of parameter development.

The staff will ascertain that a process is in-place to identify whether data are based on measurements (field or laboratory), expert judgment, and/or value judgments. The staff will also verify that a process is in-place that will aid in identifying the levels of significance and uncertainties and open questions associated with data.

Criterion T3: A thorough description of the method used to identify performance confirmation program parameters.

Review Method: The staff will ascertain that sufficient information is available that allows an adequate understanding of the methods utilized in the development of the performance confirmation program parameters specifically

- Identification and selection of uncertain parameters that are important to performance
- Methods used to collect information for each parameter
- Performance confirmation test selection and rationale
- Effect of repository design changes

Data collected during the performance confirmation period may require DOE to change its selection of FEPs and modeling approach. The staff will ascertain that DOE has a clearly laid out plan for rescreening of FEPs and model selection/revision.

Technical Basis

The validity of assessment results depends not only on the validity of the model(s), but also on the validity of the data used with the model. The staff will assess the sufficiency of data (field, laboratory and/or natural analogs) to adequately define relevant parameters and conceptual models. In addition, it is commonly found that a relatively small group of important parameters exist among many less important ones (U.S. Nuclear Regulatory Commission, 1999j). Explicit discussion of these important parameters is critical in order to assess the information gathered on those parameters.

Performance confirmation is defined in 10 CFR 60.2 as the program of tests, experiments, and analysis, which is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure will be met. A thorough description of the performance confirmation program development is critical in order to assess the ability of the DOE to comply with requirements.

4.1.1.5 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 requirement, is resilient against human intrusion, and consists of multiple barriers. Demonstration that all these requirements have been met should include performance results that are traceable to decisions regarding data, models and computer codes.

Acceptance Criteria with Review Method

DOE's approach to transparency and traceability for PA results is satisfactory if the following criteria are met.

Criterion T1:	PA results (i.e., the peak expected annual dose within the compliance period) can be traced back to applicable analyses that identify the FEPs, assumptions, input parameters, and models in the PA.
Review Method:	The staff will ascertain that sufficient documentation is available to trace back the origin of important assumptions and decisions and verify that the results obtained can be clearly linked to these decisions and assumptions. The staff will ascertain that sufficient documentation is available to allow for an adequate understanding of the process used to produce the TSPA results and that process has been consistently applied. The staff will ascertain that sufficient documentation is available that allows for an adequate understanding of the mobilization, release, and transport of RNs to the critical group.
Criterion T2:	The PA results include a presentation of intermediate results that provide insight into the assessment (e.g., results of intermediate calculations of the behavior of individual barriers).
Review Method:	The staff will ascertain that sufficient information is available to allow an adequate understanding of the technical basis for overall barrier capability and the parameters and assumptions that may affect the capability of an individual barrier.

Technical Basis

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 that these barriers consist of major repository subsystems and/or 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 up an understanding of the behavior of the total system (Nuclear Energy Agency, 1998).

4.1.1.6 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 may need to review the code to enhance staff understanding of TSPA methodology and results.

Acceptance Criteria with Review Method

DOE's approach to transparency and traceability for code design and data flow is satisfactory if the following criteria are met.

Criterion T1: The flow of information (input and output) between the various modules is clearly described.

Review Method: The staff will ascertain that adequate documentation is available (e.g., structure charts, data flow diagrams, and others) to adequately understand the data movement in the DOE TSPA code.

Criterion T2: Supporting documentation (e.g., user's manuals, design documents) clearly describes code structure and relationships between modules.

Review Method: The NRC staff will ascertain that sufficient information is available that allows an adequate understanding of the

- Overall structure of the TSPA code and coupling of modules (the degree of interdependency among modules)
- Major elements of the code as they relate to the requirements (e.g., FEPs)
- Control flow, control logic, and data structure
- Domain and range of valid (e.g.,range and precision) inputs and legitimate outputs
- External interfaces, the user interface, database organization, and error handling

Technical Basis

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

This section will be developed in Revision 3 of the IRSR. A proposed strategy for developing regulations for the disposal of HLW in a YM repository was outlined in "Proposed Strategy for Development of Regulations Governing Disposal of High-Level Radioactive Wastes in a Proposed Repository at Yucca Mountain" (U.S. Nuclear Regulatory Commission, 1997). This strategy indicates that a demonstration of multiple barriers would be maintained, but would not incorporate the existing subsystem performance objectives in 10 CFR Part 60. In demonstrating compliance with the overall system performance objective, DOE would need to present the results of intermediate calculations, along with their associated uncertainties, to demonstrate 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 4.4), and transparency of the analysis (Section 4.1.1). The final requirements for the demonstration of multiple barriers will be established after a public rulemaking and the acceptance criteria will be modified (as needed) to be consistent with the final regulations.

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 FEPs necessary to describe what can reasonably happen to the repository system and includes assumptions about the repository system and the processes and events that can effect that 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 geologic repository performance. 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/or (ii) approximating the alternative ways in which the repository system might perform in the future, through the use of scenarios.[2] Most uncertainty analyses use a combination of these two approaches.[3] The approaches are not mutually exclusive and both may be used in the analysis to treat different types of uncertainty.

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 yet-to-be promulgated YM-specific EPA standard and the NRC implementing regulations will likely 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[4] 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 (1)–(3) 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.

Although significant progress has been made over the years in resolving many of the scenarios-related Open Items, two of the most important ones remain unresolved. They are SCA Comments 95 and 105 (Open Items OSC0000001347C095 and OSC0000001347C105). The staff has noted the need for DOE to address SCA Comments 95 and 105 (and others) as its program proceeds beyond the VA (see Bell, 1997a). If effectively implemented, DOE's

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[2] 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 IRSR except to note that each scenario has a conceptual model associated with it.

[3] 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.

[4] 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.

current approach to scenario analysis, as discussed at an NRC/DOE Appendix 7 meeting held October 1998 and a technical exchange held May 1999 and in the TSPA-VA supporting documentation, will address Open Items related to scenario analysis. The staff will consider closing items after reviewing documentation of the progress and implementation of DOE's current approach.

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 has 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.

Acceptance Criteria and Review Methods

DOE's approach in identifying an initial list of processes and events will be acceptable if the following acceptance criterion is met:

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

Review Method: The staff will use the generic list of events and processes assembled by OECD/NEA (1997) to evaluate DOE's comprehensive list of processes and events. Staff will compare DOE's list to other generic and site-specific efforts to identify processes and events for geologic repositories. Staff also will review site characterization data to confirm the completeness of DOE's list.

Staff should ensure that DOE has included processes and 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 also should confirm that processes and events related to human intrusion are consistent with the constraints placed on the consideration of human intrusion in 10 CFR Part 63.[5]

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[5] It is anticipated that the human intrusion scenario will be treated through an assumed intrusion scenario.

Technical Basis

An event[6] is an occurrence at a discrete location in space and during a specific interval of time. Examples for the YM site include igneous events (such as a dike intrusion or the formation of a vent) and tectonic events (such as 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, 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, 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.[7] 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 4.4.3). These categories of processes and events may be combined to form scenarios (see Section 4.4.4). Combinations of processes and events may also be screened from the analysis (see Section 4.4.5).

Acceptance Criteria and Review Methods

DOE's classification of processes and events will be acceptable, if the following acceptance criteria are met:

Criterion T1: DOE has provided adequate documentation identifying how its initial list of processes and events has been grouped into categories.

Review Method: The staff will review DOE's categories of processes and events. Staff will audit the categorization of processes and events using DOE's initial list of processes and events and DOE's documentation of their classification. Staff will confirm that the categories include each process and event identified in the comprehensive list of processes and events.

Criterion T2: Categorization of processes and events is compatible with the use of categories during the screening of processes and events.

Review Method: The staff will review DOE's categorization of processes and events in the context of their use in screening categories of processes and events from

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[6] 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, magnitude).

[7] A number of 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.

the PA. Staff will evaluate DOE's approach to determine if categories of processes and events are appropriately defined (e.g., narrow definition of a category of processes and events to reduce the probability of occurrence is inappropriate).

Technical Basis

DOE has flexibility in how it categorizes processes and events, subject to limitations on the use of those categories to screen processes and events from the PA. 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. Narrowly defined categories of processes and events that result in the inappropriate 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[8] 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., $\mathbf{I}^{-}$). These broad categories can be used to estimate the probability that any one of a 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.

Acceptance Criteria and Review Methods

DOE's screening of categories of processes and events will be acceptable if the following acceptance criteria are met:

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

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

Review Method: Staff will examine the list of processes and events identified as not credible and the supporting bases. Staff will evaluate the rationales provided against the description of the site, design specifications, and waste characteristics. Staff will consider information from site characterization, natural analogs, and its review of the repository design during its evaluation.

Criterion T2: The probability assigned to each category of processes and events not screened based on criterion T1 or criterion T2 is consistent with site information, well documented, and appropriately considers uncertainty.

Review Method: Staff will evaluate the amount of site specific information available for assigning probabilities to the various categories of processes and events. Staff will determine whether probabilities assigned to these categories are consistent with the geologic data. The review will take into consideration whether DOE has appropriately considered the variable rates of occurrence of geologic processes in space and time in developing YM-specific probabilities. Staff will compare DOE-determined probabilities with its own independently developed probabilities through the iterative PAs and technical work in discipline-specific KTIs (e.g., IA KTI; Structural Deformation and Seismicity KTI). Staff will focus its review on those categories of processes and events that could significantly influence the calculated performance measure, as informed by earlier PAs, and those categories that have: (i) probabilities close to the screening criteria on probability and (ii) potentially significant probability weighted consequences.

Staff will consider DOE's estimates, both qualitative and quantitative, for the uncertainty associated with the rate of occurrence and probabilities assigned to processes and events, respectively. The amount and type of information used to develop the uncertainty estimates will be evaluated. Staff will evaluate whether DOE has adequately considered the range of viable conceptual models in developing its estimates of uncertainty. The staff's review of the uncertainty should be consistent with the importance of the event class to the calculation of the expected annual dose. Variability and uncertainty in the attributes of processes and events (e.g., time of occurrence, location, duration, amount of energy released, rates of propagation of disturbance) treated through parameter distributions will be reviewed during the evaluation of DOE's model abstraction.

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

Review Method: Staff will use the results of its review of probabilities for categories of processes and events. Staff will use its approach of defining event classes to identify important groups of fundamentally similar events (e.g., IA occurring within the period of regulatory interest) and will evaluate DOE's treatment of these event classes. Staff will consider the estimated probability and its uncertainty when evaluating the screening of credible processes and events. The staff review should consider the importance of each category to the calculation of the expected annual dose during its evaluation. There should be greater assurance that screened processes and events that may be associated with potentially large doses to the average member of the critical group are sufficiently unlikely and can be screened on the basis of probability.

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

Review Method: Staff will review the criteria used by DOE to screen processes and events from the PA on the basis of their contribution to the expected annual dose. Staff will review discussions or calculations of representative consequences presented to support the screening of particular processes or events. Staff should use independent assessments of the potential consequences to confirm DOE's screening of processes and events, as needed. Staff should evaluate whether DOE has provided sufficient justification for neglecting these processes from the PA, including the use of either bounding or representative estimates for the consequences. Staff also should evaluate whether DOE has adequately considered coupling in its estimates of consequences used to screen processes and events (e.g., co-volcanic seismic and fault displacement events associated with IA).

Technical Basis

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 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 IA into categories that include details of its attributes (e.g., intrusive igneous events with dike lengths of 2 kilometers or less) could, inappropriately, result in the screening of each category of IA from the PA. However, igneous processes, when they are addressed together, may be sufficiently likely to be included in the PA on the basis of their probability; If so, igneous processes would need to be considered further.

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 $\mathbf{I}^{-}$; **F** and $\mathbf{F}^{-}$; and **S** and $\mathbf{S}^{-}$), 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 result in the inappropriate screening of processes or events from the PA are unacceptable, because they result in an incomplete assessment of repository performance.

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 very 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).

Acceptance Criteria and Review Methods

DOE's treatment of processes and events that have not been omitted from the PA will be acceptable, if the following acceptance criteria are met:

Criterion T1: DOE has provided adequate documentation identifying: (i) whether processes and events have been addressed through consequence model abstraction or scenario analysis and (ii) how the remaining categories of processes and events have been combined into scenario classes.

Review Method: The staff will review DOE's documentation to see that all categories of processes and events have been addressed either through model abstraction or scenario analysis. Staff will evaluate DOE's combination of the remaining categories of processes and events into scenario classes to determine if narrowly defined scenario classes are present that might be screened from the PA as a consequence of their narrow definition.

Criterion T2: The set of scenario classes is mutually exclusive and complete.

Review Method: Staff will evaluate DOE's scenario classes to determine whether they are mutually exclusive. Staff will evaluate whether DOE's scenario classes provide comprehensive coverage of processes and events not addressed through consequence modeling.

Technical Basis

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 (**F** and $\mathbf{F^-}$), seismicity (**S** and $\mathbf{S^-}$), and IA (**I** and $\mathbf{I^-}$). These event classes can be combined into scenario classes such as **FSI**, $\mathbf{FSI^-}$, $\mathbf{FS^-I}$, $\mathbf{FS^-I^-}$, $\mathbf{F^-SI}$, $\mathbf{F^-SI^-}$, $\mathbf{F^-S^-I}$, and $\mathbf{F^-S^-I^-}$. 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 event sequences, which requires that differences in consequences associated with the timing of events has to be addressed through model abstraction. Narrow scenario class definitions that result in the inappropriate screening of scenario classes from the PA are unacceptable, because they result in an incomplete assessment of repository performance.

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. Probabilities for scenario classes must be appropriately assigned when screening is to be based on the probability of occurrence or the significance to the expected annual dose.

Acceptance Criteria and Review Methods

DOE's screening of scenario classes from the PA will be acceptable, if the following acceptance criteria are met:

Criterion T1: Scenario classes that are not credible for the YM repository because of waste characteristics, repository design, or site characteristics—individually or in combination—are identified and sufficient justification is provided for DOE's conclusions.

Review Method: Staff will examine the set of scenario classes identified as not credible and the supporting bases. Staff will evaluate the rationales provided against the description of the site, design specifications, and waste characteristics. Staff will consider information from site characterization, natural analogs, and its review of the repository design during its evaluation.

Criterion T2: The probability assigned to each scenario class is consistent with site information, well documented, and appropriately considers uncertainty.

Review Method: Staff will evaluate DOE's documentation of the probabilities assigned to the different scenario classes. Staff will determine whether probabilities assigned to these scenario classes are consistent with geologic data and appropriately account for dependencies and correlations. Staff will compare DOE-determined probabilities with its own independently developed probabilities through the iterative PAs and technical work in discipline-specific KTIs [e.g., IA KTI; Structural Deformation and Seismicity (SDS) KTI] and the relationships between processes and events within the scenario class. Staff will also evaluate whether DOE's probabilities comport with the rules of probability. Staff will focus its review on those scenario classes that could significantly influence the calculated performance measure, as informed by earlier PAs, and those scenario classes that have: (i) probabilities close to the screening criteria on probability and (ii) potentially significant consequence. Staff will consider DOE's estimates for the uncertainty associated with the rate of occurrence and probabilities assigned to processes and events, respectively, included within the scenario class and DOE's estimates for the degree of independence, or interdependence, of processes and events.

Criterion T3: Scenario classes that combine categories of processes and events may be screened from the PA on the basis of their probability of occurrence, provided: (i) the probability used for screening the scenario class is defined from combinations of initiating processes and events and (ii) DOE has demonstrated that they have a probability of less than one chance in 10,000 of occurring over 10,000 years.

Review Method: Staff will use the results of its review of probabilities for: (i) categories of processes and events and (ii) scenario classes. Staff also will evaluate the degree of independence between processes and events in the scenario class; for example, staff will consider the probability of co-volcanic fault displacement and seismicity. Scenario classes that the staff concurs are not credible for the YM repository because of the waste characteristics, repository design, and/or site characteristics may be omitted from the analysis. Staff will evaluate the screening of credible scenario classes. Staff will use its approach of defining scenario classes to evaluate DOE's scenario class probabilities. Staff will review screened scenario classes to ensure that DOE has used probability estimates for the initiating processes and events for the screening. For each screened scenario class, staff will consider its definition and the definition of related scenario classes to evaluate whether a narrow scenario class definition resulted in the screening of the scenario class. Staff will consider the estimated probability and its uncertainty when evaluating the screening of credible scenario classes. The staff review should consider the importance of each scenario class to the calculation of the expected annual dose during its evaluation. There should be greater assurance that screened scenario classes that may be associated with potentially large doses to the average member of the critical group are sufficiently unlikely and can be screened on the basis of probability.

Criterion T4 — Scenario classes may be omitted from the PA on the basis that their omission would not significantly change the calculated expected annual dose, provided DOE has demonstrated that excluded categories of processes and events would not significantly change the calculated expected annual dose.

Review Method: Staff will use the results of its review of scenario class probabilities. Staff will review the criteria used by DOE to screen scenario classes from the PA on the basis of their contribution to the expected annual dose. Staff will review discussions or calculations presented to support the screening of particular scenario classes. Staff should use independent assessments of the potential consequences to confirm DOE's screening of processes and events, as needed. Staff should evaluate whether DOE has provided sufficient justification for excluding these scenario classes from the PA, including the use of either bounding or representative estimates for the consequences. Staff also should evaluate whether DOE has adequately considered coupling in its estimates of consequences used to screen processes and events (e.g., co-volcanic seismic and fault displacement events associated with IA). For each screened scenario class, staff will consider related scenario classes to evaluate whether its narrow definition resulted in the screening of the scenario class.

Technical Basis

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. Therefore, screening on the basis of probability is limited to combinations of initiating processes and events. This restriction 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 broad classification of processes and events does not need to be maintained for screening based on consequences (i.e., contribution to the calculated performance measure) or for the PA calculation. 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, since 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: $\boldsymbol{\Theta}$ (P=0.9) and $\boldsymbol{\Psi}$ (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 $\boldsymbol{\Theta}$ or $\boldsymbol{\Psi}$ not being present or not occurring within 10,000 years can be found using the principles of probability; that is $\boldsymbol{\Theta}^-$ (P=0.1) and $\boldsymbol{\Psi}^-$ (P=0.95). These event classes can be combined to form scenario classes (e.g., $\boldsymbol{\Theta\Psi}$, $\boldsymbol{\Theta\Psi}^-$, $\boldsymbol{\Theta}$

$^-\Psi$,$\Theta^-\Psi^-$). Since 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 1 illustrates the use of the Latin Square to form scenario classes and determine probabilities.

Table 1. Example Latin Square for event classes based on two generalized event classes (Θ and Ψ)

Event Class	Ψ (P=0.05)	Ψ^- (P=0.95)	Sum
Θ (P=0.9)	$\Theta\Psi$ (P=0.045)	$\Theta^-\Psi$ (P=0.855)	0.9
Θ^- (P=0.1)	$\Theta\Psi^-$ (P=0.005)	$\Theta^-\Psi^-$ (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; unsaturated zone (UZ) flow and transport, saturated zone (SZ) 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 integrated subissues (ISIs) of the repository system that need to be appropriately abstracted into a TSPA.[9] These ISIs, in general, are the integrated processes, features, and events that could impact system performance. The judgment about which

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[9] As stated in the DOE TSPA-VA plan (TRW Environmental Safety Systems, Inc., 1996), "*... for the purpose of TSPA, [abstraction] means the development of a simplified/idealized process model, with appropriately defined inputs, that reproduces/bounds the results of an underlying detailed process model, or intermediate results from the detailed process model can be analyzed to develop response functions that can then be used as inputs to the abstracted model. In either case, it is necessary to demonstrate that predictions of both the detailed process model and the abstracted model are reasonably similar.*" Complex process models, however, may be directly incorporated into TSPAs without simplification. The criteria described in this section apply to all models that constitute the TSPA.

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 will provide 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 integrated subissue (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. Initial partitioning of FEPs to ISIs can be found in Appendix C. The initial partitioning of FEPs to ISIs provides the framework for future review and evaluation. The KTI subissues pertinent to each ISI can be found in the FEPs tables. The relationship of individual KTI subissues to a particular ISI is also described in Section 3 of the KTI IRSRs (U.S. Nuclear Regulatory Commission, 1999e–i, k–m). Finally, 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 D 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 milti-disciplinary ISI teams and will be based on the following five technical acceptance criteria. The programmatic acceptance criteria in Section 4.0 also apply to all ISIs. The general principles underlying the technical criteria apply to all ISIs and are reiterated and customized for each ISI in Sections 4.3.1 through 4.3.3.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately support the conceptual models, assumptions, and boundary conditions and to define all relevant parameters implemented in the TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the TSPA are technically defensible and reasonably account for uncertainties and variability.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately considered in the abstractions.

Criterion T4: Model Support

Models implemented in the TSPA provide results consistent with output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Criterion T5: Integration

TSPA adequately incorporates important design features, physical phenomena, and couplings and uses consistent and appropriate assumptions throughout the abstraction process.

The remainder of Section 4.3 provides more detail on these five technical acceptance criteria and the corresponding review methods for each of the 14 ISIs (see the bottom tier in Figure 3). Note that although the acceptance criteria and review methods are presented by ISI, 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 between the various ISIs are identified under T5. Successful application of criterion T5 ensures that consistent assumptions, data, and models have been implemented in the TSPA. Each ISI section includes a summary of the DOE approach to modify the ISI and NRC staff analysis of that approach. Future revisions of the IRSR will add a discussion on the path to resolution for areas of disagreement between NRC and DOE staff. The reader should refer to the relevant KTI issues for more detailed discussions and a path to resolution for these issues.

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 Tables 16 and 17 for a summary of Open Items and Table 18 for a summary of discussion points.

TSPA-VA (U.S. Department of Energy, 1998b) indicates that DOE has conducted expert elicitations used in the TSPA-VA in accordance with NUREG–1563 (Kotra et al., 1996). This approach is considered appropriate by NRC staff. However, NRC staff still has concerns that expert elicitation is used inappropriately in the TSPA-VA. Where it is reasonable, DOE should collect data or conduct detailed process modeling instead of relying on expert elicitation. Therefore, Open Items OSC0000001347C009 and OSC0000001347C007 will remain open at this time.

Open Item OSC0000001347C098 indicates that it is not appropriate to weigh 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 alternate conceptual models instead of lumping the alternate conceptual models into a single assessment of performance. However, in some areas, such as determining the corrosion rate of the WP and determining the probability of volcanism in the repository area, DOE continues to weigh alternative conceptual models by the judgment if they are correct without a sufficient technical basis. Therefore, Open Item OSC0000001347C098 will remain open at this time. This Open Item addresses the concern raised by discussion point TE5, so this discussion point is considered closed.

Open Item OSC0000001347C099 indicates that DOE should consider all possible release modes resulting from a scenario class. In the TSPA-VA, DOE considers the impacts of direct release, enhanced source term, and indirect effects due to IA. DOE also evaluates the immediate and long-term effects of human intrusion on the performance of the repository. Therefore, it is clear that DOE is evaluating all release modes associated with a scenario class, and Open Item OSC0000001347C099 is considered resolved.

Open Items OAO028MAY1993C001 and OAO028MAY1993C002 express concern that potentially adverse conditions and favorable conditions at the repository are incorporated only into scenarios and not considered in the base conceptual models for the system. NRC staff review of TSPA-VA revealed that the base conceptual models of the repository system included appropriate potentially adverse and favorable conditions and therefore, Open Items OAO028MAY1993C001 and OAO028MAY1993C002 are considered resolved.

TSPA-VA utilized Latin Hypercube Sampling (LHS) to ensure that sampling of the input parameters covered the entire range of the input distributions. This addresses the concern in discussion point TE1, which is considered closed.

The RNs selected for analysis in TSPA-VA were screened based on their half-life, sorption characteristics, and biosphere DCFs. NRC staff does not consider it inappropriate to screen RNs based on these or other criteria, but believes that the licensee must be able to show that exclusion of additional RNs from the analysis would not impact the estimated performance of the system. There is basic agreement between NRC and DOE staffs on the methodology that will be used to screen RNs from the analysis, so discussion point TE4 is not an open issue at this time. However, the methodology and results of the screening of RNs will continue to be evaluated in future TSPAs as more data on the system become available to NRC and DOE staffs.

Discussion point TE2 raises a series of questions about the role of sensitivity analyses and uncertainty and variability in DOE's TSPAs. Sensitivity analyses including regression analyses, differential analyses, one-off analyses, and alternate conceptual models have been included in the TSPA-VA (U.S. Department of Energy, 1998b). These results are used to identify where significant uncertainties remain in the models such that the program can attempt to collect additional data or perform additional modeling to reduce the uncertainty in models or parameter values. Parameter variability is defined as the change in a parameter value over space or time whereas parameter uncertainty is defined as the lack of knowledge about a parameter. Parameter variability and uncertainty are modeled in TSPA-VA through the use of LHS techniques and alternative conceptual models. Alternate conceptual models were evaluated for changes in the water chemistry due to spent nuclear fuel (SNF) alteration and to concrete in the drift to determine the sensitivity of performance to near-field environment modeling assumptions. NRC staff does not currently consider these items in significant disagreement between NRC and DOE. However, one point raised by this discussion point involves the propagation of parameter variability and uncertainty through the sequence of models outside of the Repository Integration Program (RIP). NRC staff has concerns that many parameters within the detailed process models underlying the TSPA-VA model abstractions are not tested for their effect on the performance of the total system. For example, the uncertainty in the flow fields calculated for the repository system are based only on the infiltration into the mountain and the fracture air-entry parameter. Uncertainty and variability in the porosity and permeability of the rock in the mountain can significantly impact the performance of the system. However, DOE's model is not able to identify this potential impact on performance. The DOE's analysis should include a demonstration that the failure to sample uncertain parameters in abstraction of the detailed process model will not impact the results obtained by the abstracted model. This issue will continue to be investigated by NRC staff, but will not be raised to the level of an Open Item in the TSPAI IRSR at this time.

Discussion Point TE3 questions how the abstracted data and response surfaces from the detailed process-level modeling will be calibrated. This issue will be evaluated by all KTIs under acceptance criterion T4 for all models of the repository system. This issue will continue to be investigated by NRC staff, but will not be tracked as an Open Item in the TSPAI IRSR.

4.3.1 Engineered System

The engineered system is composed of several parts: WP, drip shield, waste form, and the surrounding engineered environment. 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. In the following discussion, acceptance criteria and review methods are focused on defining those aspects of the analysis necessary to make this evaluation.

4.3.1.1 Engineered Barriers

In this section, technical acceptance criteria and review methods for the four ISIs in the engineered barriers abstraction, as identified in Figure 3 (i.e., WP Corrosion, 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 IPA 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 (RSS) (U.S. Department of Energy, 1998a). As previously noted, these ISIs represent the essential factors to be considered in demonstrating the engineered barriers' capability to improve total system performance. DOE's abstraction of the engineered barriers in its TSPA for the proposed repository at YM will be considered satisfactory if the acceptance criteria for all four ISIs are met.

4.3.1.1.1 Engineered Barrier Degradation

Review of the model abstraction for the engineered barrier degradation involves the (i) Container Life and Source Term (CLST), (ii) Evolution of the Near-Field Environment (ENFE), (iii) Repository Design and Thermal-Mechanical Effects (RDTME), (iv) IA, and (v) Thermal Effects on Flow (TEF) KTIs. The engineered barrier degradation ISI addresses the assessment of engineered barrier performance including WP 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 RNs within the EBS. Engineered barriers in the repository system include dripshields and the WPs 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. 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 ENFE and coupled THC processes will affect the chemistry, temperature, and pH of the environment contacting the engineered barriers and also 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 initiate 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. IA may affect the integrity of the engineered barriers as a result of thermal, mechanical, and chemical interactions.

The WP is the primary engineered barrier in the geologic repository planned at YM, Nevada. The ability of the WP to contain and, in the long term, limit release of RNs is primarily determined by the long-term corrosion resistance of WP materials. The WP 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 RNs with short half-lives are abundant and by limiting release of RNs with long half-lives over long 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, 1998b; 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.

Acceptance Criteria and Review Methods

DOE's approach in abstracting WP corrosion in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the contribution of the engineered system to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the WP corrosion abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and define relevant parameters in DOE's WP corrosion abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should determine whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE has identified the most important degradation modes and has provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the WP corrosion abstraction, such as the critical relative humidity (RH), material properties, pH, and chloride concentration are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the WP corrosion input/data in the performance calculations. Staff should ascertain that the input values used in the WP corrosion calculations in TSPA are reasonable, based on data from the YMR (e.g., single heater test results) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions (design features) and the repository, thermal loading strategy, thermal reflux, deep percolation flux, and presence assumptions of the conceptual models for the YM site (e.g., the RH for use in the WP corrosion calculation should be based on location of the WP in the or absence of backfill material and any other design features that may affect performance). In addition, the staff should verify that the correlations between input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the WP corrosion abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the WP corrosion abstraction. Staff should run the NRC TPA code to assist in verifying that the intermediate output of the engineered system produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

WP corrosion abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings, natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of the WP corrosion abstraction reasonably reproduces or bounds the results of the corresponding process-level models or alternative sources of data. To the extent feasible and applicable, staff should evaluate the output of DOE's WP corrosion abstraction against results produced by the detailed process-level model or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the WP corrosion abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches.[10] For example, the staff should determine whether the conditions and assumptions used to generate look-up tables or regression equations[11] are consistent with all other conditions and assumptions in the TSPA for abstracting WP corrosion. Important design features that will set the initial and boundary conditions for abstracting WP corrosion include WP design and material selection, thermal loading strategy, use of backfill, drift size and spacing, WP spacing, and others. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects, staff does not need to include such design features in its review. Staff should verify that DOE's dimensionality abstractions[12] appropriately account for the various design features, site characteristics, and alternative conceptual approaches. The following are examples of possible important physical phenomena and couplings with other ISIs:

- 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).

These relationships and other computational input/output are illustrated in Figure 4. Staff should verify that DOE's domain-based[13] and temporal abstractions appropriately handled the physical couplings (THMC) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in WP corrosion for potential inconsistency in the analysis and nondefensible predictions.

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

[11] This is called response-surface abstractions in the TSPA-VA Plan (TRW Environmental Safety Systems, Inc., 1996).

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

[13] This involves dividing the repository system into a series of sequentially linked spatial domains.

4.3.1.1.1.1 Description of the U.S. Department of Energy Approach

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, 1998b). 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 (Harrington, 1999). 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. 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; TRW Environmental Safety Systems, Inc., 1995; U.S. Department of Energy, 1998b). 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 WP environment in WAPDEG is assumed to be humid air at elevated temperatures for an extended period followed by an aqueous environment. Degradation of the WP by dry oxidation was considered to be negligible (Stahl, 1993; McCright, 1998) and hence was not included in the calculations. Degradation of the WPs is assumed from humid air corrosion and aqueous corrosion. Humid air corrosion of the carbon steel outer overpack is considered to occur when the RH is between 65 and 75 percent, whereas aqueous corrosion is considered when the RH is above 85 percent. For the carbon steel outer overpack, active general corrosion was assumed in humid air and was modeled using a parametric equation exhibiting a dependence of the corrosion rate on time, RH, and absolute temperature. The parameters were obtained by multiple linear regression analysis of atmospheric corrosion data from tropical, urban, rural, and industrial locations. Aqueous corrosion of the outer overpack was evaluated through a similar approach, using literature data acquired from polluted river water and tropical lake water. Pitting corrosion of the carbon steel overpack was modeled based on input from expert elicitation process.

Under humid air exposure at high RH, the uniform corrosion rate of Alloy 22 was derived from expert elicitation estimations ranging from 2×10^{-8} to 2×10^{-4} mm per year, with a median value of 3.4×10^{-6} mm per year at 100 °C (U.S. Department of Energy, 1998b). Under dripping water conditions, general corrosion rates are also based on expert elicitation estimates. At 100 °C, the composite cumulative distribution of corrosion rates as a result of expert elicitation estimates considering a range of possible repository environments ranged from 1×10^{-7} to 2×10^{-2} millimeters per year with a median value of 4×10^{-5} millimeters per year.

Pitting corrosion of Alloy 22 was also modeled on the bases of the input provided by the expert elicitation process. It was assumed that pitting corrosion of the Alloy 22 inner container did not occur below 80 °C. The pit growth rate was assumed controlled by a diffusional process with a time dependence factor equal to $(\text{time})^{-0.5}$. An expression for the penetration [P (mm)=exp © + Q/T + ε) $t^{0.5}$] due to localized corrosion was then computed on the bases of data obtained at the Lawrence Livermore National Laboratory (LLNL) (long-term tests in simulated groundwaters and potentiodynamic polarization measurements in NaCl and $FeCl_3$ solutions) together with data reported by Haynes International for exposures to 10 percent $FeCl_3$. The expression predicts that the localized corrosion rate will decay with time and the mean value at 100 °C after 1,000 years exposure will be about 4×10^{-7} mm per year, whereas the highest value for the three standard deviation will be 7×10^{-4} mm per year.

On the bases of these abstracted models, the basecase results for TSPA-VA (U.S. Department of Energy, 1998b), in which dripping and no dripping conditions are included and the 50th percentile for the Alloy 22 corrosion rate is used, indicate that the first WP failure due to pit penetration occurred at about 3,000 years, and all the WPs failed in 1,000,000 years. The median lifetime is about 180,000 years. However, if only dripping conditions with the 95th percentile of the corrosion rate are assumed, all WPs failed in 200,000 years and the median lifetime is reduced to approximately 20,000 years. Nevertheless, one of the most important factors affecting the evaluation of the WP lifetime is the uncertainty in the corrosion rate, as recognized in the DOE sensitivity analyses.

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 about 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, 1998b), 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.

Table 2 provides the relationship of the engineered barrier degradation ISI to DOE's factors and Process Model Reports (PMRs) (U.S. Department of Energy, 1998b, 1999a)

Table 2. Relationship between the engineered barrier degradation integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Degradation of engineered barriers	Performance of drip shield	Engineered barrier system
	Performance of waste package barriers	Waste package
	Mechanical stress, moisture, temperature, and chemistry on the drip shield	Waste form
	Mechanical stress, moisture, temperature, and chemistry on the waste package	
	Mechanical stress, moisture, temperature, and chemistry within the waste package	

4.3.1.1.1.2 Analysis of the U.S. Department of Energy Approach

The DOE approach considers uniform corrosion under condensed water films. In addition, the possibility of failure from uniform corrosion and localized corrosion (such as pitting and crevice corrosion) is considered. The DOE's corrosion abstraction evaluates corrosion processes under dripping conditions in a range of possible repository environments that include variations in pH and redox potential (U.S. Nuclear Regulatory Commission, 1999e). However, the technical basis for the selection of the range of environmental conditions is not well defined. Values of the parameters used by the DOE for both the passive corrosion rate and localized corrosion propagation rate appear to be inconsistent with the values reported in the literature and with the DOE laboratory data. The DOE approach does not consider the possibility of SCC at stress intensities less than an experimentally determined K_{ISCC}. In addition, the effects of welding on the mechanical properties and corrosion resistance, although recognized (Gdowski, 1991; Edgecombe-Summers et al., 1999), are not considered in the DOE PA.

Uniform corrosion rates used by the DOE in the TSPA-VA vary by more than 5 orders of magnitude. The large range of corrosion rates was based on expert elicitation estimates. Experimental determinations of the corrosion rates of several candidate container materials, including Alloy 22, have been performed by the DOE. Measured corrosion rates for Alloy 22 range from 4.1×10^{-5} to 7.3×10^{-4} millimeters per year in simulated acidified water (SAW) containing 0.79 molar chloride at pH 2.7 (TRW Environmental Safety Systems, Inc., 1998; Farmer et al., 1998). The wide range of uniform corrosion rates used in the TSPA-VA is not supported by test data. In addition, the wide range of corrosion rates disperses the calculated container failure times from 3,000 years for the first failure to 1,000,000 years for all WP to fail. The wide dispersion of failure times may contribute to the prolonged, slow release of RNs that, in turn, limits the dose rate to members of the receptor group living near the site. Calculation of the container lifetimes using the measured corrosion rates for Alloy 22 may significantly reduce the range of failure times and increase the dose rate at shorter times.

The susceptibility of Alloy 22 to localized corrosion is based on a critical pitting temperature (CPT) of 80 °C. No DOE data are available to support this critical temperature for localized corrosion. Wide variations of CPT and critical crevice temperatures (CCT) have been reported for Ni-Cr-Mo alloys (Sridhar et al., 1994). For example, Renner et al. (1986) reported a CCT of more than 80 °C for Ni-Cr-Mo Alloys 22, C-4, and C-276 in 10 percent $FeCl_3 \cdot 6H_2O$ solution, whereas Hibner (1987) reported a CCT of 55 °C for Alloy 22. Localized corrosion was not observed on Alloy 22 specimens during long-term testing at temperatures of 60 and 90 °C in SAW containing 0.79 molar chloride at pH 2.7 (McCright, 1998). However, the correlation between the environment used in the long-term tests and those estimated through expert elicitation is unclear.

The localized corrosion penetration rates also have an extremely wide range and neither the mean value nor even the highest value (three standard deviations) can be considered characteristic of a localized corrosion process. The lowest localized corrosion penetration rate of 4×10^{-7} mm per year is not representative of a localized corrosion penetration rate. The value of the lowest localized corrosion penetration rate is typical of the dissolution rate under passive conditions (U.S. Nuclear Regulatory Commission, 1999e). The calculated dose rates are strongly influenced by the wide range of assumed localized corrosion penetration rates. Lower dose rates to members of the receptor group may again be the result of dispersing the failure times of the WPs.

Although localized corrosion in the form of pitting corrosion is addressed in the TSPA-VA, the possible failure of the containers by SCC is not considered. Residual stresses approaching the yield strength of Alloy 22 have been measured in the vicinity of the unannealed closure welds of Alloy 22 mockup containers (TRW Environmental Safety Systems, Inc., 1998). SCC of Alloy 22, in 5 percent NaCl at 90 °C, has been reported by McCright (1998) and Roy et al. (1998). The test environment in which SCC was reported is within the range of WP exposure conditions estimated through the expert elicitation process. Crack propagation rates measured on fatigue precracked double cantilever beam test specimens were in the range of 1.27×10^{-7} to 1.79×10^{-7} millimeters per second (4.02–5.65 millimeters per year), which is within the expected SCC propagation rates measured for stainless steel and Ni base alloys. The SCC propagation rates greatly exceed the localized corrosion propagation rate used to calculate container lifetimes and dose rates. Auxiliary calculations performed by the DOE, using a fracture mechanics approach and the value of K_{ISCC} determined at LLNL, indicate that given the magnitude of expected residual stresses, a flaw exceeding 50 percent of the wall thickness would be required to initiate SCC of the Alloy 22 container. Although this approach seems to be technically valid, K_{ISCC} could be lower in a different environment than that tested (Speidel, 1981).

The detrimental effects of welding and thermal exposure on the phase stability and mechanical properties of Alloy 22 have been investigated by the DOE (Gdowski, 1991; Edgecombe-Summers et al., 1999). Exposure of Ni-Cr-Mo alloys to temperatures in the range of 250–550 °C can result in an ordering transformation (Raghavan et al., 1982; Hodge and Ahluwalia, 1993) that can lead to an increased susceptibility to SCC and hydrogen embrittlement. In addition to the ordering, the formation of topologically close packed (TCP) phases, shown to occur at temperatures from 425–1,285 °C (Rebak and Koon, 1998; Heubner et al., 1989; Cieslak et al., 1986) can substantially reduce the ductility of Alloy 22 (Edgecombe-Summers et al., 1999). Long-term corrosion testing of welded Alloy 22 specimens have been conducted at LLNL (McCright, 1998) for a period of up to 1 year in several variants of J-13 water at 60 and 90 °C. Although no localized corrosion was observed on the test specimens, the relationship between the long-term test environment and the expected conditions in the repository, estimated through expert elicitation, is unclear. Previous reports have shown that welding reduces the CPT of Alloys 22 and C-276 (Sridhar, 1990). Thermal exposures are known to degrade the corrosion resistance of Alloy 22 (Farmer, 1999). The increased susceptibility of Alloy 22 to hydrogen embrittlement and SCC as a consequence of ordering and the reduced corrosion resistance of the container welds arising from the formation of TCP phases are not addressed in the DOE PA calculations.

Although the possibility of SCC of Alloy 22 needs to be evaluated, in particular for welded or thermally treated microstructures, the selection of appropriate test methods and representative environmental conditions is critical in assessing the susceptibility to SCC. From this perspective, concerns exist regarding the procedures used and the results obtained in the SCC testing of Alloy 22 at LLNL (Dunn et al., 1999). The SCC susceptibility of Alloy 22 and the possible increased susceptibility of the alloy as a result of WP fabrication and welding are a key concern (U.S. Nuclear Regulatory Commission, 1999e).

4.3.1.1.2 Mechanical Disruption Path to Resolution of Engineered Barriers

Review of the model abstractions for the mechanical disruption of engineered barriers requires evaluation of input from four KTIs: (i) RDTME, (ii) CLST, (iii) SDS, and (iv) IA. 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. Input from the CLST KTI is used to evaluate possible mechanical failure processes of the barriers enhanced or facilitated by TC effects. 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 WPs, 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 life time 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 PA 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 RNs 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 TM 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. PA 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 RN 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 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, 1998b) 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, 1998b; 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 YMR igneous events is on the order of 10^6–10^8 cubic meters, whereas the volume of the repository is on the order of 10^6 cubic meters. 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 igneous disruption is on the order of 5×10^{-7} (U.S. Nuclear Regulatory Commission, 1999i). As a consequence, the contribution to peak expected annual dose 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.

PA 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 EP 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). PA 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.

Acceptance Criteria and Review Methods

DOE's approach to abstracting mechanical disruption of the engineered barriers in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate engineered systems contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing mechanical disruption of the engineered barriers abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models used and to define relevant parameters in DOE's mechanical disruption of the engineered barriers abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should determine whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain disruptive scenarios in its TSPA.[14]

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the mechanical disruption of the engineered barriers abstraction, such as probabilistic seismic hazard curves, probability of dike intrusion, and the probability and amount of fault displacement, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated mechanical disruption of the engineered barriers input/data in the performance calculations. Staff should ascertain that the input values used in the mechanical disruption of the engineered barriers calculations in TSPA are reasonable, based on data from the YMR (e.g., seismic catalogues) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are suitable for the repository design and footprint and are consistent with the assumptions of the conceptual models for the YM site (e.g., estimation of WP failure owing to rockfall should be based on the dimension of the emplacement drift, presence of backfill material, and any other design features that may affect performance). In addition, the staff should verify that the correlation between input values has been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the mechanical disruption of the engineered barriers abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the mechanical disruption of the engineered barriers abstraction. Staff should use the NRC TPA code to assist in verifying that intermediate output of the engineered system produced by DOE's approach reflects or

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[14] The acceptance criteria and review methods for the proper inclusion or exclusion of disruptive scenarios will be provided in Section 4.4.

bounds the range of uncertainties resulting from alternative modeling approaches.

Criterion T4: Model Support

Mechanical disruption of the engineered barriers abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of mechanical disruption of the engineered barriers abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's mechanical disruption of the engineered barriers abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the mechanical disruption of the engineered barriers abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches; (e.g., if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting mechanical disruption of the engineered barriers). Important design features that will set the initial and boundary conditions for abstracting mechanical disruption of the engineered barriers include WP design and material selection, use of backfill, drift size and spacing, WP spacing, and others. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects, staff does not need to include such design features in its review. Staff should verify that DOE's dimensionality abstractions appropriately account for the various design features, site characteristics, and alternative conceptual approaches. The following is an example of possible important physical phenomena and couplings with another ISI:

- 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).

This relationship and other computational input/output are illustrated in Figure 5. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (e.g., hydrological and mechanical) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in mechanical disruption of the engineered barriers for potential inconsistency in the analysis and nondefensible predictions.

4.3.1.1.2.1 Description of the U.S. Department of Energy Approach

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, 1998b). 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 RNs.

Section 10.5.1 of the TSPA-VA Technical Basis Document (TBD) (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 RN 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 WP disturbance.

The TBD 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/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 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 (Civilian Radioactive Waste Management System Management and Operating Contractor, 1996c,d) using three-dimensional (3D) finite element analyses. Degradation (thinning as a result of corrosion) of WPs was considered in the rockfall model (Civilian Radioactive Waste Management System Management and Operating Contractor, 1996c,d).

(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 85th and 15th 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 de-amplification. 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, 1998b), 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 the through-crack mass falls on the WP, it is assumed that the package is breached.

In the TSPA-VA (U.S. Department of Energy, 1998b), 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, 1998b).

(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, 1998b). 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 (1×10^{-8} per year) to require consequence analyses.[15]

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.

DOE's TSPA-VA (U.S. Department of Energy, 1998b) 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 breeched
- HLW from the breeched 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, 1998b).

In its Disposal Criticality Analysis Methodology Topical Report YMP/TR–004Q (U.S. Department of Energy, 1998c), 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.

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

Table 3 provides the relationship between the Mechanical Disruption of Engineered Barriers ISI and the DOE program (U.S. Department of Energy, 1998b, 1999a).

Table 3. Relationship between the mechanical disruption of engineered barriers integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Engineered barriers	Performance of drip shield Performance of waste package barriers Mechanical stress, moisture, temperature, and chemistry on the drip shield Mechanical stress, moisture, temperature, and chemistry on the waste package Mechanical stress, moisture, temperature, and chemistry within the waste package Seismicity/structural deformation Volcanism	Engineered barrier system Waste package Tectonic

4.3.1.1.2.2 Analysis of the U.S. Department of Energy Approach

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 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 exceedence 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 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" (Civilian Radioactive Waste Management System Management and Operating Contractor, 1997a, Section 10.5.1.6) was modeled. This approach appears not to be conservative. The Civilian Radioactive Waste Management System Management and Operating Contractor recognizes this and stated in the TBD 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 (21×10^{-6} per year) 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 1×10^{-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, 1997b). 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, 1999b).

In reviewing the DOE's Disposal Criticality Report YMP/TR–004Q (U.S. Department of Energy, 1998c), 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.

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

Review of the quantity and chemistry of water contacting WPs and waste forms model abstraction involves the (i) CLST; (ii) ENFE; (iii) RDTME; (iv) TEF; (v) Unsaturated and Saturated Zone Flow under Isothermal Conditions (USFIC); and (vi) SDS KTIs. The quantity and chemistry of water contacting WPs and waste forms ISI addresses how much and what type of water interacts with the WP 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 spatial and temporal distribution of flow ISI in the UZ flow and transport component of the geosphere.

RN 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 RN 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 PAs 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 RNs 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 the seepage of water into emplacement drifts and how that water contacts both the WP and waste forms.

WP degradation and the RN 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 RNs in water are dependent on pH, carbonate concentration, and oxygen content (i.e., oxidative dissolution of UO_2). Distribution coefficients (K_ds), which affect the availability of RNs 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 RNs.

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 impact 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 the 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, 1999k). Near-field coupled THC processes will affect both the quantity and chemistry of water entering the emplacement drifts (U.S. Nuclear Regulatory Commission, 1999l). 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, 1999l). As the host rock geochemically alters, 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, 1999k). 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, 1999k). In addition, differential opening and closing of fractures from TM effects will change the hydraulic conductivity of fractures (U.S. Nuclear Regulatory Commission, 1999g). The change in the engineered barriers design concept to one where there is a titanium drip-shield and backfill over the drip-shield changes the assessment of water contacting the WP (U.S. Nuclear Regulatory Commission, 1999e). This design concept is largely untested, however, and the processes that will control the quantity of water that could contact the WP are poorly constrained.

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, 1999l).

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, 1999l). 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, 1999l). As water interacts with the materials inside the WP the water will change in composition.

The following factors are important for determining the quantity of water that could contact WPs: (i) the presence or absence of backfill, its physical characteristics and moisture retention and permeability properties (U.S. Nuclear Regulatory Commission, 1999h); (ii) the presence of a drip-shield (U.S. Nuclear Regulatory Commission, 1999e); (iii) the presence of any coatings, such as shotcrete, on walls of tunnels (U.S. Nuclear Regulatory Commission, 1999h); (iv) fracture geometry, frequency, coatings, intersections, and degree of heterogeneity (U.S. Nuclear Regulatory Commission, 1999f,h); (v) hydraulic properties of fractures, including heterogeneity of properties (U.S. Nuclear Regulatory Commission, 1999h); (vi) percolation flux at the drift and its spatial and temporal variability (U.S. Nuclear Regulatory Commission, 1999h); (vii) the diversion of matrix flow and dripping from fractures at the crown of the drift (U.S. Nuclear Regulatory Commission, 1999h); (viii) flow focusing toward or diversion away from drifts (U.S. Nuclear Regulatory Commission, 1999h,k); (ix) the percolation threshold, below which no seepage into the drift will occur; (x) the effect of cavity wall roughness (U.S. Nuclear Regulatory Commission, 1999k); (xi) 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, 1999k); (xii) the TM effects on drift geometry (U.S. Nuclear Regulatory Commission, 1999g); (xiii) the coupled TMH effects on fracture hydraulic properties (U.S. Nuclear Regulatory Commission, 1999g,k); and (xiv) the coupled THC processes leading to changes in the hydraulic properties of fractures (U.S. Nuclear Regulatory Commission, 1999l).

In addition, several factors affect the quantity of water that could contact 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, 1999k); (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 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, 1999l).

Finally, several factors affect the chemistry of water that could contact the WP and waste forms: (i) interactions between thermal fluids and the host rock, including dissolution of host minerals and precipitation of alteration minerals (U.S. Nuclear Regulatory Commission, 1999l); (ii) interactions between thermal fluids and the engineered barriers materials, including dissolution of the backfill, drip-shield, roof supports materials, WP materials, cladding, and waste forms, and precipitation of alteration minerals of the engineered materials (U.S. Nuclear Regulatory Commission, 1999l); (iii) evaporative concentration of fluids contacting the WP and waste forms (U.S. Nuclear Regulatory Commission, 1999k); (iv) microbial activity (U.S. Nuclear

Regulatory Commission, 1999l); (v) radiolysis (U.S. Nuclear Regulatory Commission, 1999e); and (vi) changes in the gas composition due to coupled THC processes (U.S. Nuclear Regulatory Commission, 1999l).

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
- RT in the UZ

The materials dissolved and released from the EBS are a function of 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 RNs in the UZ. For example, many of the metal oxides that could precipitate have strong sorptive characteristics (e.g., Turner, 1995).

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 PAs (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, 1997b; U.S. Nuclear Regulatory Commission, 1999k; 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 the quantity of water contacting the WP and waste forms are important to total system performance (U.S. Nuclear Regulatory Commission, 1999j; Mohanty et al., 1999; U.S. Department of Energy, 1998b).

Acceptance Criteria and Review Methods

DOE's approach in abstracting quantity and chemistry of water contacting WPs and waste forms in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the engineered systems contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the quantity and chemistry of water contacting WPs and waste forms abstraction in a TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately qualified through a QA program. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563 (Kotra et al., 1996). Additionally, staff should determine whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the quantity and chemistry of water contacting WPs and waste forms abstraction, such as the pH, carbonate concentration, chloride concentration, and amount of water flowing in and out of the breached WP, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated quantity and chemistry of water contacting WPs and waste forms input/data in the performance calculations. Staff should ascertain that the input values used in the quantity and chemistry of water contacting WPs and waste forms calculations in TSPA are reasonable, based on data from the YMR (e.g., drift-scale heater test results) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models and design concepts for the YM site [e.g., estimation of the quantity of water contacting the waste forms should be based on the WP design, WP degradation (corrosion and mechanical disruption), deep percolation flux, presence of backfill material and a drip shield, the thermal reflux model, and other design features that may affect performance]. In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set, and use the TPA code to test sensitivity of the system performance to the input values and correlation used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the quantity and chemistry of water contacting WPs and waste forms abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and justified approaches used in the quantity and chemistry of water contacting WPs and waste forms abstraction. Staff should use the NRC TPA code to assist in verifying that the intermediate output of the engineered system produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

Output of quantity and chemistry of water contacting WPs and waste forms abstraction are supported by comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified the output of quantity and chemistry of water contacting WPs and waste forms abstraction reasonably reproduce or bound the results of corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's abstraction against results produced by process-level models developed by the staff.

Criterion T5: Integration

Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the quantity and chemistry of water contacting WPs and waste forms abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. For example, staff should verify that the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting the quantity and chemistry of water contacting the WPs and waste forms. Important design features that will set the initial and boundary conditions for calculations of the quantity and chemistry of water contacting the WPs and waste forms include WP design and material selection, use of backfill and a drip shield, drift lining, presence of cladding, and others. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects on overall performance, staff does not need to include such design features in its review. Staff should verify that DOE's dimensionality in the abstractions appropriately accounts for the various design features, site characteristics, and alternative conceptual approaches. The following are examples of possible important physical phenomena and couplings with other ISIs :

- Distribution of flow affects amount of water contacting the WPs and waste forms (spatial and temporal distribution of flow).

- Corrosion products may affect chemistry of the water contacting the waste forms. Quantity and chemistry of water contacting WPs affects WP corrosion (EBS degradation).

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

These relationships are illustrated in Figure 6. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (THC) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in estimating the quantity and chemistry of water contacting WPs and waste forms for potential inconsistency in the analysis and nondefensible predictions.

4.3.1.1.3.1 Description of the U.S. Department of Energy Approach

The following approach is used in the TSPA-VA (U.S. Department of Energy, 1998b) to determine the quantity of water contacting the WP. Mean annual infiltration (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, 1998b). 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 one-dimensional (1D), two-dimensional (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, 1999k).

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, 1998b). 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, 1998b) were the 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 EPA-11 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, 1998b). 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, 1998b): (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, 1998b). 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, 1998b). In addition, the chemistry of water expected inside the WP was not used in the cladding degradation models.

Table 4 provides the relationship between the quantity and chemistry of water contacting WPs and waste forms ISI and the DOE program (U.S. Department of Energy, 1998b, 1999a).

Table 4. Relationship between the quantity and chemistry of water contacting waste packages and waste forms integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms	Seepage into drifts	Near-field environment
	Performance of drip shield	Engineered barrier system
	Performance of WP barriers	Waste package
	Coupled processes—effects on seepage	Waste form
	Mechanical stress, moisture, temperature, and chemistry on the waste package	
	Mechanical stress, moisture, temperature, and chemistry on the drip shield	
	Mechanical stress, moisture, temperature, and chemistry within the waste package	
	CSNF waste form (including cladding and canister) performance	
	DSNF, Navy fuel, Pu disposition on waste form performance	
	HLW glass waste (including canister) performance	

4.3.1.1.3.2 Analysis of the U.S. Department of Energy Approach

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, 1999a,h,k).

Many physical properties of repository drifts are not considered in the seepage model (U.S. Nuclear Regulatory Commission, 1999h,k). 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 DOE (U.S. Nuclear Regulatory Commission, 1999h). 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.

Problems with DOE's fracture characterization efforts include under-constrained fracture aperture distributions, under-constrained fracture connectivity across stratal boundaries, and fracture orientations (strike and dip) and lengths not corrected for sampling bias (U.S. Nuclear Regulatory Commission, 1999f). For example, ESF fracture surveys mainly include only larger apertures (U.S. Nuclear Regulatory Commission, 1999f). Additionally, the calculated range of fracture-alpha values considered in the TSPA-VA may be biased because ESF line surveys of fracture frequency have not been corrected for the under-representation of fractures that intersect the ESF at low angles (U.S. Nuclear Regulatory Commission, 1999f). Fracture frequency estimates may also be biased by use of a one-meter cutoff length for the fracture surveys, and the difficulty of counting fractures in swarms (U.S. Nuclear Regulatory Commission, 1999f). Underestimating fracture frequency results in overestimation of effective fracture apertures which, in turn, overestimates the fracture alpha (U.S. Nuclear Regulatory Commission, 1999h). An additional concern is that there are no reported data about fracture properties at the scale of concern in the proposed repository formation (i.e., Tptpll; U.S. Nuclear Regulatory Commission, 1999f). Finally, DOE has not adequately constrained downward-convergent connected fracture networks (flow paths) and excavation-induced fractures and their impact on seepage (U.S. Nuclear Regulatory Commission, 1999f; Drift Seepage Peer Review Panel, 1999).

The analyses used to support the TSPA-VA deal with uncertainty in the seepage fraction and seep flow rate by obtaining model results using nine combinations of fracture permeability and fracture-alpha value (U.S. Nuclear Regulatory Commission, 1999h). However, it has not been adequately demonstrated that the range of values used in these parameter combinations bounds the range of uncertainty in these important characteristics. Further, the discrete probabilities assigned to the nine TSPA parameter sets appear to be arbitrary (U.S. Nuclear Regulatory Commission, 1999h). In the TSPA-VA basecase analysis, only the uncertainty in fracture-alpha values and the rate of present-day infiltration are investigated, and all other parameter values are held constant for the calibrated steady-state flow fields used. The only parameter that was adjusted to achieve model calibration was the fracture-matrix (F/M) reduction factor. This approach does not reasonably bound the uncertainty in the distribution of UZ flow between rock matrix and fractures (U.S. Nuclear Regulatory Commission, 1999h). Additionally, using the F/M reduction factor as the sole model calibration parameter for the basecase flow fields results in the false conclusion that the assumed fracture hydraulic properties have little effect on predictions of repository performance (U.S. Nuclear Regulatory Commission, 1999h).

Another consideration not included 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 (U.S. Nuclear Regulatory Commission, 1999a; Drift Seepage Peer Review Panel, 1999).

Both laboratory-scale heater tests and analog site heater tests have indicated the potential for liquid water to contact a heat source under heterogenous or transient boiling conditions (U.S. Nuclear Regulatory Commission, 1999k). Both the potential for gravity-driven re-fluxing during the thermal period and other coupled processes' effects on seepage were neglected by DOE in their basecase analysis (U.S. Nuclear Regulatory Commission, 1999g,k,l).

A final concern is that the seepage model does not consider the importance of transient (episodic) infiltration (U.S. Nuclear Regulatory Commission, 1999h). This 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 contact WPs 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).

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 4.3.1.1.1.3 (WP degradation ISI). DOE sensitivity analyses in the TSPA-VA show that by decreasing the corrosion rate of the inner overpack material by a factor of 60, the annual dose at 10,000 years decreases from 2 mrem to less than 10^{-3} mrem. The corrosion rate of the inner overpack material is one of the many WP parameters affecting the prediction of WP lifetime in the TSPA-VA. Several WP parameters have been defined based on expert elicitation rather than long-term test data, especially those for the corrosion-resistant material (U.S. Nuclear Regulatory Commission, 1999e). Even if the design was fixed today, only limited data will be available to substantiate the adequacy of the WP design for the LA (U.S. Nuclear Regulatory Commission, 1999a).

Analysis of DOE's approach to cladding degradation is presented in Section 4.3.1.1.4.3 (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, 1999a,e). 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 (U.S. Nuclear Regulatory Commission, 1999a).

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 TSPA-VA TBD (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, 1999l). 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, 1999l). Coupled THC processes that affect seepage were not considered explicitly in the TSPA-VA (U.S. Nuclear Regulatory Commission, 1999l). The effects of coupled THC processes that affect seepage are also important in characterization of the WP chemical environment. We found that the bulk of the long-term data used 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,l). 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,l). 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 (U.S. Nuclear Regulatory Commission, 1999a). 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, 1999l).

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 (U.S. Nuclear Regulatory Commission, 1999a).

4.3.1.1.4 Radionuclide Release Rates and Solubility Limits

Review of the RN release and solubility limits abstraction involves evaluation of input from the CLST, and ENFE KTIs. The RN release and solubility limits ISI addresses the release of RNs 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.

RN 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 RNs 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 RNs away from the waste form to the geosphere generally requires a liquid water pathway. RNs 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 RNs have become incorporated (e.g., schoepite uranyl-hydrate); or (iii) the solubility of the RNs 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 RNs 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 RN elements might limit concentrations in WP water if release of RNs 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 RNs are released from the WP into the waste emplacement drifts, interaction with other engineered components could affect the release of RNs to the geosphere.

Near-field coupled THC processes will affect the environment for RN 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) RN 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 RNs; (vi) secondary mineral formation and co-precipitation; (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 RNs 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.

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
- 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 RNs 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 RNs, 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, 1998b). 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, 1999j; Mohanty et al., 1999; U.S. Department of Energy, 1998b). Four different spent waste 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 an order of magnitude or more (Mohanty et al., 1999).

Acceptance Criteria and Review Methods

DOE's approach in abstracting RN release rates and solubility limits in a TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the engineered systems contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing RN release rates and solubility limits abstracted in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately qualified through a QA program. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on other appropriate sources such as an expert elicitation conducted in accordance with NUREG–1563 (Kotra et al., 1996). Additionally, staff should determine whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the RN release rates and solubility limits abstraction, such as the pH, temperature, colloidal release, and amount of liquid contacting the waste forms, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated RN release rates and solubility limits input/data in the performance calculations. Staff should ascertain that the input values used in estimating the RN release rates and solubility limits in the TSPA are reasonable, based on data from the YMR (e.g., drift-scale heater test results) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions in the conceptual models for the YM site [e.g., estimation of the amount of the RN released from breached WPs should be based on the initial inventory, chemical forms of the RNs, WP degradation model (i.e., how water flows in and out of the failed WPs), deep percolation flux (i.e., how much water is available), and other design features that may affect performance]. In addition, the staff should verify that the correlation between the input values is appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlation used by DOE.

Criterion T3: Model Uncertainty

Alternative waste form dissolution and RN release modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the RN release rates and solubility limits abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the RN release rates and solubility limits abstraction. Staff should run the NRC TPA code to assist in verifying that the intermediate output of the engineered system produced by DOE's approach reflects or bounds the range of uncertainties resulting from alternative modeling approaches.

Criterion T4: Model Support

RN release rates and solubility limits abstraction output is supported by comparison to outputs of detailed process models or empirical observations (field, laboratory, or natural analog data).

Review Method: Staff should ascertain whether DOE verified the output of RN release rates and solubility limits abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's RN release rates and solubility limits abstraction against the results produced by the process-level models developed by the staff.

Criterion T5: Integration

Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the RN release rates and solubility limits abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. For example, staff should determine if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with other conditions and assumptions in the TSPA for abstracting the RN release rates and solubility limits. Important design features that will set the initial and boundary conditions for abstracting the RN release rates and solubility limits include WP design and material selection, type of SNF, waste forms, thermal loading strategy (for temperature and RH considerations), use of backfill and a drip shield, drift size (for mechanical disruption considerations), and others. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's, DOE's, or both, analyses to provide only benefits and no deleterious effects, staff does not need to include such design features in its review. Staff should verify that DOE's dimensionality abstractions appropriately account for the various design features, site characteristics, and alternative conceptual approaches. Examples of possible important physical phenomena and couplings with other ISIs are:

- 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).

These relationships and other computational input/output are illustrated in Figure 7. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (THC) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in estimating the RN release rates and solubility limits for potential inconsistency in the analysis and nondefensible predictions.

4.3.1.1.4.1 Description of the U.S. Department of Energy Approach

The conceptual framework that DOE used was for degraded WPs. 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, 1998b). The conceptual model used by DOE composed 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, 1998b). 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, 1998b). 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, 1998b). 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, 1998b). 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, 1998b). 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, 1998b). 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, 1998b). 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, 1998b).

Table 5 provides the relationship of the RN release rates and solubility limits ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a)

Table 5. Relationship between the radionuclide release rates and solubility limits integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Radionuclide Release Rates and Solubility Limits	Dissolved radionuclide concentration limits	Waste form
	Mechanical stress, moisture temperature, and chemistry within the waste package	Engineered barrier system
	CSNF waste form (including cladding and canister) performance	
	DSNF, Navy fuel, Pu disposition, waste form performance	
	HLW glass waste (including canister) performance	
	In-package radionuclide transport	
	Colloid-associated radionuclide concentrations	
	EBS radionuclide migration—transport through invert	

4.3.1.1.4.2 Analysis of the U.S. Department of Energy Approach

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, 1998b) 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, 1999l). 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, 1999l). 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, 1998b) 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, 1999l). 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, 1998b), 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 (U.S. Nuclear Regulatory Commission, 1999a). 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 hydrogen embrittlement 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 (U.S. Nuclear Regulatory Commission, 1999a).

DOE took credit for partially failed containers as another barrier to RN release (U.S. Department of Energy, 1998b). 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 kilometers 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, 1998b) consistent with the methodology proposed in the topical report on disposal criticality (U.S. Department of Energy, 1998c). 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, 1999l).

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, 1998b). 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, 1999l).

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, 1999l). DOE did not attempt to evaluate potential microbial effects on RN release (U.S. Department of Energy, 1998b). 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, 1999l).

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, 1999l).

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, 1998b), and the sorption coefficients used in the TSPA-VA are referred to as "placeholder K_ds" 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, 1999l). 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, 1999l).

4.3.2 Geosphere

From the standpoint of transport of RNs 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 RNs to the water table below the proposed repository. In the following discussion, acceptance criteria and review methods are focused on defining those aspects of the analysis necessary to make this evaluation.

4.3.2.1 Unsaturated Zone Flow and Transport

In this section, the technical acceptance criteria and review methods for the three key elements under the UZ flow and transport abstraction, as identified in Figure 3 (i.e., spatial and temporal distribution of flow, distribution of mass flux between fracture and matrix, and retardation in the UZ), are discussed. The key elements for this abstraction were derived from staff experience with previous and current IPA activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system levels, and reviews of DOE's hypotheses in its RSS. Further, these key elements represent the essential factors to be considered in demonstrating the UZs capability to improve total system performance. DOE's abstraction of the UZ flow and transport in its TSPA for the proposed repository at YM will be considered satisfactory if the acceptance criteria for all three ISIs are met.

4.3.2.1.1 Spatial and Temporal Distribution of Flow

Review of the spatial and temporal distribution of flow model abstraction involves evaluation of input from the (i) ENFE; (ii) RDTME; (iii) SDS; (iv) TEF; and (v) USFIC KTIs. The spatial and temporal distribution of flow ISI addresses the near-surface hydrologic processes, such as precipitation, temperature, climate change, and infiltration. Infiltration is ultimately the amount of water reaching the repository horizon and 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 spatial and temporal distribution of flow and other ISIs are illustrated in Figure 8.

The percolation flux at the repository horizon depends on the precipitation and temperature of the modeled climate, the estimate of shallow 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. The hydrologic characteristics of flow in the shallow 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 occurs in both the fractures and the rock matrix.

Generally, the present and future factors that affect the spatial and temporal distribution of flow include temperature and precipitation, heterogeneities of soil cover and bedrock, surface-water runoff, topography, evapotranspiration, near-field THC processes, and thermally driven water. Thermally driven water may also affect the fracture and matrix hydraulic pathways in vertical and near-vertical fractures due to gravity-driven refluxing.

The mean annual precipitation (MAP), MAI, mean annual temperature, and deep percolation fluxes are important to performance in the TPA code. Two climate variables, temperature and precipitation, have the dominant effect on infiltration. Deep percolation fluxes, resulting from infiltration of meteoric waters, have been shown important to performance in the repository model. Infiltration is important because it determines the quantity of water flow past the WPs, which provides the mechanism for mobilization of dissolved RNs moving through the UZ. Climate models strongly affect performance predictions by their influence on precipitation and evapotranspiration, which in turn affect infiltration. Magnitude and timing of climate change are thus important. The biggest 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 percolation rate at the repository horizon is generally assumed uniform in time and equal to shallow infiltration. Factors such as soil cover, evapotranspiration, and type of bedrock determine the quantity of shallow 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 shallow infiltration is not spatially or temporally uniform, the wetting pulses are attenuated en route to the repository; they spread to become more spatially and temporally uniform. Thus, percolation is assumed uniform at the repository horizon in all YM PAs. The 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 over 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 shallow infiltration, fracture pathways through the paintbrush nonwelded tuff (PTn), and heterogeneities in the PTn may contribute to episodic pulses of flow to the repository horizon and lower. Determination of the portion of flow that moves in episodic fashion along the fast pathways relative to the entire UZ flow is problematic.

Acceptance Criteria and Review Methods

DOE's approach in abstracting spatial and temporal distribution of flow in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the geospheres contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the spatial and temporal distribution of flow abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definition of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should ascertain whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the spatial and temporal distribution of flow abstraction [such as the effects of climate change on infiltration, near surface influences (e.g., evapotranspiration and runoff) on infiltration, structural controls on the spatial distribution of deep percolation, and thermal reflux owing to repository heat load] are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated spatial and temporal distribution of flow input data in the performance calculations. Staff should ascertain that the input values used in the spatial and temporal distribution of flow calculations in TSPA are reasonable, based on data from the YMR (e.g., niche infiltration tests) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site [e.g., estimation of the deep percolation flux into the drift should be based on the infiltration rate, structural control (for flow diversion via faults), thermal loading strategy (for reflux), and other design features that may affect spatial and temporal distribution of flow]. In addition, the staff should verify that the correlation between the input values has been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlation used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches, consistent with available data and current scientific understanding, are investigated and results and limitations appropriately factored into the spatial and temporal distribution of flow abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models (e.g., alternative thermal reflux models) and provided supporting information for the approaches used in the spatial and temporal distribution of flow abstraction. Staff should run the TPA code to assist in verifying that the intermediate output of the geosphere produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

Spatial and temporal distribution of flow abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain that DOE demonstrated that the output of spatial and temporal distribution of flow abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's spatial and temporal distribution of flow abstraction against results produced by process-level models developed by the staff, or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the spatial and temporal distribution of flow abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. For example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting the spatial and temporal distribution of flow. Important design features that will set the initial and boundary conditions for abstracting the spatial and temporal distribution of flow include thermal loading strategy, drift size and spacing, and others. Staff should verify that dimensionality in DOE's abstractions appropriately account for the various design features, site characteristics, and alternative conceptual approaches. The following are examples of possible important physical phenomena and couplings with other ISIs :

- Distribution of flow affects amount of water contacting WPs and waste forms (quantity and chemistry of water contacting WPs and waste forms).
- Spatial and temporal distribution of flow contributes to partitioning of mass flux between fractures and matrix (distribution of mass flux between fracture and matrix).

These relationships are illustrated in Figure 8. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (THCM) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in spatial and temporal distribution of flow for potential inconsistency in the analysis and nondefensible predictions.

4.3.2.1.1.1 Description of the U.S. Department of Energy Approach

A 3D mountain-scale UZ flow model was used to calculate unsaturated groundwater flow at YM for the TSPA-VA. 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 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, 1998b) used a spatially heterogeneous shallow 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.

Subarea averaging of the percolation is used as input to the drift-scale seepage model. For shallow infiltration, DOE links the periodicity of MAI to glacial cycles through postulated MAP. The recent DOE model for shallow infiltration incorporates the effects due to runoff/runon and variations in vegetation and temperature due to climate change.

Table 6 provides the relationship of the spatial and temporal distribution of flow ISI to DOE's PMRs and factors identified in the Repository Safety Strategy, Revision 3 (U.S. Department of Energy, 1998b, 1999a).

Table 6. Relationship between the spatial and temporal distribution of flow integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Spatial and Temporal Distribution of Flow	Climate	Unsaturated zone flow and transport
	Infiltration	Near field environment
	Unsaturated zone flow above the repository	
	Coupled processes—effects on unsaturated zone flow	
	Unsaturated zone flow and transport—advective pathways	

4.3.2.1.1.2 Analysis of the U.S. Department of Energy Approach

The DOE has recognized the need to validate the spatial and temporal distribution of flow in the mountain-scale model. Ongoing work in the alcoves and niches of the ESF along with the planned work in the east-west cross drift will increase confidence in the mountain-scale model.

The current infiltration is calculated for each 30 x 30 meters pixel over the mountain-scale model of UZ flow. 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, 1997a) 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 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 infiltration maps.

The mountain-scale UZ flow model is used to translate shallow 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.

Calibrations were performed by simultaneous inversion of 1D columns associated with each borehole. The relevance of 1D parameter inversions to a 3D flow model has been acknowledged as a problem. The next calibration will be a 3D inversion (LA plans and DOE PA workshop on UZ, December 13–16, 1998). The 3D inversion will better account for lateral flow below the repository, an issue important for transport calculations. Based on descriptions provided in the TSPA-VA TBD, the DOE multiscale TH model appears to be an acceptable systematic analysis of TEF at the proposed YM repository. Insufficient detail is included in the TBD 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.

4.3.2.1.2 Flow Paths in the Unsaturated Zone

Review of the flow paths in the UZ model abstraction involves evaluation of input from the (i) ENFE); (ii) SDS; (iii) TEF; and (iv) USFIC KTIs. The flow paths in the UZ ISI addresses the distribution of moisture flow in unsaturated fractured rock. This ISI is 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 ground water table occurs in both the fractures and the rock matrix. The proportion of water flowing through the rock matrix is dependent on total percolation flux, which is the liquid-water flux below the zone of shallow infiltration that moves downward through the UZ. 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 draw infiltrating water into the rock matrix. When the flow of infiltrating water in the UZ approaches or exceeds the matrix flow capacity, an increasingly greater proportion 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 though the matrix, thereby making more likely the possibility of liquid water entering the drifts.

Near-field THC processes may effect 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 matric 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 infiltration 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 RNs within the tuff and valley-fill aquifers.

Flow paths in the UZ are potentially important to system performance because of the influence on:

- RT in the UZ and SZ
- Quantity of water contacting the WP and waste forms

Deep percolation fluxes, resulting from infiltration of meteoric waters, have been shown to be of importance to isolation performance of the proposed repository (Wescott et al., 1995; U.S. Department of Energy, 1998b; 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.

Acceptance Criteria and Review Methods

DOE's approach in abstracting flow paths in the UZ in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the geospheres contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the flow paths in the UZ in the abstraction in TSPA. Where adequate data cannot be readily obtained, other information sources such as expert elicitation or bounding values have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should ascertain whether DOE has performed sensitivity and uncertainty analyses to test for the significance of this aspect to repository performance and the possible need for additional data. Staff should also verify that DOE has provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the flow paths in the UZ in the abstraction, such as hydrologic properties, stratigraphy, and infiltration rate, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated flow paths in the UZ input/data in the performance calculations. Staff should ascertain that the input values used in the flow paths in the UZ calculations in TSPA are reasonable, based on data from the YMR (e.g., niche test results) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site (e.g., estimation of the flow partition should be based on the infiltration rate, percolation flux, stratigraphy, matrix conductivity, thermal loading strategy, thermal reflux models, and other design features that may affect the flow partition between fracture and matrix). In addition, the staff should verify that the correlation between the input values has been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlation used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the distribution on mass flux between fracture and matrix in the abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the flow paths in the UZ in the abstraction. Staff should run the TPA code to assist in verifying that the intermediate output of the models representing the geosphere produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

Flow paths in the UZ abstraction output are justified through comparison to output of detailed flow process models or empirical observations (laboratory testings, natural analogs, or both).

Review Method: Staff should ascertain that DOE demonstrated that the output of flow paths in the UZ abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's flow paths in the UZ in the abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the flow paths in the UZ abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches; for example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting the flow paths in the UZ. Important design features that will set the initial and boundary conditions for calculating the flow paths in the UZ include thermal loading strategy, drift spacing, drift design, and others. Staff should verify that DOE's dimensionality abstractions appropriately account for the various design features, site characteristics, and alternative conceptual approaches. The following are examples of possible important physical phenomena and couplings with other ISIs:

- Spatial and temporal distribution of flow contributes to partitioning of mass flux between fractures and matrix (spatial and temporal distribution of flow).
- Amount of flow in fractures in the UZ affects the importance of retardation in fractures (retardation in fractures in the UZ).

These relationships and other computational output are illustrated in Figure 9. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (THC) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in flow paths in the UZ for potential inconsistency in the analysis and nondefensible predictions.

4.3.2.1.2.1 Description of the U.S. Department of Energy Approach

A 3D mountain-scale UZ flow model was used to calculate unsaturated groundwater flow at YM for the TSPA-VA. The model implemented the dual-permeability formulation for F/M interactions and consisted of nearly 80,000 elements. Hydrologic properties 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 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 α_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 drives transfer of fluid between the continua. The α_f value is important because, for any given saturation level the assumed α_f value affects how strongly a fracture retains the water that resides within it. Of course, the assumed alpha value for matrix α_m is equally important for the same reason, however, there are numerous laboratory measurements from which to estimate α_m, whereas there is little basis for estimating α_f values. In the DOE UZ flow model, α_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 multi-scale modeling approach was used to abstract thermal hydrology processes into the TSPA-VA. The multi-scale 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 multi-scale 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 multi-scale 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} square meters
- 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.

Table 7 provides the relationship of the flow paths in the UZ ISI to DOE's PMRs and factors identified in the Site Recommendation Report, Revision 3 (U.S. Department of Energy, 1998b, 1999a).

Table 7. Relationship between the flow paths in the unsaturated zone integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Flow Paths in the Unsaturated Zone	Unsaturated zone above the repository Coupled processes—effects on unsaturated zone flow Unsaturated flow and transport—advective pathways	Unsaturated zone flow and transport Near field environment

4.3.2.1.2.2 Analysis of the U.S. Department of Energy Approach

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.

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 (α_F) values used in the TSPA-VA analyses, the estimated range of α_F values may be too high. Higher values of α_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 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, 1998b, Volume 3) does not adequately bound this uncertainty, so the expected benefits of water flowing through rock matrix may be overly optimistic. This assertion is discussed further in the following paragraphs.

For example, to account for parameter uncertainty in TSPA-VA analyses, alternative model scenarios were developed using estimated minimum, mean, and maximum α_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, 1998b, 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. Additionally, in a recent 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

Based on descriptions provided in the TSPA-VA TBD, the DOE multiscale TH model appears an acceptable systematic analysis of TEF at the proposed YM repository. Insufficient detail is included in the TBD 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.

4.3.2.1.3 Radionuclide Transport in the Unsaturated Zone

Review of the RT in the UZ model abstraction involves the USFIC, ENFE, SDS, and RT KTIs. 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 RN 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_m is the average linear velocity of the RN, 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 RNs in the UZ are sorption, precipitation, dispersion, diffusion, and radioactive decay in the nonwelded units that underlie the repository. Processes that influence RNs associated with colloids include those processes described previously for the dissolved species along with filtration and settling.

Transport of RNs through the UZ has been shown to 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 RNs 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, 1998b), 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.

Acceptance Criteria and Review Methods

DOE's approach in abstracting RT in the UZ in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. The staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the geospheres contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the RT in the UZ abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA. Alternatively, the parameters or models lacking sufficient data have been replaced by bounding parameter values or models.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563 (Kotra et al., 1996). Additionally, staff should ascertain whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the RT in the UZ abstraction, such as the sorption on fracture surfaces, and K_d for the matrix, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated RT in the UZ input/data in the performance calculations. Staff should ascertain that the input values used in the RT in the UZ calculations in TSPA are reasonable, based on data from the YMR, and other applicable laboratory tests and natural analogs. Alternatively, bounding values of the input values have been used in the calculations such as assuming that RNs traveling in fractures in the UZ do not exhibit any retardation. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site [e.g., estimation of the RN retardation along transport path from the repository to the water table should be based on the chemical properties of the RN, the deep percolation flux (for flow and transport) and the properties of the various hydrogeologic units]. In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the RT in the UZ abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the RT in the UZ abstraction. Staff should run the TPA code to assist in verifying that the intermediate outputs of the models representing the geosphere produced by DOEs approach reflect or bound the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

RT in the UZ abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain whether DOE has demonstrated that the output of RT in the UZ abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's RT in the UZ abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important physical phenomena and couplings and consistent and appropriate assumptions are incorporated into the consideration of RT in the UZ abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. For example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting RT in the UZ. Staff should verify that the dimensionality in DOE's abstractions appropriately accounts for the site characteristics and alternative conceptual approaches. The following are examples of possible important physical and chemical phenomena and couplings with other ISIs.

- The pH and dissolved constituents may affect the sorption characteristics (RN release rates and solubility limits).
- The amount of flow in fractures affects the importance of retardation in fractures (distribution of mass flux between fracture and matrix).

These relationships are illustrated in Figure 10. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (THC) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach to RT in the UZ for potential inconsistency in the analysis and nondefensible predictions.

4.3.2.1.3.1 Description of U.S. Department of Energy Approach

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, 1998b) 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, 1998b, 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 kilometers 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, 1998b, Volume 3, Section 4.3.1.1).

Table 8 provides the relationship of the RT in the UZ ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a).

Table 8. Relationship between the radionuclide transport in the unsaturated zone integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Radionuclide Transport in the Unsaturated Zone	Unsaturated zone flow and transport—sorption and matrix diffusion Unsaturated zone flow and transport—advective pathways Unsaturated zone flow and transport—colloid-facilitated transport Coupled processes—effects on unsaturated zone transport	Unsaturated zone flow and transport Near field environment

4.3.2.1.3.2 Analysis of the U.S. Department of Energy Approach

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 kilometers 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 kilometers 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 LANL (Triay et al., 1992) to validate K_d values from batch sorption tests is logical and defensible (U.S. Nuclear Regulatory Commission, 1999m). 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, 1998b), 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 meters) 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.

4.3.2.2 Saturated Zone Flow and Transport

In this section, the technical acceptance criteria and review methods for the two key elements under the SZ flow and transport abstraction are discussed, as identified in Figure 3 (i.e., flow rates in water-production zones and retardation in water-production zones and alluvium). The key elements for this abstraction were derived from the staff experience from previous and current IPA activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system level, and reviews of DOE's hypotheses in its RSS. Further, these key elements represent the essential factors to be considered in demonstrating the SZs capability to improve total system performance. DOE's abstraction of the SZ flow and transport in its TSPA for the proposed repository at YM will be considered satisfactory if the acceptance criteria for both key elements are met.

4.3.2.2.1 Flow Paths in the Saturated Zone

Review of the flow paths in the SZ model abstraction involves two KTI's: SDS and USFIC. The flow paths in the SZ ISI address 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 RNs from the proposed repository to the accessible biosphere at receptor locations downstream of YM. RN dose to the critical group at the receptor location is dependent on the transport times from the repository to the receptor locations, the RN 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 RNs 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 RNs at the receptor locations. Mixing and the resulting dilution of RNs in the groundwater along the flow path between the repository and the receptor location will also affect the RN dose at the receptor location.

RNs 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 RNs during transport.

Acceptance Criteria and Review Methods

DOE's approach in abstracting flow paths in the SZ in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria and review methods are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the geospheres contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient hydrogeologic data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the flow paths in the SZ abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG-1563. Additionally, staff should evaluate whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the flow paths in the SZ abstraction, such as the effect of climate change on the SZ fluxes and water table level and well pumping practices, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated flow paths in the SZ input/data in the performance calculations. Staff should ascertain that the input values used in the flow paths in the SZ calculations in TSPA are reasonable, based on data from the YMR (e.g., C-Wells test results) and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions (structural control) and the assumptions of the conceptual models for the YM site (e.g., regional discharge/recharge, channelization in stratigraphic features, fracture network connectivity, and other features that may affect performance). In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE input values by comparison to the corresponding input values in the staff data set and use the TPA code to test the sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the flow paths in the SZ.

Review Method: Staff should ascertain that DOE has considered plausible alternative models and justified the approaches used in the flow paths in the SZ abstraction. Staff should run the TPA code to assist in verifying that the intermediate output of the geosphere produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

Flow paths in the SZ abstraction output are justified through comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output from the flow paths in the SZ abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible and applicable, staff should evaluate the output of DOE's flow paths in the SZ abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important site (geologic and hydraulic) features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the flow paths in the SZ abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. For example, staff should determine if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting flow paths in the SZ. If DOE decides not to take credit for certain site features that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects, staff does not need to include such features in its review. Staff should verify that the dimensionality in DOE's abstractions appropriately account for the various site characteristics and alternative conceptual approaches. The following are examples of possible important physical phenomena and couplings with other ISIs:

- 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 RNs in groundwater (dilution of RNs 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).

These relationships and other computational input are illustrated in Figure 11. Staff should verify that DOE's domain-based and temporal abstraction appropriately handled the UZ and SZ coupling. To the extent feasible, staff should use the TPA code to selectively probe DOEs approach in flow paths in the SZ for potential inconsistency in the analysis and nondefensible predictions.

4.3.2.2.1.1 Description of the U.S. Department of Energy Approach

The TSPA 3D SZ flow model was developed using FEHMN with a model domain of about 20 × 36 kilometers to a depth of 950 meters below the water table (TRW Environmental Safety Systems, Inc., 1998). The model domain was discretized into a uniform orthogonal mesh with 500 × 500 × 50-meter 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 meters along the potential flow paths down-gradient 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 meters 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-kilometer long streamtubes that are about 3,000 meters in width and 10–20 meters in depth (width). The volumetric flow rate of each streamtube was determined at the water table from the UZ site-scale model (Bodvarsson et al., 1997). Specific discharge into each streamtube was 0.6 meters 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-meter 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 meters or more of offset were recorded in 1:24,000 scale studies, while faults with 1 meter or more of offset were recorded in the more detailed studies (U.S. Department of Energy, 1998b). Many of these studies have recently been integrated and summarized in the DOE YM Site Description (U.S. Department of Energy, 1998b): 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.

Table 9 provides the relationship of the flow paths in the SZ ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a).

Table 9. Relationship between the flow paths in the saturated zone integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Flow Paths in the Saturated Zone	Dilution in saturated zone Saturated zone flow and transport—advective pathways	Saturated zone flow and transport

4.3.2.2.1.2 Analysis of the U.S. Department of Energy Approach

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 (TRW Environmental Safety Systems, Inc., 1995) evaluation of dilution in the SZ relied on largely unsupported values for vertical mixing (i.e., mixing depths up to 2.9 kilometers). 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 (DLS) 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 meter also may modify fracture intensity interpretations near faults such as the Ghost Dance fault in the ESF, where the 1 meter 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

4.3.2.2.2 Radionuclide Transport in the Saturated Zone

Review of the RT in the SZ model abstraction involves evaluation of data needs identified in the USFIC, SDS, and RT KTIs. 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 RN 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_m is the average linear velocity of the RN, ρ is the bulk density, θ 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 (U.S. Nuclear Regulatory Commission, 1999m).

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

The transport of RNs 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 RNs 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, 1998b), 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 have identified SZ transport parameters as being influential to overall system performance (Mohanty et al., 1999).

Acceptance Criteria and Review Methods

DOE's approach in abstracting RT in the SZ in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. The staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate geospheres contribution to total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the RT in the SZ abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563 (Kotra et al., 1996). Additionally, staff should ascertain whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the RT in the SZ abstraction, such as the sorption on fracture surfaces and K_d for matrix, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated RT in the SZ input/data in the performance calculations. Staff should ascertain that the input values used in the RT in the SZ calculations in TSPA are reasonable, based on data from the YMR, and other applicable laboratory tests and natural analogs. Alternatively, bounding values of the input values have been used in the calculations such as assuming that RNs traveling in fractures in the UZ do not exhibit any retardation. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site [e.g., estimation of the RN retardation along transport path from the repository to the water table should be based on the chemical properties of the RN, the deep percolation flux (for flow and transport) and the properties of the various hydrogeologic units]. In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the RT in the SZ abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the RT in the SZ abstraction. Staff should run the TPA code to assist in verifying that the intermediate outputs of the models representing the geosphere produced by DOE's approach reflect or bound the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

RT in the SZ abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain whether DOE has demonstrated that the output of RT in the SZ abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's RT in the SZ abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important physical phenomena and couplings and consistent and appropriate assumptions are incorporated into the consideration of RT in the SZ abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches; for example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting RT in the UZ. Staff should verify that the dimensionality in DOE's abstractions appropriately account for the site characteristics and alternative conceptual approaches. The following are examples of possible important physical phenomena and couplings with other ISIs:

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

- Amount of flow in fractures affects the importance of retardation in fractures (distribution of mass flux between fracture and matrix).

These relationships are illustrated in Figure 12. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (THC) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach to RT in the SZ for potential inconsistency in the analysis and nondefensible predictions.

4.3.2.2.2.1 Description of the U.S. Department of Energy Approach

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 kilometers. 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, 1998b) 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).

Table 10 provides the relationship of the RT in the UZ ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a).

Table 10. Relationship between the radionuclide transport in the saturated zone integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Radionuclide Transport in the Saturated Zone	Saturated zone flow and transport—sorption and matrix diffusion Saturated zone flow and transport—advective pathways	Saturated zone flow and transport

4.3.2.2.2.2 Analysis of the U.S. Department of Energy Approach

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, 1999m) finds that the approach adopted by LANL (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, 1998b), 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, 1998h) 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 kilometers of the repository. With the resultant increase in the length of the flowpath to the biosphere to 20 kilometers, consistent proposed for 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999c), 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_ds 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 meters (110 feet) in well NC–EWDP–3S to more than 490 meters (1,618 feet) 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_ds 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.

4.3.2.3 Direct Release and Transport

The technical acceptance criteria and review methods for the two key elements under direct release and transport, as identified in Figure 3 (i.e., volcanic disruption of WPs and airborne transport of RNs) are discussed in this section. These key elements for this abstraction were derived from the staff experience from previous and current IPA activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system levels, and reviews of DOE's hypotheses in its RSS. Further, the key elements represent the essential factors to be considered in evaluating the effect of direct release and transport on the total system performance. DOE's abstraction of the direct release and transport in its TSPA for the proposed repository at YM will be considered satisfactory if the acceptance criteria for both key elements are met.

4.3.2.3.1 Volcanic Disruption of Waste Packages

Review of the volcanic disruption of WPs model abstraction involves evaluation of input from the (i) IA; (ii) SDS; and (iii) CLST KTIs. 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 TM 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 elevation of 4–10 kilometers 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 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).

Acceptance Criteria and Review Methods

DOE's approach in abstracting the volcanic disruption of WPs in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models that are used in the performance calculations to demonstrate the effects of direct release and transport on the total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for abstracting the volcanic disruption of WPs in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: Acceptable models will be consistent with the geologic record of basaltic IA in the YMR. Staff should determine the adequacy and sufficiency of DOE characterization and documentation of past YMR IA, including uncertainties about the interpreted characteristics of past activity, such that reasonable projections can be made of the expected characteristics of potential future eruptions in the YMR. Because many important data cannot be derived directly from ancient YMR igneous systems, staff also will compare proposed parameters and models with data measured directly at reasonably analogous, historically active basaltic igneous systems. Particular emphasis will be placed on igneous processes that directly affect the ability of igneous events to disrupt and transport HLW into the accessible environment. Models and supporting data will need to address the apparent changes in disruption potential for YMR basaltic volcanic events since approximately 4–5 Ma. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definition of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the volcanic disruption of WPs abstraction are technically defensible and reasonably account for uncertainties and variability. The technical basis for the parameter values used in the PA needs to be provided.

Review Method: Acceptable parameters should be constrained by data from YMR igneous features and from appropriate analog systems such that the effects of IA on waste containment are not underestimated. Staff will review parameters used in DOE performance models for consistency with the range of characteristics interpreted for YMR basaltic igneous systems. Because many important parameters cannot be derived directly from YMR igneous systems, staff should compare proposed parameters values with parameters measured directly at reasonably analogous, historically active basaltic igneous systems. Acceptable parameters should account quantitatively for the variability in parameter values observed in site data and the available literature (i.e., data precision), and the uncertainty in applying parameter values to process models (i.e., data accuracy). Staff also should verify that possible correlation between parameters has been appropriately established by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the volcanic disruption of WPs abstraction.

Review Method: Staff should ascertain that DOE considered credible alternative modeling approaches for significant processes affecting volcanic disruption of the WP. Alternative modeling approaches should be consistent with current scientific understanding, as evinced by publication of models or supporting data in peer-reviewed literature or publications arising from approved QA programs. Staff should determine if credible alternative modeling approaches reflect, bound, or exceed the range of uncertainty in the expected annual dose proposed by DOE.

Criterion T4: Model Support

Outputs of the volcanic disruption of WPs abstraction are justified through comparison to outputs of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Acceptable models will be justified against igneous processes observed at active or recently active analog igneous systems, or through appropriate experimental investigations. Staff should determine if DOE has demonstrated that proposed process-level consequence models are consistent with data from reasonably analogous small-volume basaltic volcanic systems, laboratory models, or other process-level observations. In particular, staff should evaluate the effectiveness of proposed models in quantifying processes observed at basaltic violent-strombolian volcanoes. Staff will compare proposed models with igneous processes and deposits documented for reasonably analogous eruptions, including but not limited to in violent strombolian eruptions, 1975 Tolbachik, Russia; 1943–1952 Parícutin, Mexico; and 1850–1995 Cerro Negro, Nicaragua.

Criterion T5: Integration

Important site and design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the volcanic disruption of WPs abstraction and the technical bases are provided.

Review Method: Staff should evaluate models for consistency with physical processes commonly observed at active igneous features, or generally interpreted from older igneous features, that are reasonably analogous to igneous features of the YMR. Processes include, but are not limited to, ascent characteristics of igneous magmas, heat and mass transfer, chemical evolution (e.g., magmatic degassing), and interactions with surrounding rock and groundwater systems. Staff should verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena or features in its conceptual models. Staff also should ascertain that process model assumptions are consistent with similar process models used elsewhere in the TSPA, such as waste-package and waste-form evolution through time. Staff should determine if DOE models have accounted for significant changes in igneous processes that are effected by construction of the subsurface geologic repository and emplacement of HLW, and if models adequately account for the behavior of engineered barriers and HLW under basaltic magmatic conditions. Figure 13 illustrates computational input/output for this ISI.

4.3.2.3.1.1 Description of the U.S. Department of Energy Approach

The latest iteration of DOE's TSPA (U.S. Department of Energy, 1998b) 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, 1998b) 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 meters and a maximum diameter of 120 meters
- 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 post closure (U.S. Department of Energy, 1998b).

Table 11 provides the relationship of the volcanic disruption of WPs ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a)

Table 11. Relationship between the volcanic disruption of waste packages integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Volcanic disruption of waste packages	Performance of waste package barriers	Waste package
	Volcanism	Tectonics

4.3.2.3.1.2 Analysis of the U.S. Department of Energy Approach

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 significant 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, 1999b).

4.3.2.3.2 Airborne Transport of Radionuclides

Review of the airborne transport of RNs model abstraction involves the IA KTI. The airborne transport of RNs ISI evaluates the transport of RNs 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 RNs released from volcanic disruption of WPs. Output from this model abstraction is a probabilistic assessment of the mass of RNs deposited on the ground surface as a result of volcanic eruptions. This result is used by related subissues (lifestyle of the critical group and dilution of RNs 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 RNs 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, 1998b) 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.

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 1×10^{-8} to 1×10^{-6} per year (Ho, 1991; Geomatrix, 1996; Connor and Hill, 1995; Connor et al., in press), with NRC IA staff currently adopting a value of 1×10^{-7} per year (U.S. Nuclear Regulatory Commission, 1999i) as a conservative bound on the probability of a volcanic eruption through the repository. Initial dose calculations for basaltic volcanic activity were completed using NRC's TPA Version 3.1.3 code. This approach has not changed significantly in the current version of the code, TPA 3.2. These calculations show that should a volcanic event occur, the annual peak dose is approximately 8 rem year^{-1} with a standard error on the mean of 2 rem year^{-1} (U.S. Nuclear Regulatory Commission, 1999i). These dose estimates depend on numerous parameters including eruption magnitude, duration, and number of WPs disrupted by basalt magma. These 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. Thus although the probability of volcanic disruption of the repository is low, the high estimated doses associated with potential volcanic activity make volcanism a relatively significant contributor to overall risk.

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; Manteufel et al., 1997; Woods and Sparks, 1998). 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.

Acceptance Criteria and Review Methods

DOE's approach in abstracting the airborne transport of RNs in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the effect of direct release and transport on the total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the airborne transport of RNs abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should assess whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the airborne transport of RNs abstraction, such as the magnitude of eruption and deposition velocity, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated airborne transport of RNs input/data in the performance calculations. Staff should ascertain that the input values used in the airborne transport of RNs in TSPA are reasonable, based on data from the YMR, applicable atmospheric tracer experiments, and natural analogs. Staff also should verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site (e.g., estimation of the amount of waste released via the airborne pathway should be based on the type of eruption, eruption power and duration, wind speed, amount of waste entrained in the tephra, and other features/processes that may affect performance). In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test the sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the airborne transport of RNs abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the airborne transport of RNs abstraction. Staff should run the TPA code to assist in verifying that the results produced by DOE's approach reflect or bound the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

Airborne transport of RNs abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testing, natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of the airborne transport of RNs abstraction reasonably reproduces or bounds the results of the corresponding process-level models or alternative sources of data. To the extent feasible and applicable, staff should evaluate the output of DOE's airborne transport of RNs against the results produced by the process-level models developed by the staff.

Criterion T5: Integration

Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the airborne transport of RNs abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches; for example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting the airborne transport of RNs. If DOE decides not to take credit for certain features and processes (e.g., partitioning of the released RNs into several different plumes going toward different directions owing to shifting of wind directions during release) that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects, staff does not need to include such features in its review. Staff should verify that the dimensionality of DOE's abstractions appropriately account for the various natural processes (e.g., plume dispersion), site characteristics, and alternative conceptual approaches. The following are examples of important physical phenomena and couplings with other ISIs:

- Depending on the characteristics of transport, tephra deposits may be thick, effectively shielding some RNs (dilution of RNs 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).

These relationships and other computational input are illustrated in Figure 14. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in airborne transport of RNs for potential inconsistency in the analysis and nondefensible predictions.

4.3.2.3.2.1 Description of U.S. Department of Energy Approach

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

$$X(x,y) = \int_{\rho_{\min}}^{\rho_{\max}} \int_{0}^{H} \frac{5P(z)f(\rho)Q}{8\pi C t^{5/2}} \exp[-\frac{5(x-ut)^2+y^2)}{8Ct^{5/2}}] dz d\rho$$

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*(ρ). These distribution functions are empirically derived from analogous volcanic eruptions.

Table 12 provides the relationship of the airborne transport of RNs ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a).

Table 12. Relationship between the airborne transport of radionuclides integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Airborne Transport of Radionuclides	Volcanism	Tectonics
	Biosphere transport and uptake	Biosphere

4.3.2.3.2.2 Analysis of the U.S. Department of Energy Approach

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, 1998b), 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, 1998b). 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.

4.3.3 Biosphere

Assuming the RNs 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 RN 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 technical 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, dilution of RNs in soil due to surface processes, and location and lifestyle of critical group), are discussed. The ISIs for this abstraction were derived from the staff experience from previous and current IPA activities, reviews of DOE's TSPAs, sensitivity studies performed at the process and system level, and reviews of DOE's hypotheses in its RSS. Further, the key elements represent essential factors to be considered in dose calculation, which is expected to be the measure of total system performance. DOE's abstraction for the dose calculation in its TSPA for the proposed repository at YM will be considered satisfactory if the acceptance criteria for all three ISIs are met.

4.3.3.1.1 Dilution of Radionuclides due to Well Pumping

Review of the dilution of RNs due to well pumping model abstraction involves the USFIC KTI. The dilution of RNs due to well pumping ISI examines the methods that can be used to calculate the effects of well pumping on RN 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 RNs due to well pumping and other ISIs are illustrated in Figure 16.

RN 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 PA of YM because it provides a mechanism by which RN 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 RN concentrations reaching the biosphere has been noted by DOE in the following excerpt taken from the TSPA-VA (U.S. Department of Energy, 1998b, 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 PA 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 RN concentrations reaching the biosphere and its ultimate impact on PA 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 RN concentrations were possible. Research by staff at SNL (Civilian Radioactive Waste Management System Management and Operating Contractor, 1997a) has also indicated the potential for well pumping to cause significant reductions in RN 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 RNs due to well pumping involves evaluating the approach and method(s) used to calculate the dilution effects of well pumping on the RN concentrations at the wellhead. The review will include evaluating FEPs that may directly or indirectly impact the RN 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 RN 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 RN 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 RN concentrations at the pumping well supplying water at the receptor location largely depends on the approach used to model the transport of RNs 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 RNs captured by the well(s) by the volumetric discharge rate.

If a complex 3D transport model incorporating the effects of the pumping well on the flow-field is used to estimate resident RN concentrations, borehole RN concentrations may be explicitly calculated by flux-weighting the resident RN 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* RN 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 RN 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.

Acceptance Criteria and Review Methods

DOE's approach in abstracting dilution of RNs in groundwater due to well pumping in the TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the effect of the various processes in the biosphere on the total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the dilution of RNs due to well pumping abstraction in the TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definition of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should determine whether DOE has performed sensitivity or uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models of water well hydraulics.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the dilution of RNs in groundwater due to well pumping abstraction, such as the pumping well characteristics and water usage by the receptor groups, are technically defensible and account for uncertainty and variability.

Review Method: This acceptance criteria will focus on the integrated dilution of RNs in groundwater due to well pumping input/data in the performance calculations. Staff should ascertain that the input values used in the dilution of RNs in groundwater due to well pumping calculations in TSPA are reasonable, based on data from the YMR, [e.g., Amargosa Valley surveys (Cannon Center for Survey Research, 1997)] and other applicable laboratory testing and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions (site characteristics) and the assumptions of the conceptual models for the YM site (e.g., estimation of the RN concentration in the groundwater used by a receptor group should consider the flow through the repository footprint, flow in the aquifer production zones, pumping rates necessary to support activities of the receptor group, and other features and processes that may affect performance). In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test the sensitivity of the system performance to the input values and correlation used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the dilution of RNs in groundwater due to well pumping abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the dilution of RNs in groundwater due to well pumping abstraction. Staff should run the TPA code to assist in verifying that the intermediate output of biosphere produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Model Support

Dilution of RNs due to well pumping abstraction output is justified through comparison to outputs of detailed process models or empirical observations (laboratory test).

Review Method: Staff should ascertain whether DOE demonstrated that the output of dilution of RNs due to well pumping abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible and applicable, staff should evaluate the output of DOE's dilution of RNs due to well pumping abstraction against results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

PA analyses incorporate important hydrogeologic features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the dilution of RNs due to well pumping abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. Important site features that will set the initial and boundary conditions for abstracting the dilution of RNs due to well pumping include hydraulic gradient, hydraulic conductivities of the production zones, the effect of climate change, and others. If DOE decides not to take credit for certain site features or processes that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects, staff does not need to include such features or processes in its review. Staff should verify that DOE's dimensionality abstractions appropriately account for the various site characteristics and alternative conceptual approaches. The following are examples of important physical phenomena and couplings with other ISIs:

- Large amounts of pumping may perturb the flow-field and affect the flow rates in water-production zones. Flow in water-production zones affects well capture area and potential for dilution of RNs due to pumping (flow rates in water-production zones).
- The lifestyle of receptor groups may be related to the availability of groundwater, hence affecting well pumping rates and dilution (lifestyle of critical group).

These relationships are illustrated in Figure 16. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the couplings between the SZ and biosphere. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in dilution of RNs due to well pumping for potential inconsistency in the analysis and nondefensible predictions.

4.3.3.1.1.1 Description of the U.S. Department of Energy Approach

In the TSPA-VA (U.S. Department of Energy, 1998b), 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, 1998b, 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, 1998b, 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 (TRW Environmental Safety Systems, Inc., 1995).

Table 13 provides the relationship of the dilution of RNs due to well pumping ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a)

Table 13. Relationship between the dilution of radionuclides in groundwater due to well pumping integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Dilution of Radionuclides in Groundwater Due to Well Pumping	Dilution of saturated zone	Saturated zone flow and transport
	Biosphere transport and uptake	Biosphere

4.3.3.1.1.2 Analysis of the U.S. Department of Energy Approach

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 RN dilution due to well pumping, the staff review should ascertain that the maximum pumping rate used in the TSPA is realistic and defensible considering the critical group characterization and aquifer sustainable (safe) yield and the presumed uniform RN concentration in the pumped water is realistic and defensible considering the water use and distribution practices at the receptor location. It is noted that there may be an inherent inconsistency in the conditions that could satisfy both a large critical group and a uniform RN concentration in all the pumped water. In reality, the larger the critical group the less likely that the RN concentrations in the pumped water will be uniform. A smaller critical group size, perhaps consisting of one or two lines of wells across the flow tube would be more likely to produce a uniform RN concentration in the well pumping and lead to a uniform level of exposure and dose.

4.3.3.1.2 Redistribution of Radionuclides in Soil

Review of the redistribution of RNs in soil model abstraction involves evaluation of input from the IA and RT KTIs. The redistribution of RNs in soil ISI addresses the processes that cause concentration or dilution of RNs 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 RNs in soil and other ISIs are illustrated in Figure 17.

This ISI relates to the calculation of the redistribution of RNs 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 RNs 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 RNs 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 RNs 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 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 will unknowingly 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.

Acceptance Criteria and Review Methods

DOE's approach in abstracting redistribution of RNs in soil in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the effect of the various processes in the biosphere on the total system performance.

Criterion T1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the redistribution of RNs in soil abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. When evaluating the sufficiency of data, the reviewer should consider whether additional data are 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. The primary source of data should be field, laboratory, or natural analog data that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definition of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should determine whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the redistribution of RNs in soil abstraction, such as depth of the plowed layers and mass loading factor, are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criteria will focus on the integrated dilution of RNs in soil input/data in the performance calculations. Staff should ascertain that the input values used in the redistribution of RNs in soil calculations in TSPA are reasonable, based on data from the YMR [e.g., Amargosa Valley survey (Cannon Center for Survey Research, 1997)], studies of surface processes in the Fortymile wash drainage basin and other applicable laboratory testings and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site [i.e., redistribution of RNs in soil should consider the current farming practices (e.g., soil types, crop type, growing seasons, and others)] as well as consideration of those areas untilled, such as yards. In addition, the staff should verify that the correlations between the input values have been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to the corresponding input values in the staff data set and use the TPA code to test the sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and their results and limitations appropriately factored into the redistribution of RNs in soil abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the redistribution of RNs in soil abstraction. Staff should run the TPA code to assist in verifying that the intermediate output of biosphere produced by DOE's approach reflects or bounds the range of uncertainties due to alternative modeling approaches.

Criterion T4: Model Support

Redistribution of RNs in soil output is justified through comparison to output of detailed process models or empirical observations (laboratory testings, natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of redistribution of RNs in soil abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible and applicable, staff should evaluate the outputs of DOE's redistribution of RNs in soil abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs.

Criterion T5: Integration

Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the redistribution of RNs in soil abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches. For example, staff should verify that the conditions and assumptions used to generate the look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting the redistribution of RNs in soil. If DOE decides not to take credit for certain site features or processes that have been demonstrated in NRC's, DOE's, or both analyses to provide only benefits and no deleterious effects, staff does not need to include such features or processes in its review. Staff should verify that the dimensionality of DOE's abstractions appropriately account for the various site characteristics and alternative conceptual approaches. The following are examples of important physical phenomena and couplings with other ISIs:

- A receptor group consisting of resident farmers will plow the soil for agricultural use (location and lifestyle of critical group).
- Depending on the characteristics of transport, ash blankets may be thick, effectively shielding some RNs (airborne transport of RNs).
- Leaching of the ash blanket and downward transport to the groundwater system could increase the dose from the groundwater pathway (retardation in the UZ).
- These relationships are illustrated in Figure 17. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the couplings between direct release and biosphere (e.g., RT, deposition, and decay). To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in dilution of RNs in soil for potential inconsistency in the analysis and nondefensible predictions.

4.3.3.1.2.1 Description of the U.S. Department of Energy Approach

The most recent DOE TSPA (U.S. Department of Energy, 1998b) 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 centimeters (6 inches) 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 centimeters 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 1.9×10^{-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.

Table 14 provides the relationship of the redistribution of RNs in soil ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b, 1999a).

Table 14. Relationship between the redistribution of radionuclides in soil integrated subissue and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Redistribution of Radionuclides in Soil	Biosphere transport and uptake	Biosphere

4.3.3.1.2.2 Analysis of the U.S. Department of Energy Approach

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, 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.

4.3.3.1.3 Lifestyle of the Critical Group

Review of the lifestyle of the critical group model abstraction involves the (i) USFIC; (ii) RT; and (iii) IA KTIs. 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 RN concentrations in the biosphere. In PA 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 RNs 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 RN concentrations to a common performance indicator, individual doses. The biosphere dose conversion factors (BDCFs) used in PA dose calculations (that convert water and soil RN concentrations to dose) are based on assumptions about the lifestyle of the critical group. BDCFs proportionally affect PA 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 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 !SI relative to others, DOE analyses suggest the BDCFs that result from this ISI are of moderate importance to post-closure performance (U.S. Department of Energy, 1998b). Moderate importance means uncertainty in the DCF contributes a factor of 5–50 increase or decrease in peak dose from the expected value.

Acceptance Criteria and Review Methods

DOE's approach in abstracting the lifestyle of the critical group in TSPA for the proposed repository at YM is satisfactory if the following acceptance criteria are met. Staff review will focus on the assumptions, input data, and models used in the performance calculations to demonstrate the biospheres contribution to total system performance.

Criterion 1: Data and Model Justification

Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models as necessary for developing the lifestyle of critical group abstraction in TSPA. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. Staff will ensure DOE has provided sufficient information to demonstrate that FEPs that describe the biosphere are consistent with present knowledge of conditions in the region surrounding YM. Staff will assess whether DOE's abstraction of the influences of climate changes on the critical group lifestyle is supported by sufficient data from the geologic record that pertains to the YMR. Staff will confirm that the behaviors and characteristics of the farming community forming the basis for the critical group are based on sufficient data relevant to current conditions of the YMR. The staff review will also confirm that behaviors and characteristics of the critical group such as land use practices, lifestyle, diet, human physiology, and metabolics have not been allowed to vary with time. Staff will ensure DOE has provided sufficient information to support determination that the behaviors and characteristics of the critical group are based on the mean value of the critical group's variability range.

When evaluating the sufficiency of data, the reviewer should consider whether additional data are likely to provide new information that could invalidate prior modeling results. Reviewers should also consider the sensitivity of the performance of the system to the parameter value or model. The primary source of data should be field, laboratory, or analog data from scientific literature that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definitions of parameter values and conceptual models are based on appropriate other sources such as expert elicitation conducted in accordance with NUREG–1563. Additionally, staff should evaluate whether DOE has performed sensitivity and uncertainty analyses to test for the possible need for additional data. Staff should also verify that DOE provided sound bases for the inclusion or exclusion of FEPs in its conceptual models.

Criterion 2: Data Uncertainty

Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the lifestyle of critical group abstraction such as consumption rates, plant and animal uptake factors, mass loading factors, and BDCFs are technically defensible and reasonably account for uncertainties and variability.

Review Method: This acceptance criterion will focus on the integrated lifestyle of the critical group and biosphere input/data in the performance calculations. Staff should ascertain that the input values used in the critical group calculations in TSPA are reasonable, based on data from the YMR (e.g., locally derived food/water consumption rates, agricultural practices, cultural practices, and others) and other applicable research and analog sources of information. Staff should also verify that these values are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site (e.g., irrigation and leach rates for the biosphere model should be consistent with climate and precipitation conditions assumed for release and transport models). Staff will ensure that DOE has provided technically defensible bases to demonstrate that FEPs that describe the biosphere are consistent with present knowledge of conditions in the region surrounding YM. Staff will assess whether DOE's abstraction of the influences of climate changes on the reference biosphere and critical group is based on defensible information from the geologic record that pertains to the YMR. Staff will confirm the behaviors and characteristics of the farming community that form the basis for the critical group are adequately supported by data relevant to current conditions of the YMR and reasonable assumptions. Staff will ensure DOE has provided a technically defensible basis to support determination that the behaviors and characteristics of the critical group are based on the mean value of the critical group's variability range. The staff should also verify that any correlation between the input values (if used) has been appropriately established in DOE's TSPA. To the extent feasible, staff should evaluate DOE's input values by comparison to corresponding input values in the staff data set and use the TPA code to test the sensitivity of the system performance to the input values and correlation used by DOE.

Criterion 3: Model Uncertainty

Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the lifestyle of critical group abstractions.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the lifestyle of critical group abstraction. Staff should run the TPA code to assist in verifying that the intermediate output produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches. Results of sensitivity studies should provide information to focus DOE's approach and NRC's review of alternative conceptual models. Staff should confirm that DOE has chosen areas for alternative modeling in the critical group abstraction that are important to performance. Based on present information, examples of possible topics of interest for alternative modeling include: food production and consumption practices, plant uptake of RNs from soil, soil resuspension, and the inhalation dose model for igneous events.

Criterion 4: Model Support

Dose calculation output pertaining to lifestyle of the critical group is justified through comparison to output of detailed process models, and/or empirical observations (field data, laboratory data, or natural analogs).

Review Method: Staff should ascertain whether DOE has demonstrated that the output of the critical group abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible and applicable, staff should evaluate the output of DOE's lifestyle of the critical group abstraction against the results produced by the process-level models developed by the staff or against field and laboratory data and natural analogs. Initially this can be done by comparison of DOE biosphere BDCFs with the results of dose modeling using the GENII-S code and DOE input parameter data. Staff should also compare results of the NRC TPA code modeling using DOE biosphere BDCFs to check for differences in implementation of dose conversion modules. It may also be possible to make a few confirmatory runs using alternative dose calculation codes and DOE input parameters. Sensitivity results should inform staff regarding the importance of any modeling differences identified during the review.

Criterion 5: Integration

Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the lifestyle of the critical group abstraction.

Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches (e.g., if the conditions and assumptions used to generate look-up tables or regression equations are consistent with all other conditions and assumptions in the TSPA for abstracting the biosphere and critical group lifestyle). Staff should verify that DOE's biosphere abstraction consistently applies to arid or semi-arid conditions in the vicinity of YM. Staff should confirm that DOE's incorporation of climate change into the biosphere modeling is consistent with, and appropriately synchronized with, climate changes (such as for precipitation) assumed in other modules of the TSPA code. Other FEPs of the biosphere and critical group such as soil types, K_ds, assumed or known volcanic ash properties, and the physical/chemical properties of RNs should be checked for consistency of assumptions with other TSPA modules. Consistency of assumptions within the biosphere and critical group abstraction should also be checked by staff. This includes ensuring that the abstraction correctly sums RN-specific dose estimates so that, conceptually, total dose estimates represent the dose contribution of all RNs expected present in the biosphere for a given point in time (i.e., timestep). Staff should also verify that the implementation of the abstraction (including introduction of stochastic modeling techniques) to dose conversion does not bias results to a significant degree when compared with original process modeling.

If DOE decides not to take credit for certain site features or processes that have been demonstrated in NRC's, DOE's (or both) analyses to provide only benefits and no deleterious effects, staff does not need to include such features or processes in its review. Staff should verify that the dimensionality of DOE's abstractions appropriately account for the various site characteristics and alternative conceptual approaches. The following is an example of possible important physical phenomena and couplings with other ISIs :

- RT through fractured rock (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 RN 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 RNs from surface soils. These assumptions should be checked for consistency.

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

These assumptions should be checked for consistency to the extent practicable.

The above relationships are illustrated in Figure 18. Staff should use the TPA code to selectively probe DOE's approach to the reference biosphere and lifestyle of the critical group for potential inconsistency in the analysis and nondefensible predictions.

4.3.3.1.3.1 Description of the U.S. Department of Energy Approach

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-kilometers 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.

Table 15 provides the relationship of the lifestyle of the critical group ISI to DOE's PMRs and factors (U.S. Department of Energy, 1998b,1999a).

Table 15. Relationship between the lifestyle of the critical group integrated subissues and U.S. Department of Energy's factors and process model reports

ISI	Factors	Process Model Reports
Lifestyle of the Critical Group	Dilution in saturated zone	Saturated zone flow and transport
	Biosphere transport and uptake	Biosphere

4.3.3.1.3.2 Analysis of the U.S. Department of Energy Approach

A comparison of critical group and biosphere parameters showed, in general, good agreement between DOE and NRC values. DOE input parameter choices were compared with current parameter selections for TPA Version 3.2. Additionally, a sample of DCF calculations was confirmed by running the GENII-S (Leigh et al., 1993) code. One notable difference was the range of values for the mass loading factor used in the inhalation model. DOE's range (2.4×10^{-6}, 1.54×10^{-4}) is less conservative than the range selected by NRC/CNWRA staff for use in TPA 3.2 (1.0×10^{-4}, 1.0×10^{-2}). 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.

4.4 DEMONSTRATION OF THE OVERALL PERFORMANCE OBJECTIVE

A proposed strategy for developing regulations for the disposal of HLW in a YM repository was outlined in "Proposed Strategy for Development of Regulations Governing Disposal of High-Level Radioactive Wastes in a Proposed Repository at Yucca Mountain" (U.S. Nuclear Regulatory Commission, 1997b). This strategy indicates that all post-closure requirements would focus on assessing the ability of the YM repository system to meet the individual dose or risk standard identified as the performance objective (i.e., the expected dose to the average member of the critical group). NRC has published a draft rule to be applied to the YM repository, 10 CFR Part 63 (U.S. Nuclear Regulatory Commission, 1999c). Demonstration of compliance with the overall performance objective will be supported with 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 will be modified (as needed) to be consistent with the final regulations.

Since the development of the SCP, DOE has produced a series of TSPAs (Wilson et al., 1993; TRW Environmental Safety Systems, Inc., 1995; U.S. Department of Energy, 1998b) to evaluate the repository system and has focused the scope of testing and collection of data based on the results of these TSPAs. This iterative process addresses the major concern of Open Item OSC0000001347C001; and therefore, this open item is considered resolved. However, some specific concerns of the Open Item, such as excessive reliance on expert elicitation instead of data, are still relevant and will continue to be evaluated in this and other IRSRs.

NRC regulations do not require the demonstration of performance of the repository to include performance allocation to repository subsystem. Therefore, Open Item OSC0000001347C002 is considered resolved because it addresses deficiencies in performance allocation, which is no longer an NRC concern.

4.4.1 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, an 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 utilized 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, ΔT 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 p_i is the annual event probability of event i and K is 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 above. 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 $\{\Theta\Psi\}$ 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 $\{\Theta\Psi\}$ is added into the scenario $\{\Theta^{-}\Psi\}$. 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 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 class Θ and Ψ, respectively.

Figure 25 shows the summation of the expected annual dose curves of these three scenario class. 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 from the repository over time.

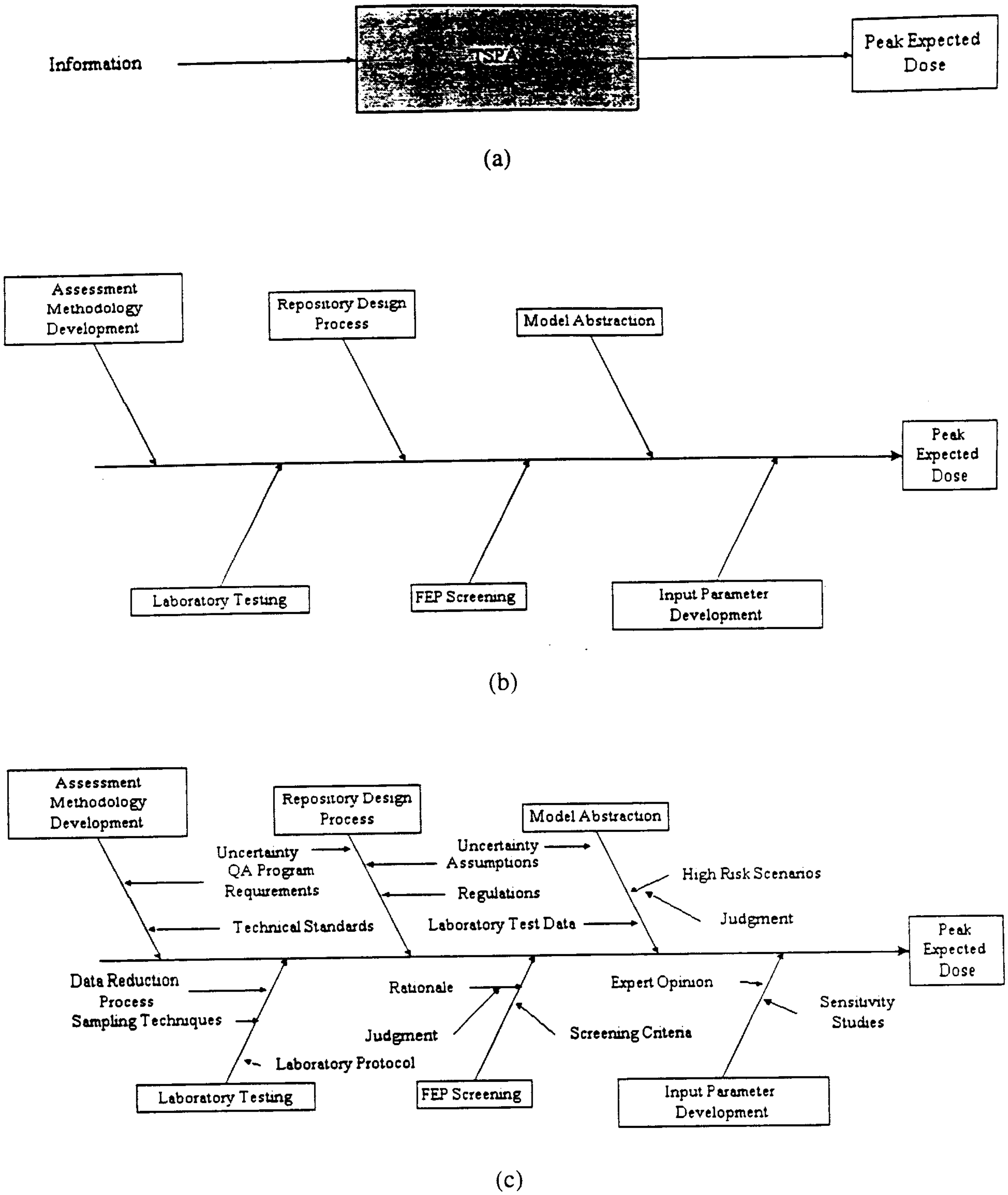


Figure 1. An illustration of degrees of Transparency of DOE's TSPA: (a) black box, (b) partially transparent, (c) transparent

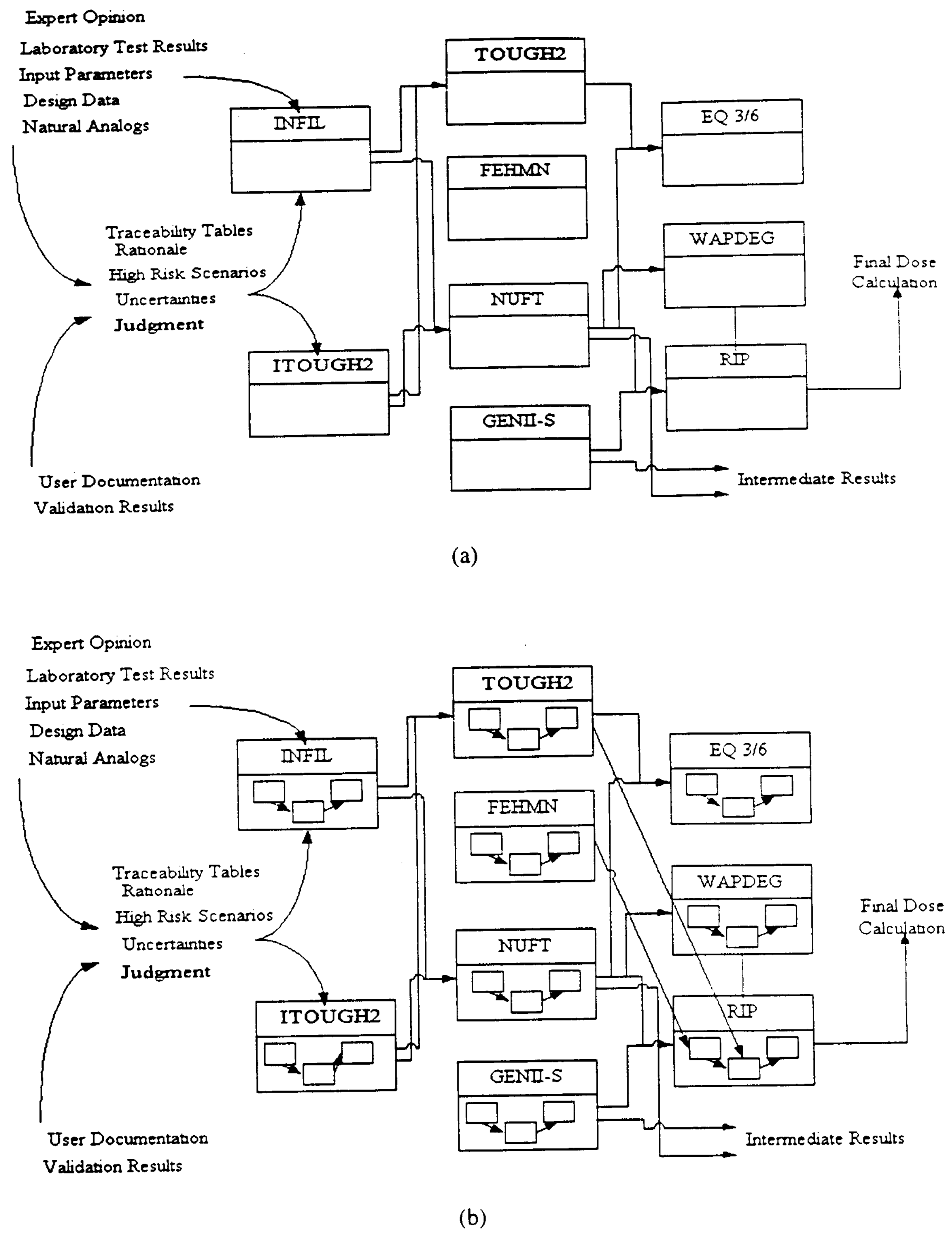


Figure 2. An illustration of degrees of transparency of U.S. Department of Energy's Total System Performance Assessment code: (a) partially transparent, (b) transparent

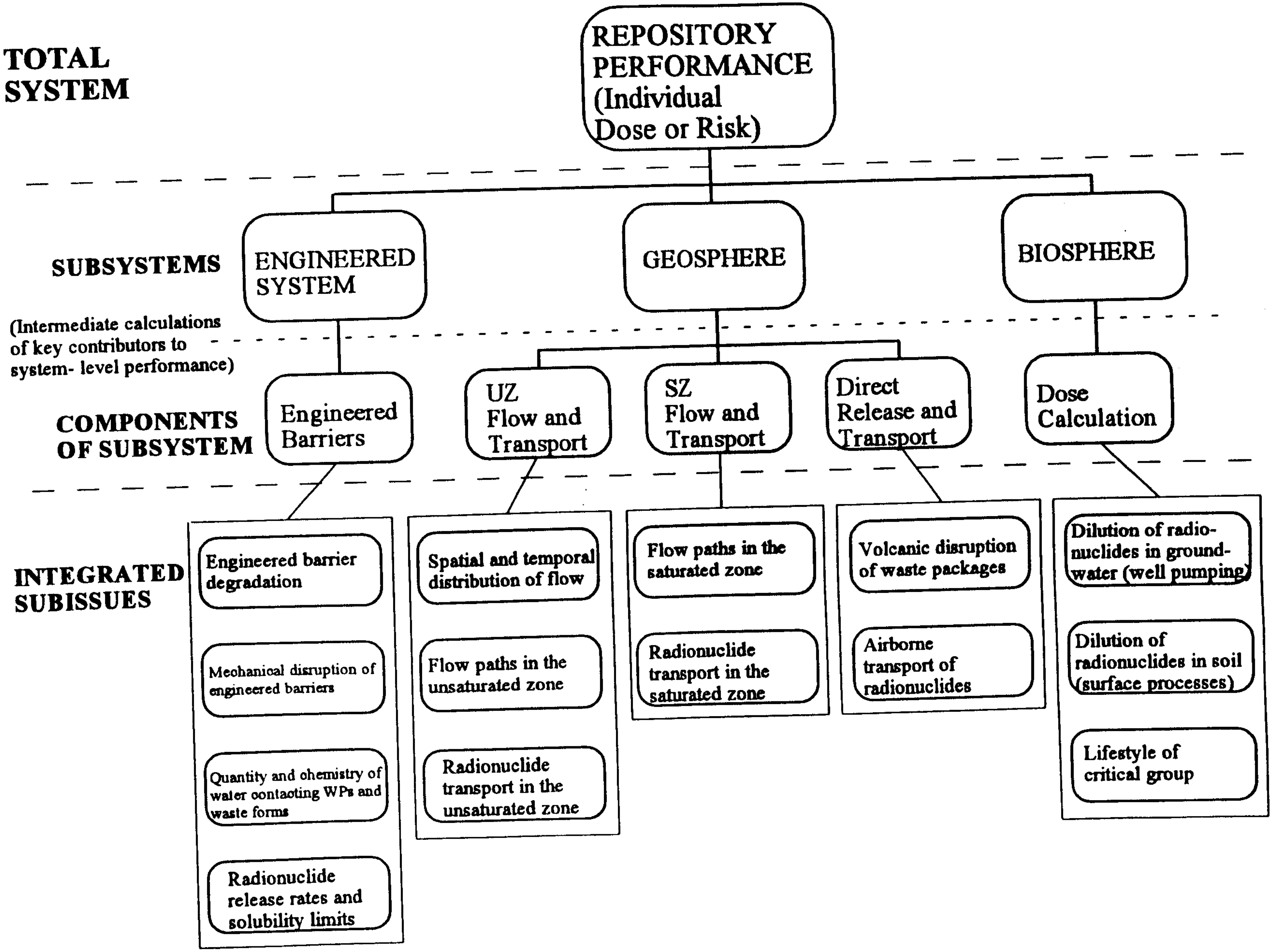
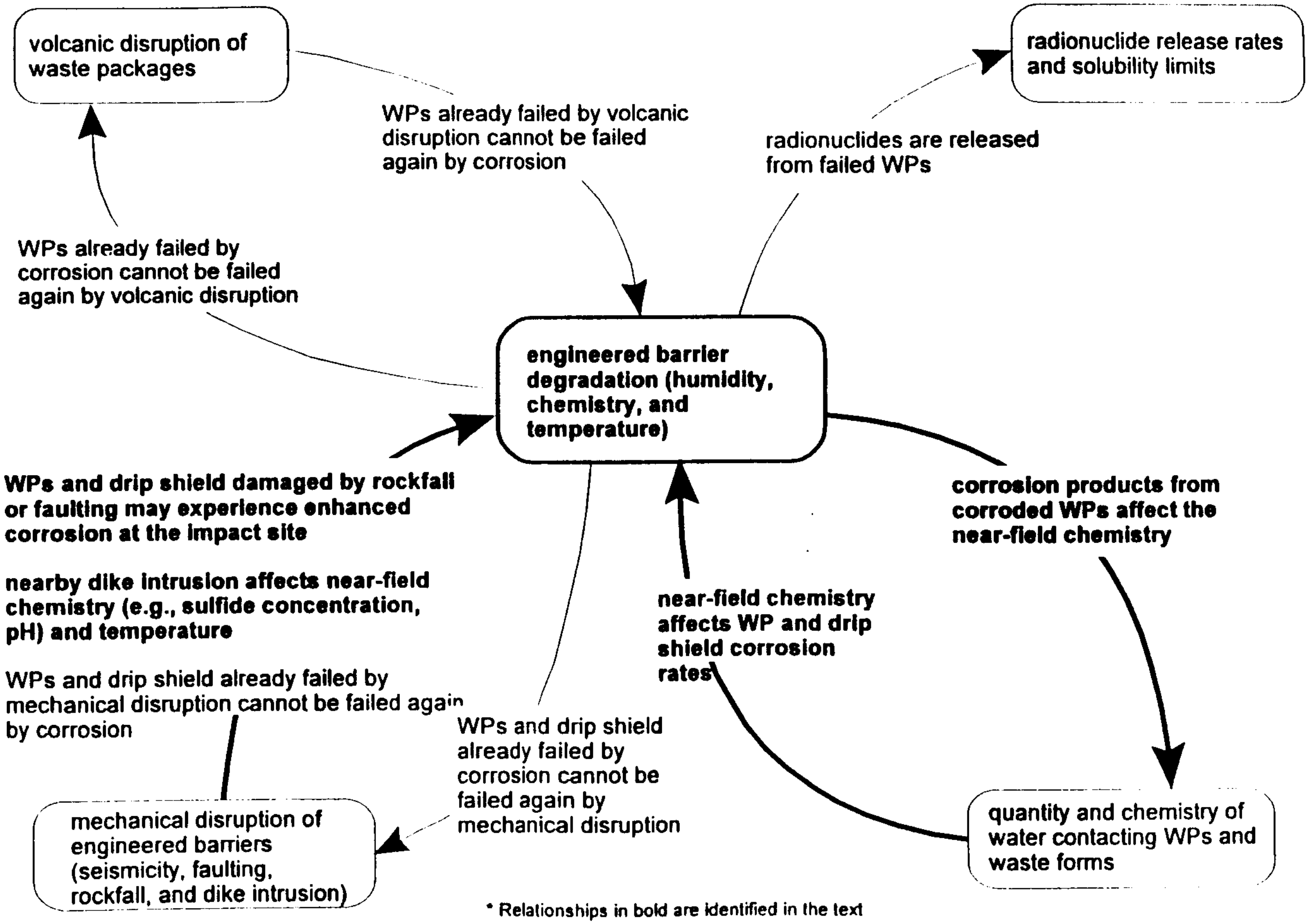


Figure 3. Flowdown diagram for total system performance assessment.



* Relationships in bold are identified in the text

Figure 4. A diagram illustrating the relationships between "engineered barrier degradation" and other integrated subissues.

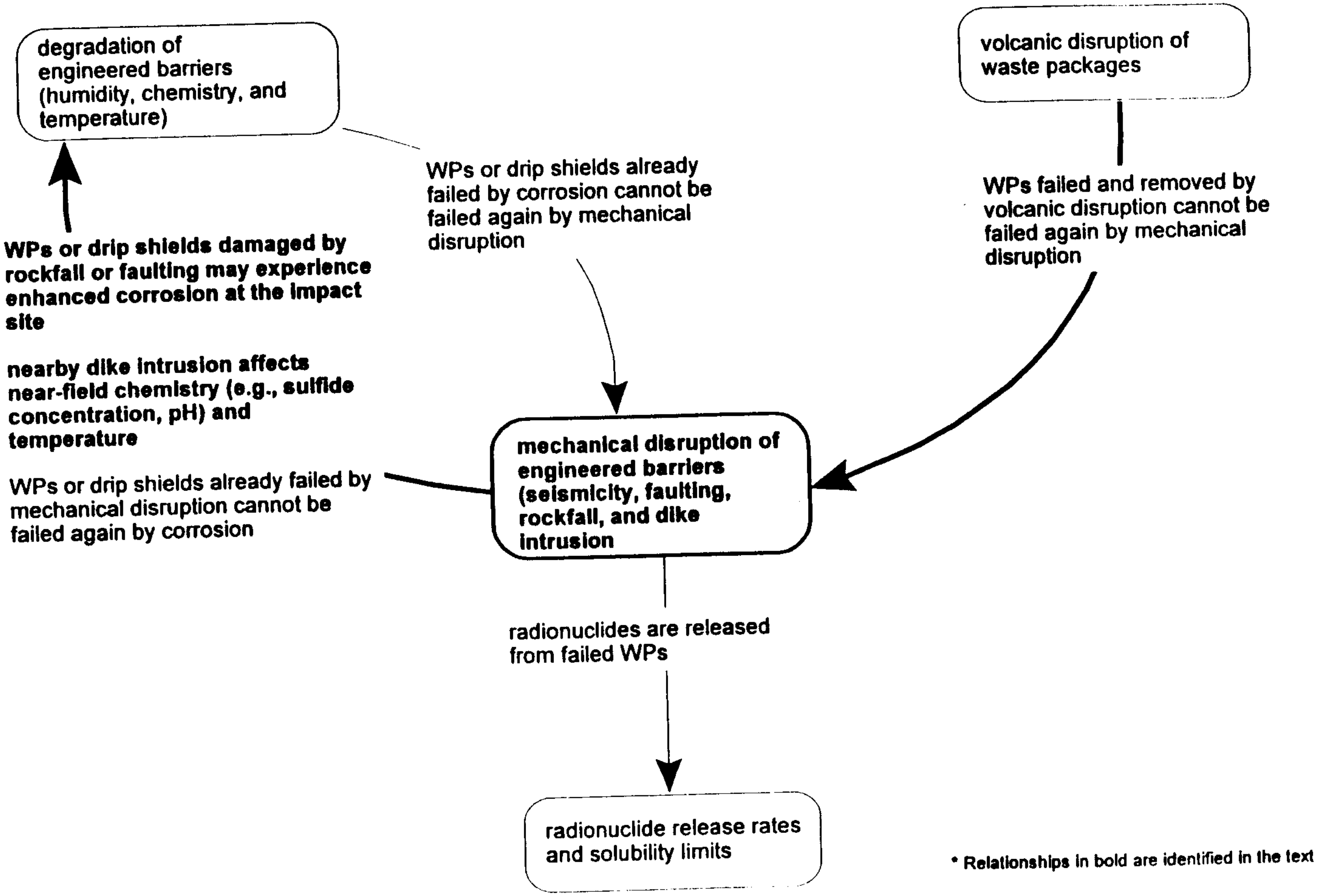
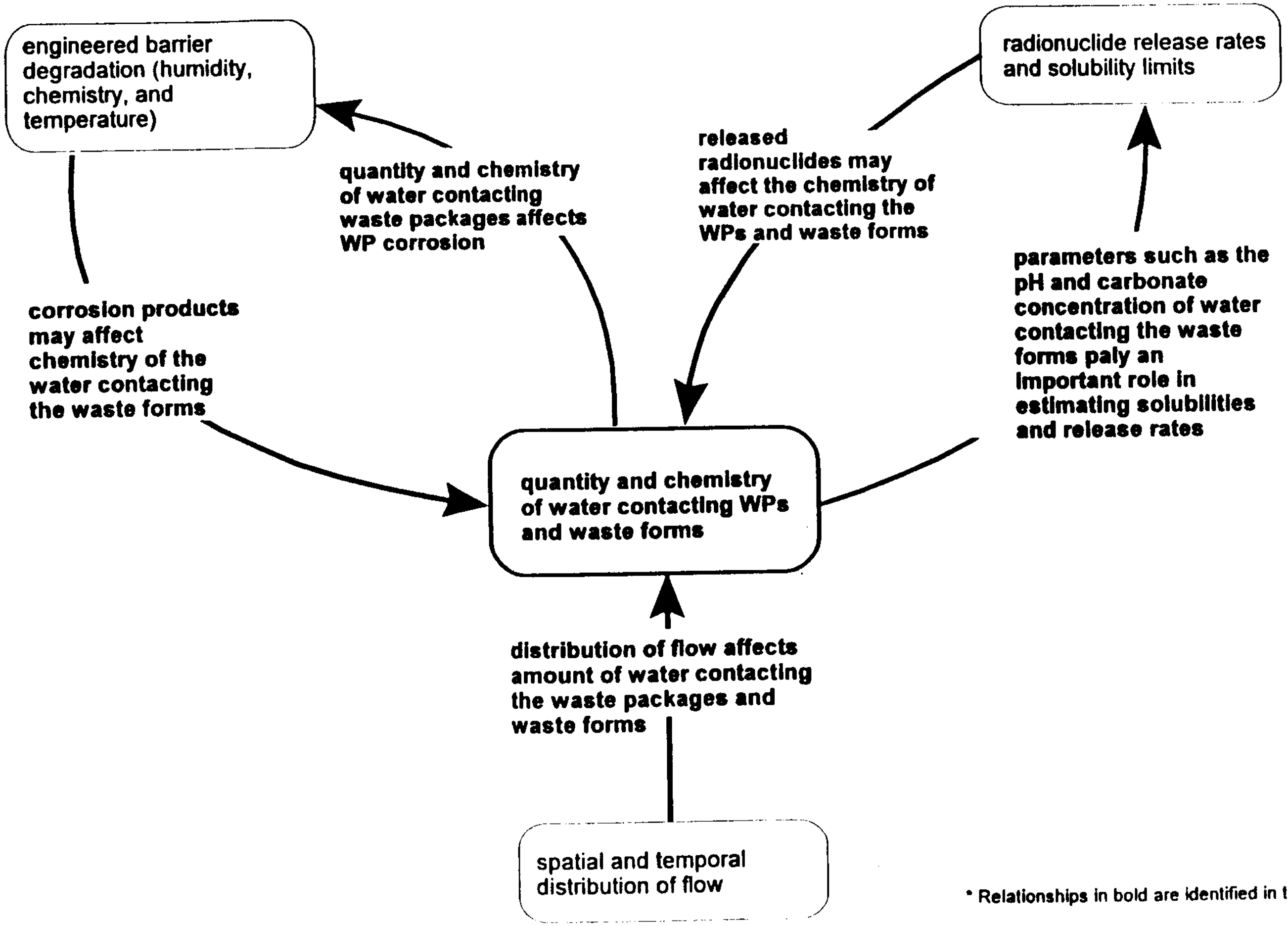
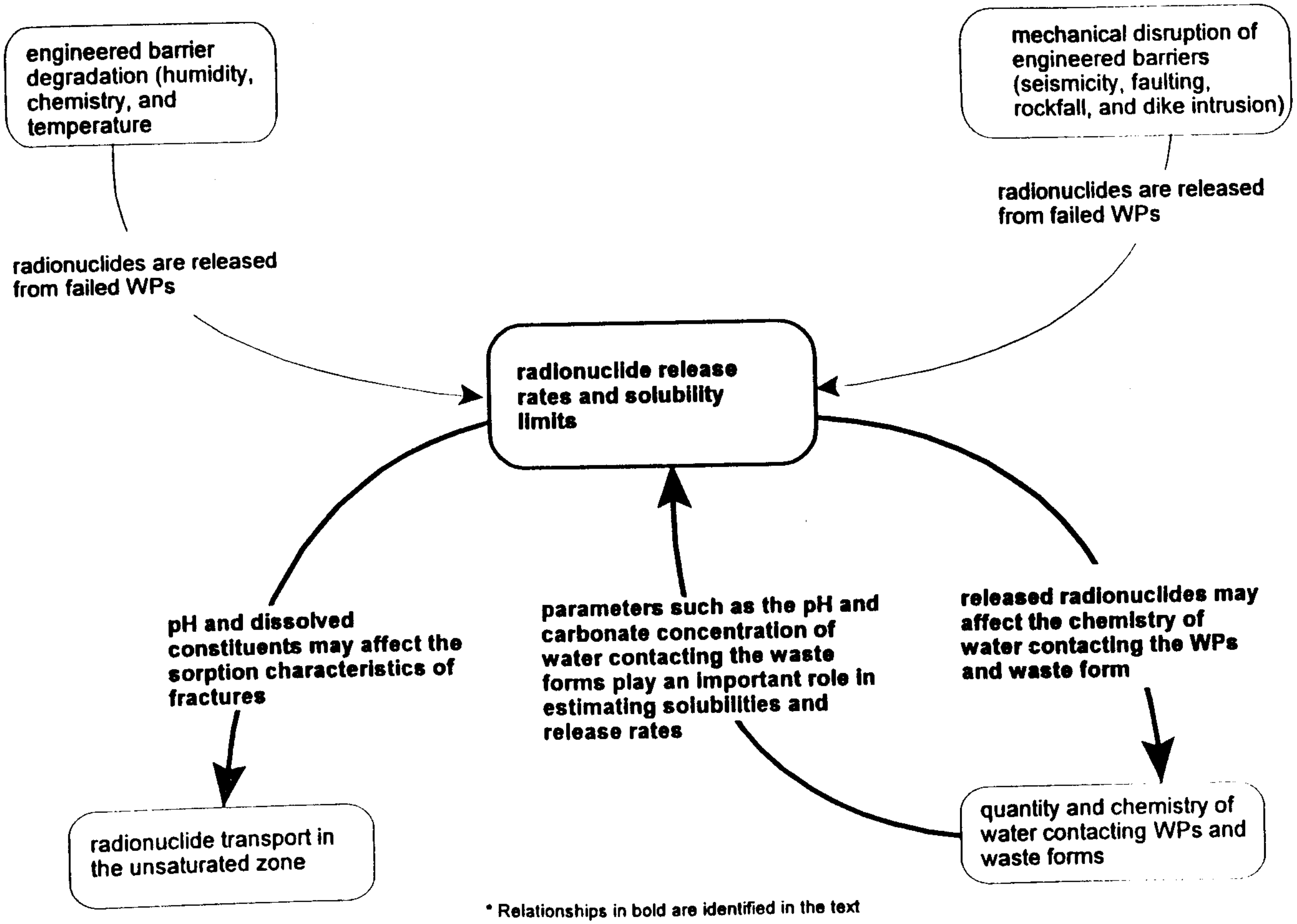


Figure 5. A diagram illustrating the relationships between "mechanical disruption of engineered barriers" and other integrated subissues.



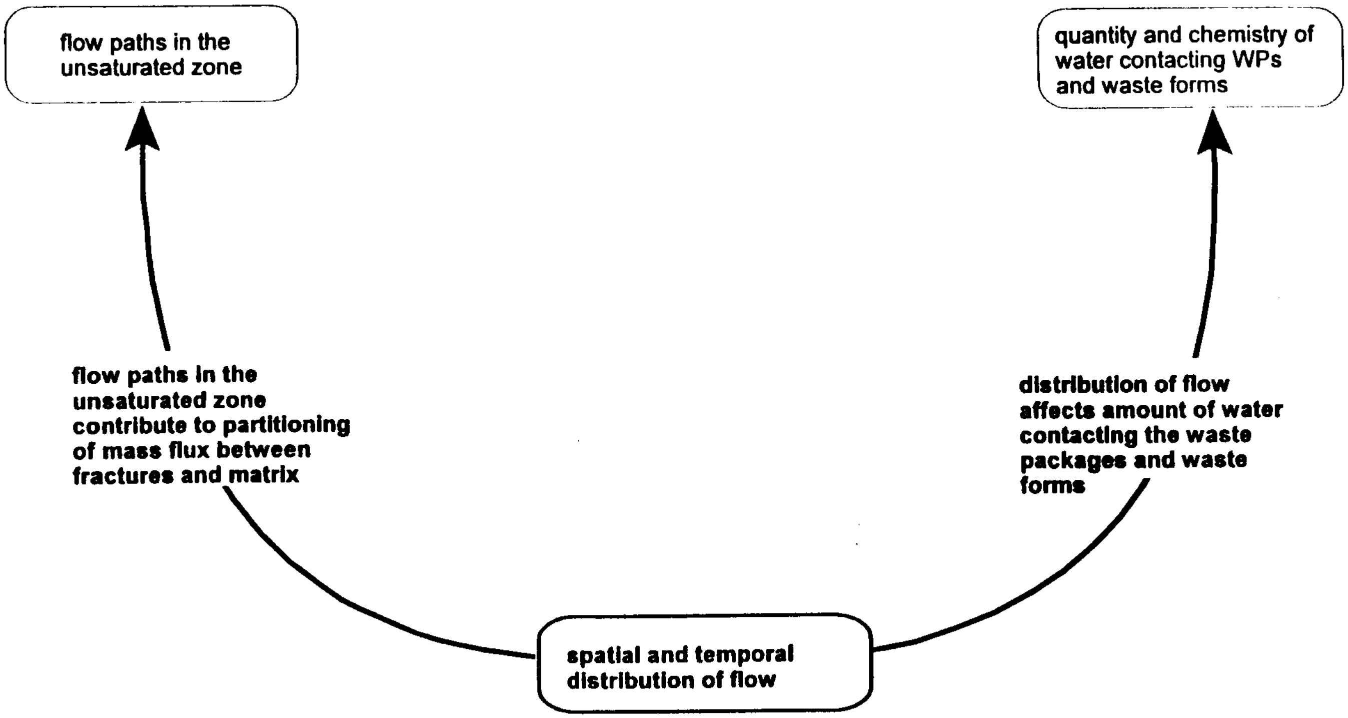
* Relationships in bold are identified in the text

Figure 6. A diagram illustrating the relationships between "quantity and chemistry of water contacting WPs and waste forms" and other integrated subissues.



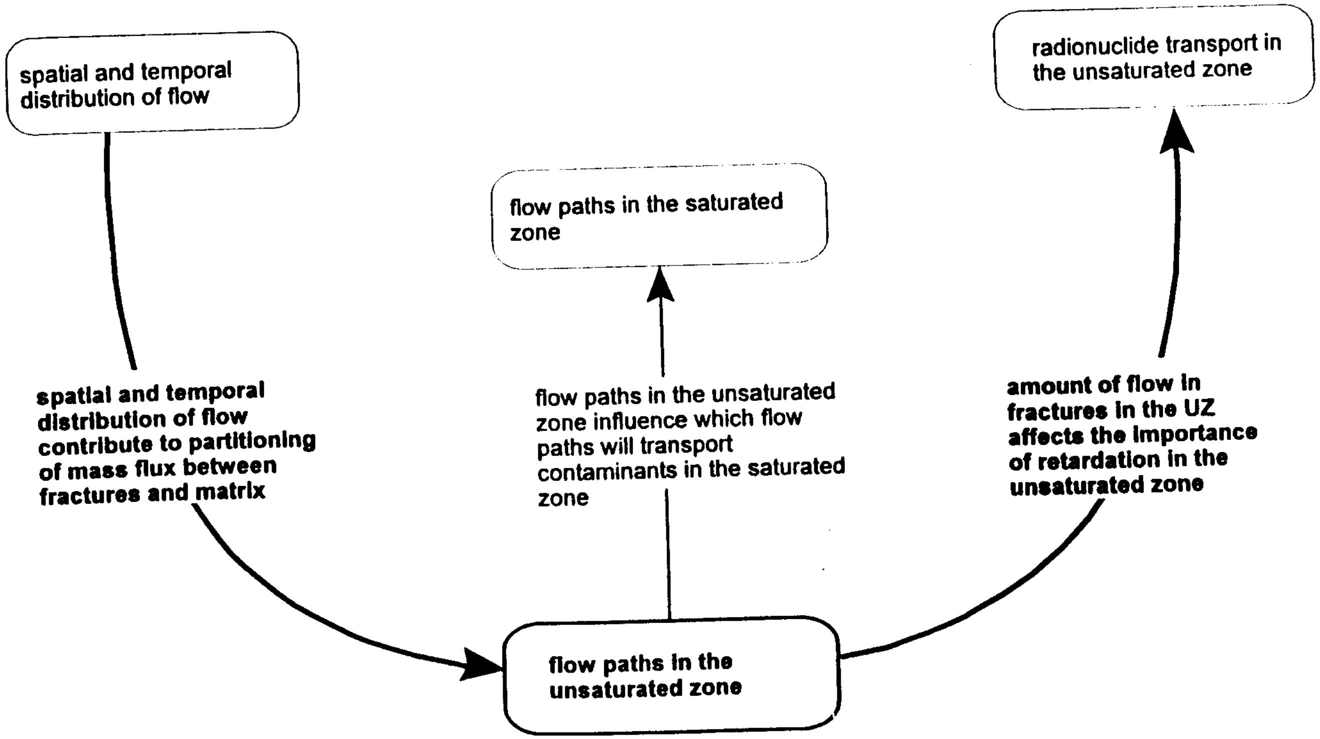
* Relationships in bold are identified in the text

Figure 7. A diagram illustrating the relationships between "radionuclide release rates and solubility limits" and other integrated subissues.



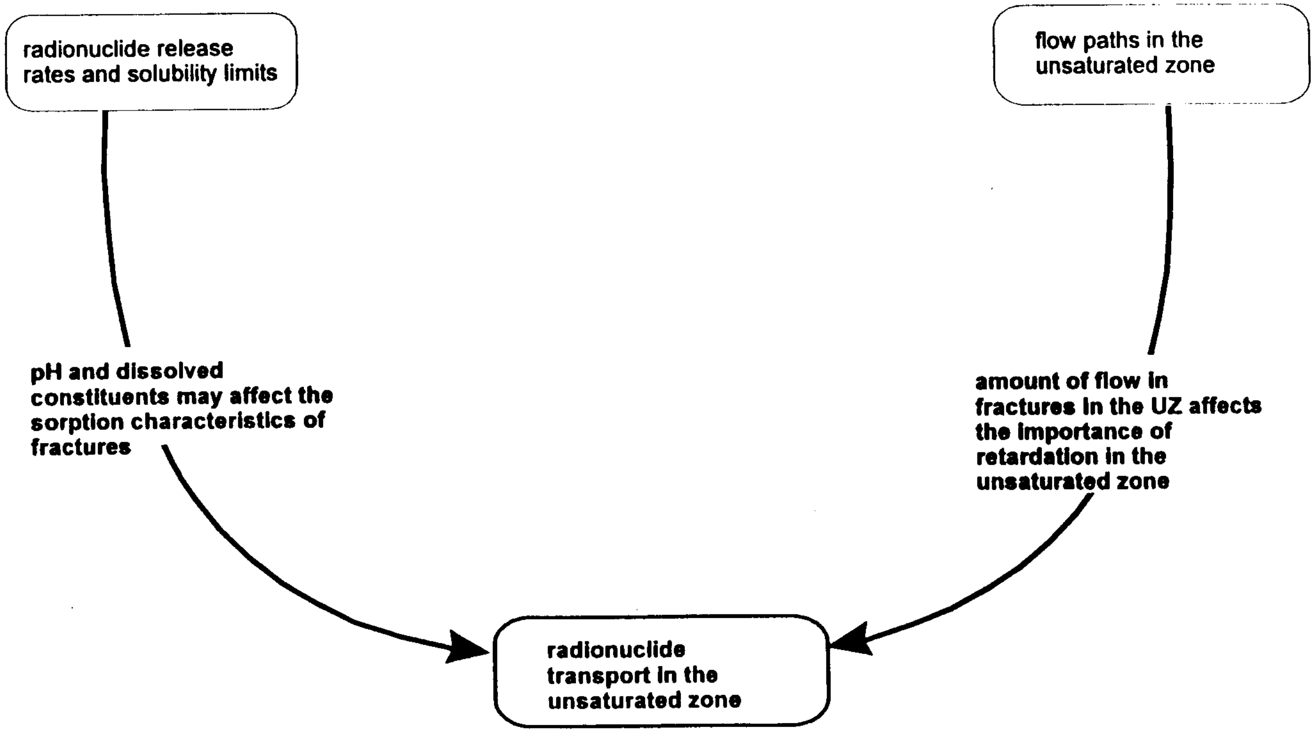
* Relationships in bold are identified in the text

Figure 8. A diagram illustrating the relationships between "spatial and temporal distribution of flow" and other integrated subissues.



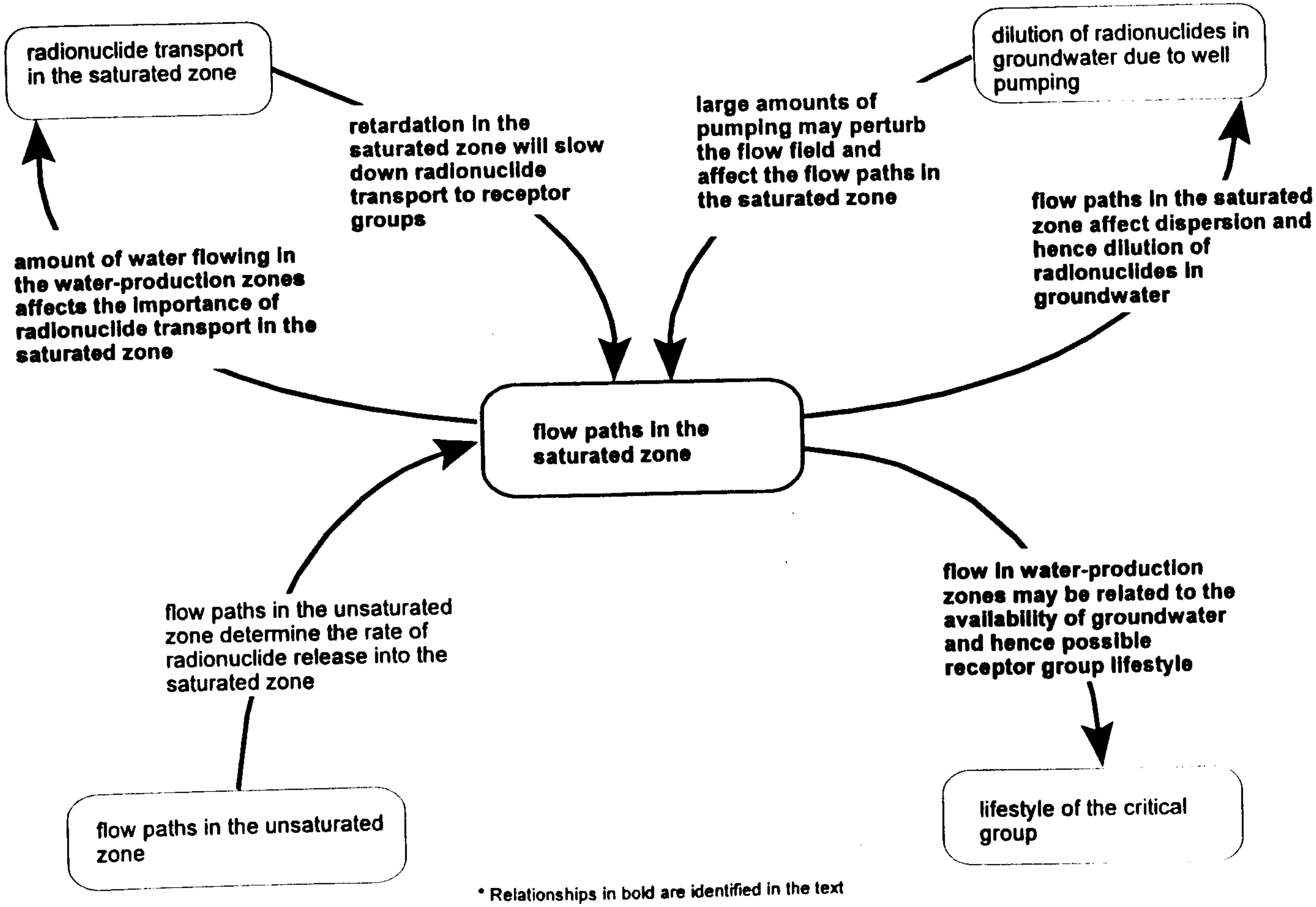
* Relationships in bold are identified in the text

Figure 9. A diagram illustrating the relationships between "flow paths in the unsaturated zone" and other integrated subissues.



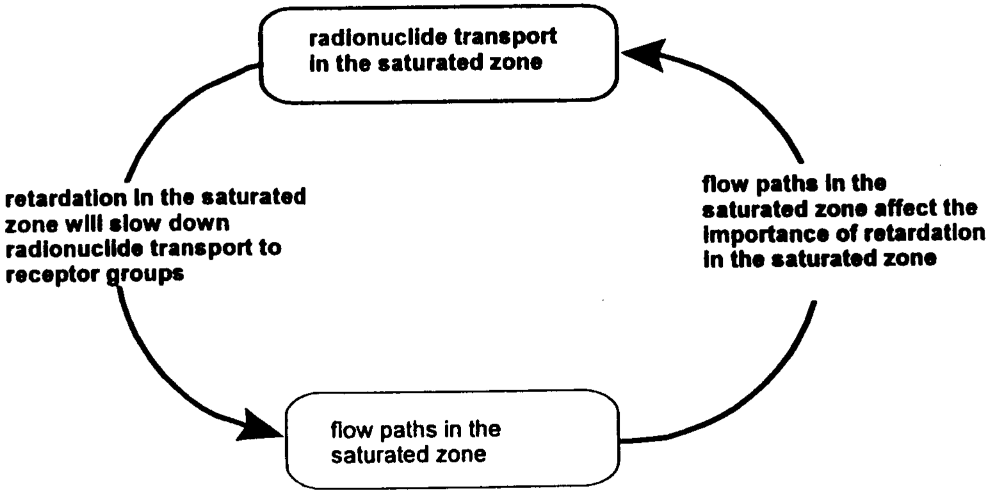
* Relationships in bold are identified in the text

Figure 10. A diagram illustrating the relationships between "radionuclide transport in the unsaturated zone" and other integrated subissues.



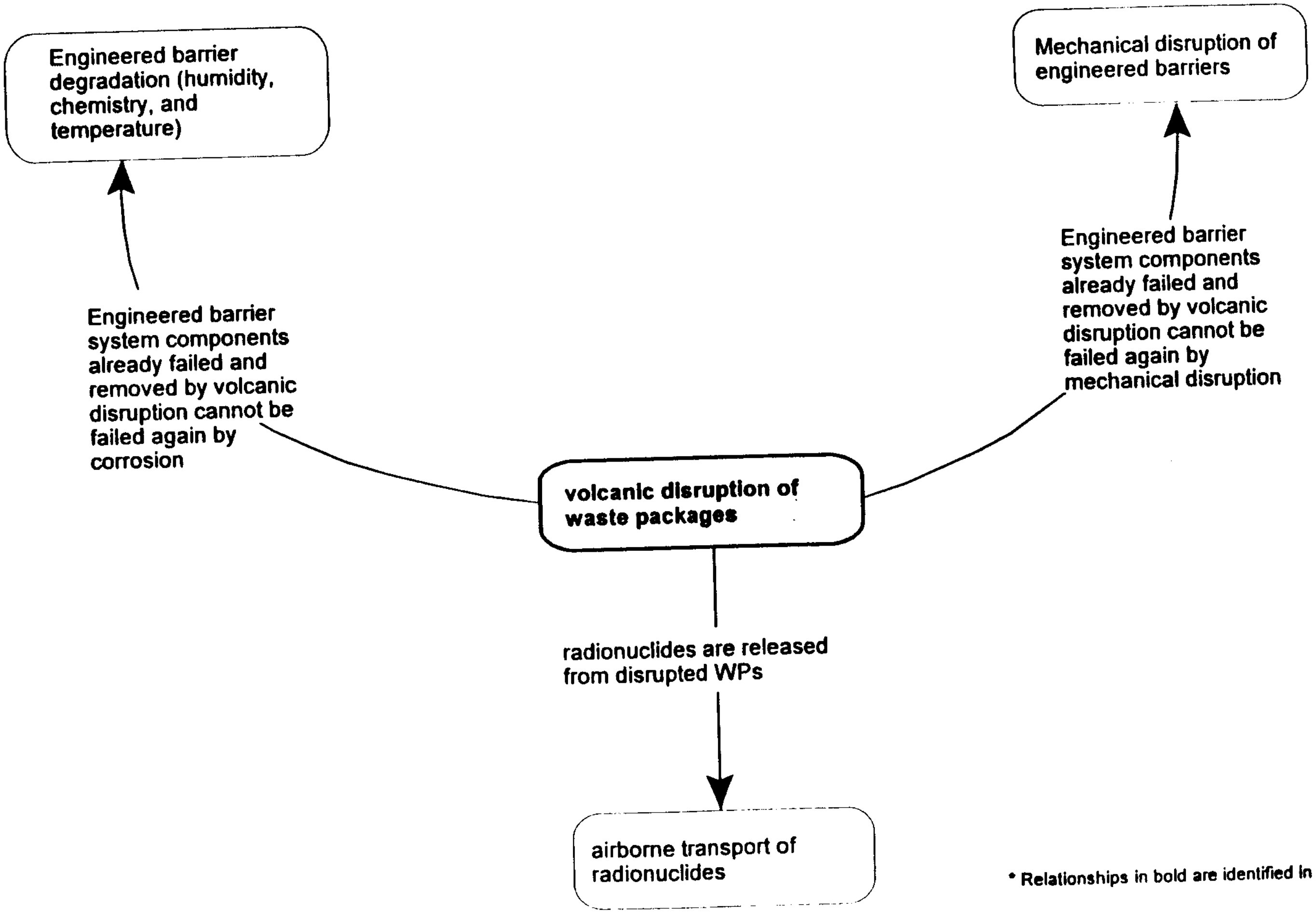
* Relationships in bold are identified in the text

Figure 11. A diagram illustrating the relationships between "flow paths in the saturated zone" and other integrated subissues.



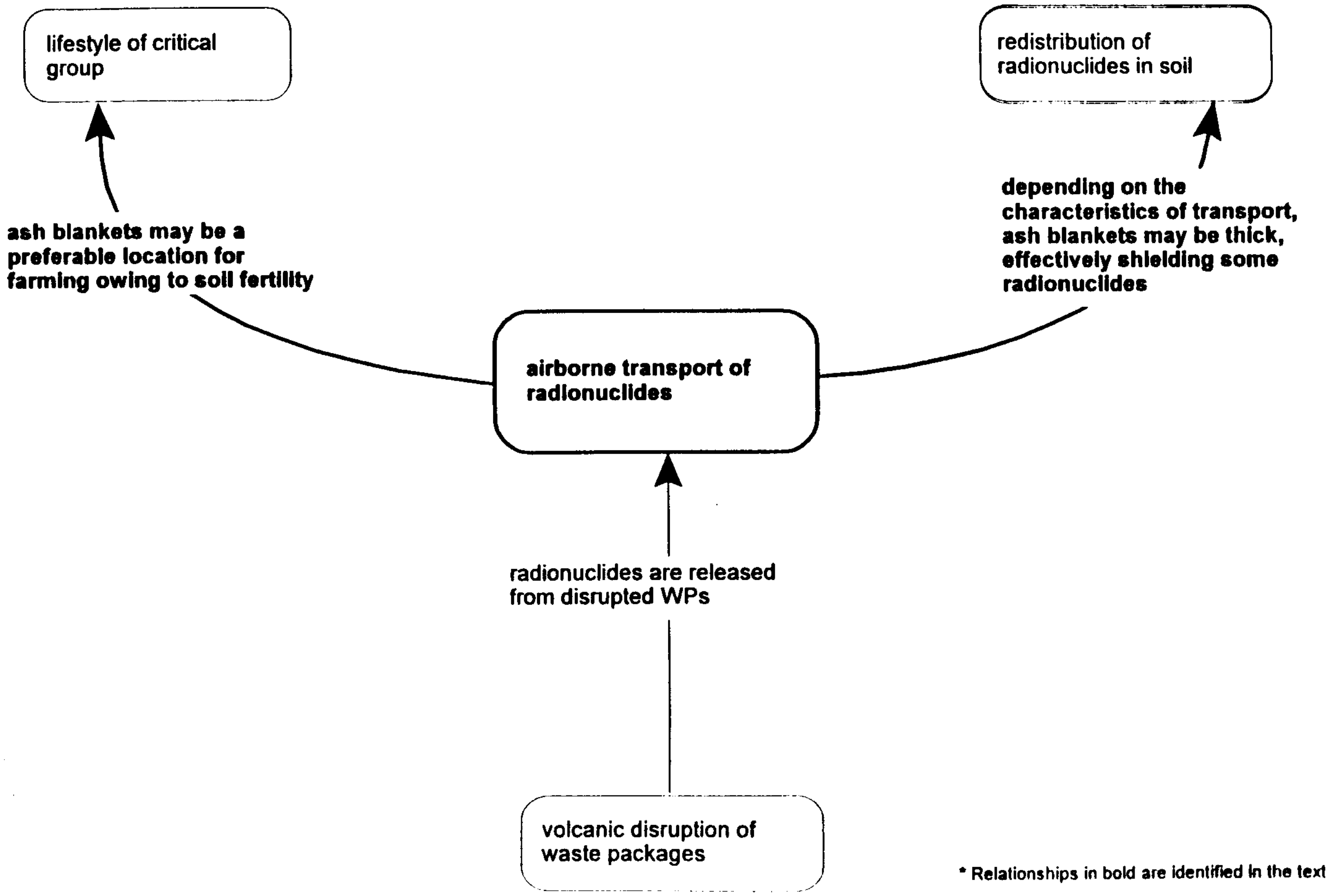
* Relationships in bold are identified in the text

Figure 12. A diagram illustrating the relationships between "radionuclide transport in the saturated zone" and other integrated subissues.



* Relationships in bold are identified in the text

Figure 13. A diagram illustrating the relationships between "volcanic disruption of waste packages" and other integrated subissues.



* Relationships in bold are identified in the text

Figure 14. A diagram illustrating the relationships between "airborne transport of radionuclides" and other integrated subissues.

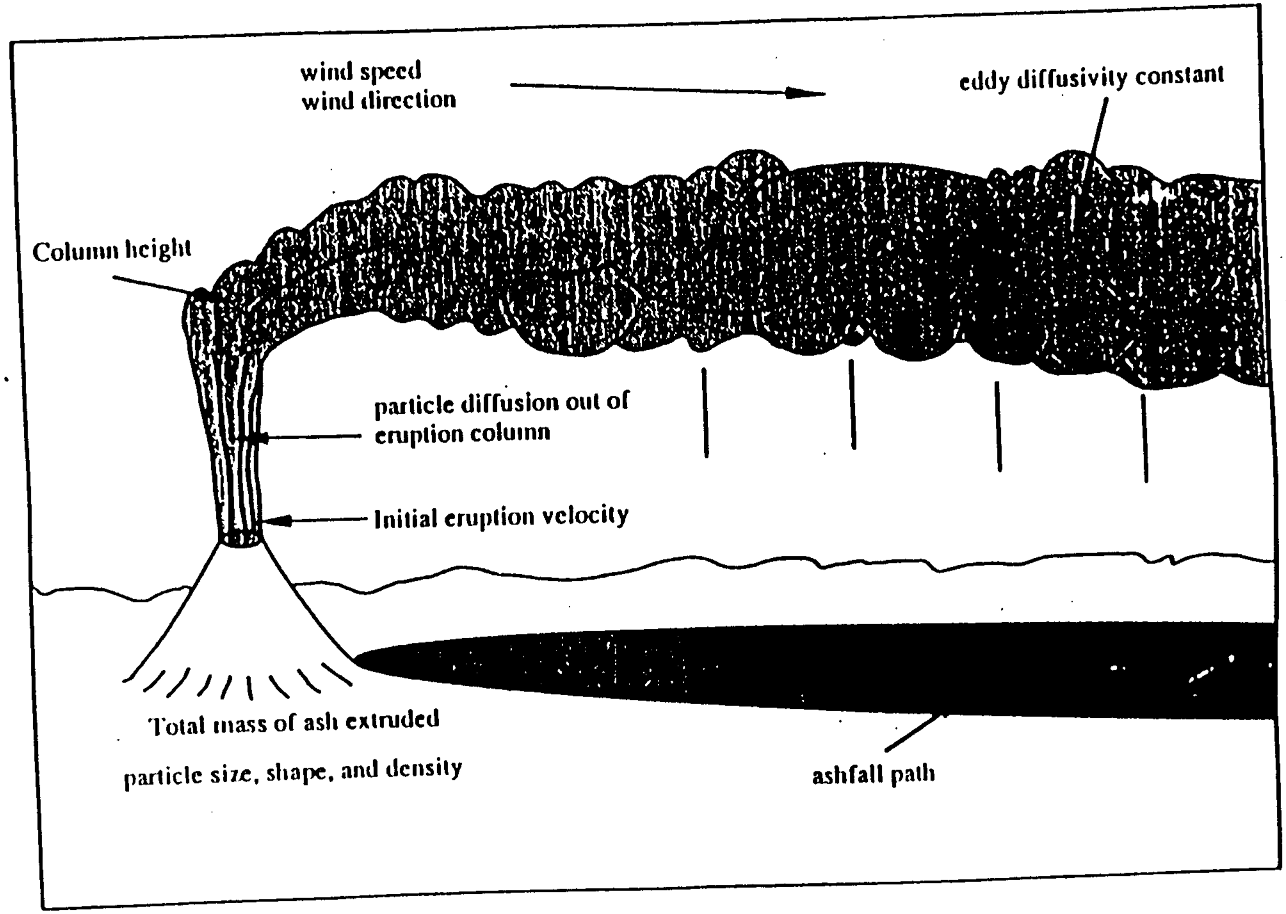
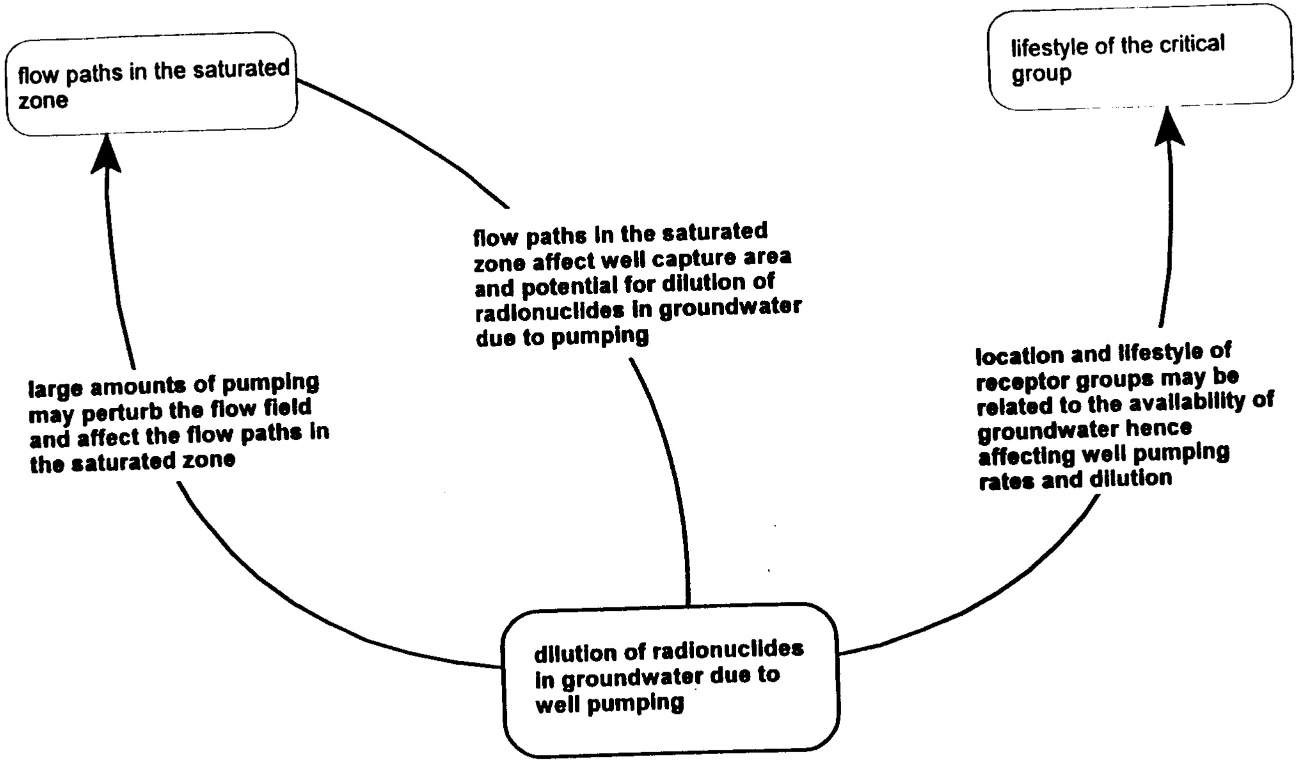
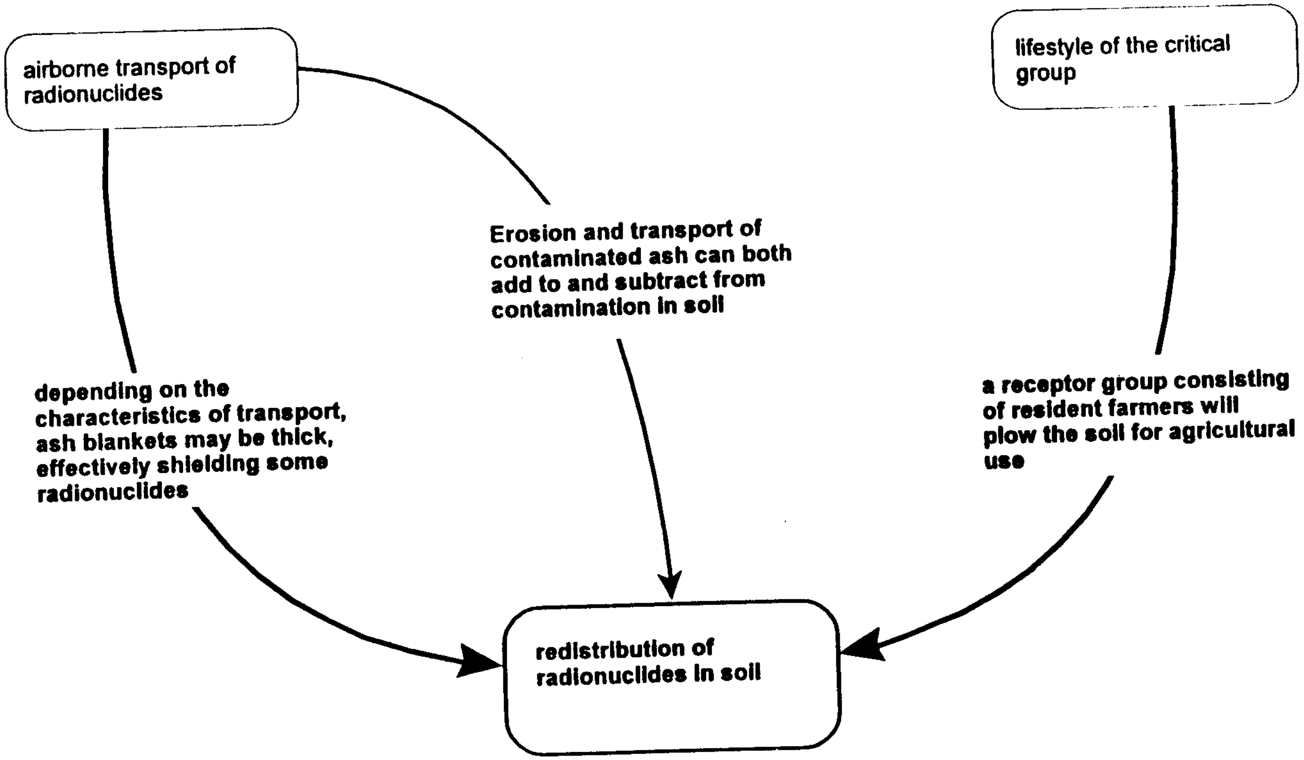


Figure 15. An illustration of the important processes and parameters for estimating airborne transport of tephra.



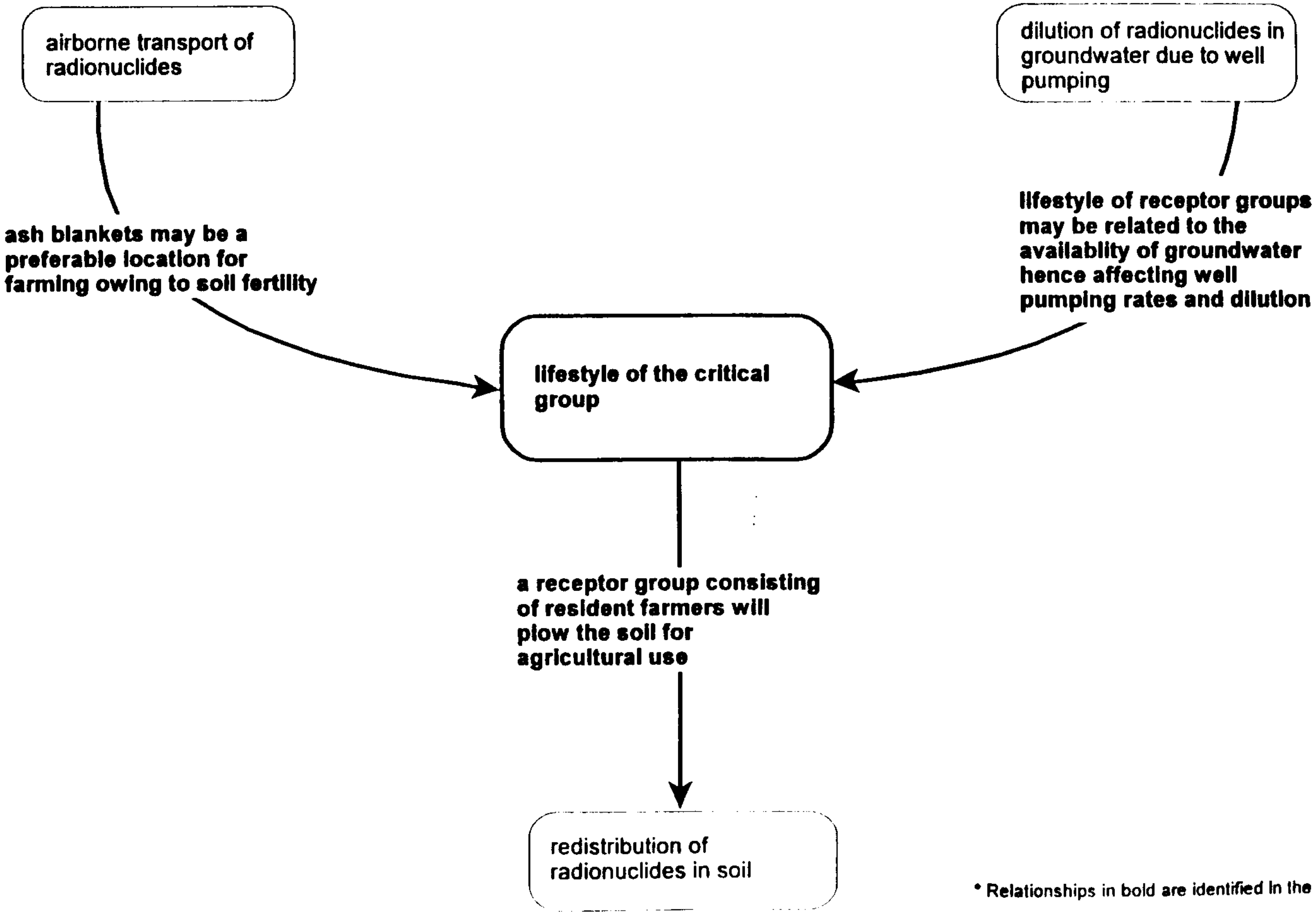
* Relationships in bold are identified in the text

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



* Relationships in bold are identified in the text

Figure 17. A diagram illustrating the relationships between "redistribution of radionuclides in soil" and other integrated subissues.



* Relationships in bold are identified in the text

Figure 18. A diagram illustrating the relationships between "lifestyle of the critical group" and other integrated subissues.

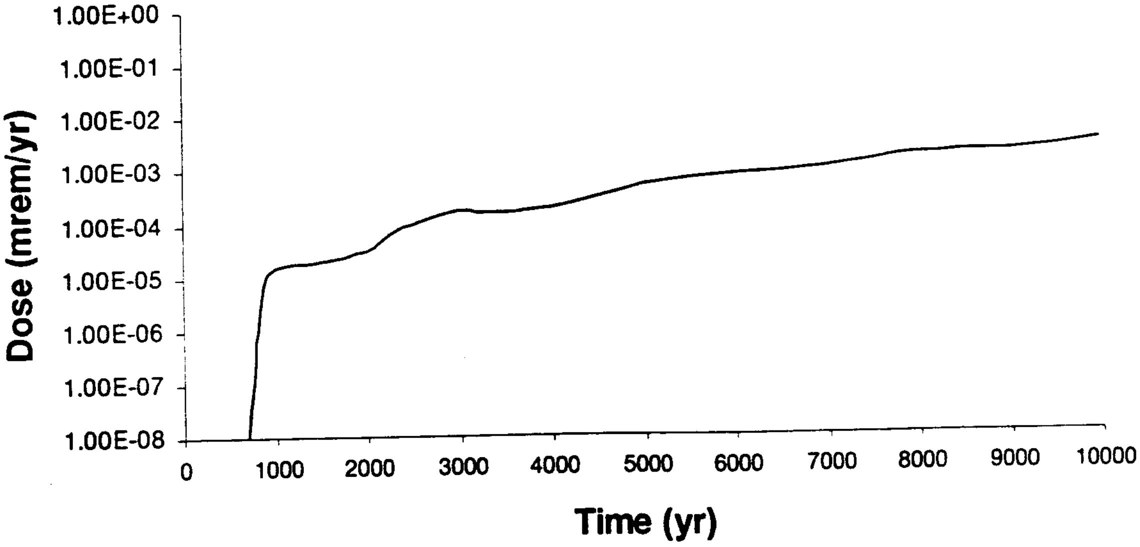


Figure 19. Mean Dose History for the Base Case Performance of the Repository

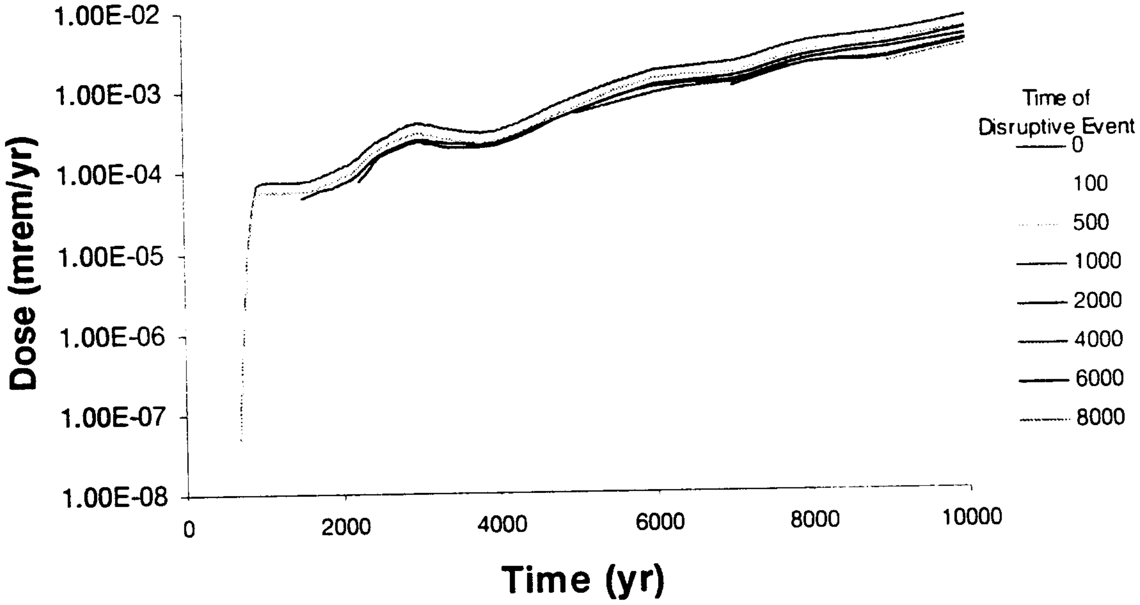


Figure 20. Scenario Class Dose History for Scenario Class ⊖ Based on Time of Occurrence of the Disruptive Event

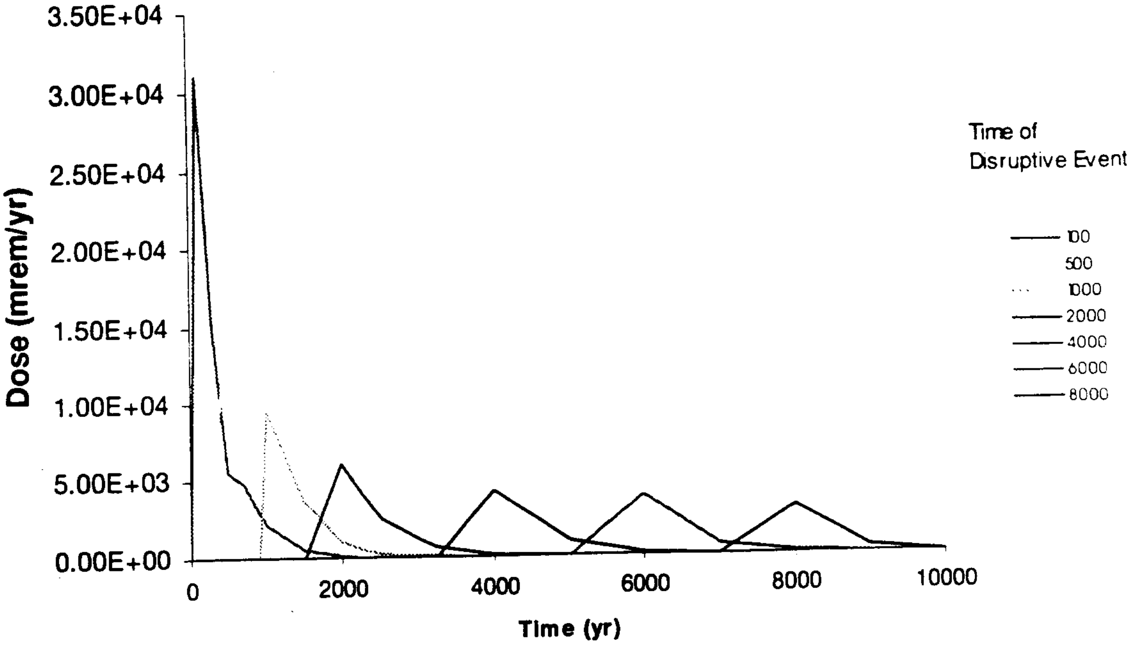


Figure 21. Scenario Class Dose History for Scenario Class Ψ Based on Time of Occurrence of the Disruptive Event

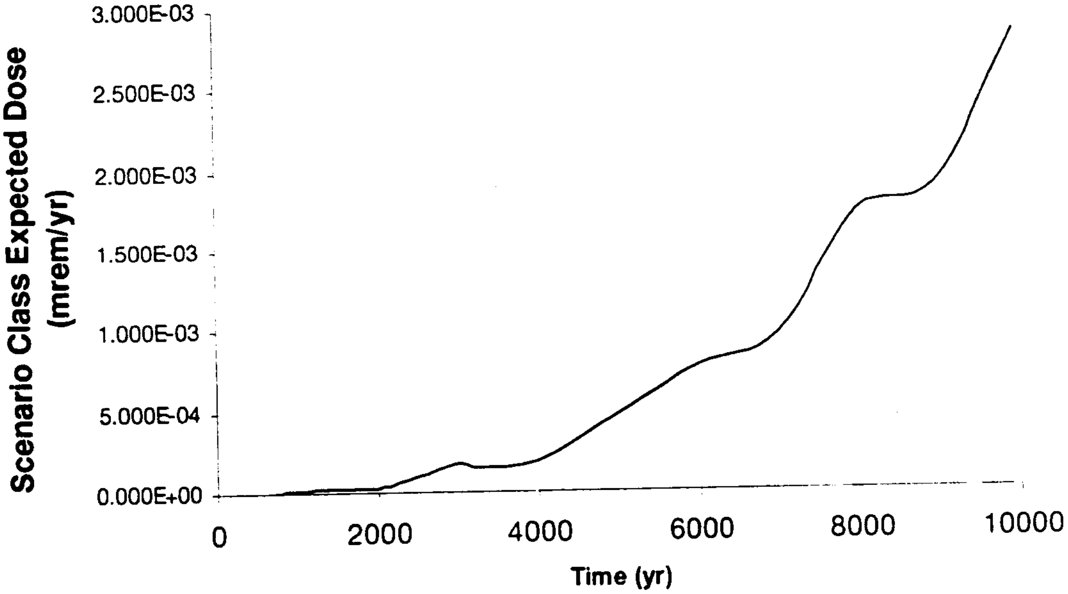


Figure 22. Scenario Class Expected Dose History for Base Case

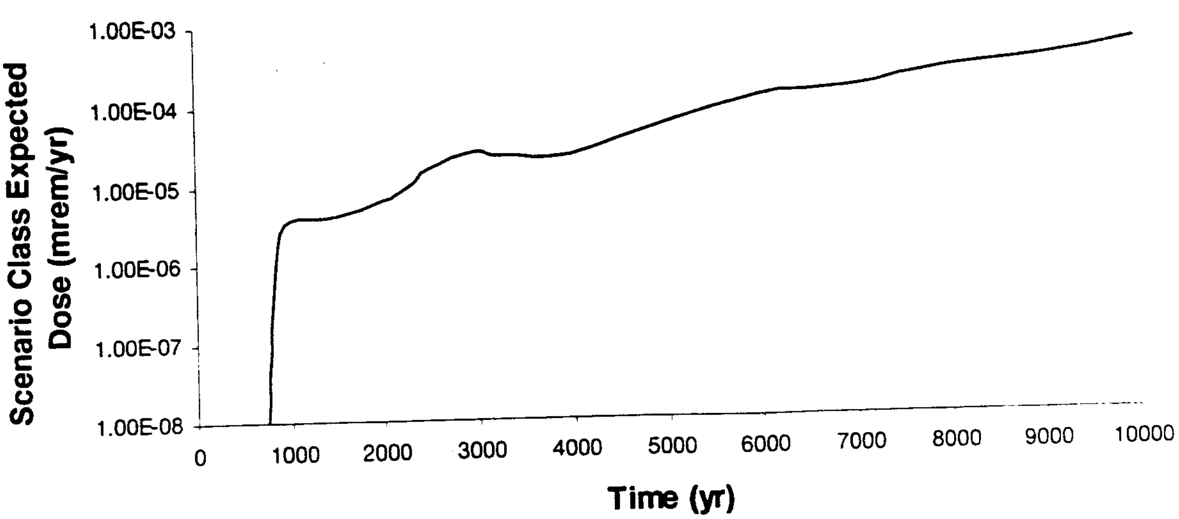


Figure 23. Scenario Class Expected Dose History for Scenario Class Θ

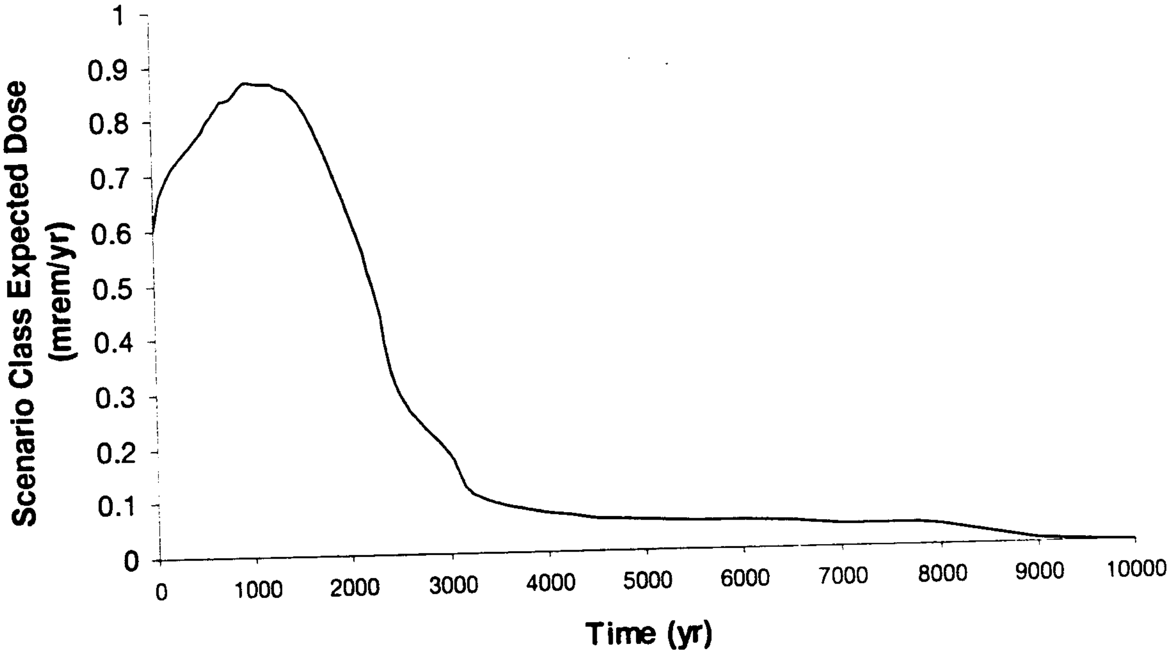


Figure 24. Scenario Class Expected Dose History for Scenario Class Ψ

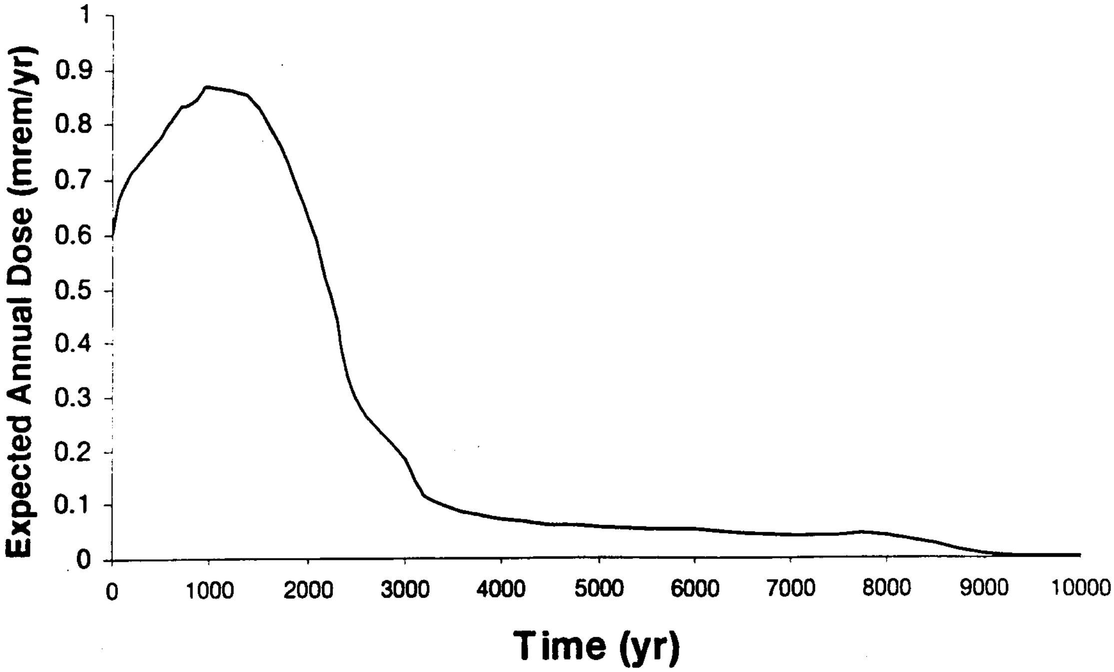


Figure 25. Expected Annual Dose

5.0 STATUS OF ISSUE RESOLUTION AT THE STAFF LEVEL

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/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. The discussion points that were raised during the last three DOE/NRC TSPA Technical Exchanges (i.e., July 1997, November 1997 and March 1998) are listed as having been resolved or having been elevated to the status of Open Items based on information from TSPA-VA. 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. (Subsequent to the staff's review of the SCP, additional scenario-related Open Items were identified in other KTI areas. To the extent that additional Open Items have been identified in other KTI areas, their status has been documented in the applicable IRSR.) As a result of the pre-licensing 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.[16] The status of the resolution of TSPAI Open Items is summarized in Table 17, including scenario-related Open Items.

Table 18 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 and 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.

Tables 19–32 contain summaries of the status of resolution of the KTI subissues associated with each of the ISIs. It is cautioned that closure of all of the KTI subissues associated with an ISI does not necessarily mean that the ISI is closed because the KTI subissues may not be

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In addition to the review of the site characterization activities specified in NRC's geologic repository regulations, the Commission contemplates an ongoing review of information on site investigation and site characterization, such as those with long procurement times, so as to allow for the early identification and resolution of potential licensing issues. Moreover, NRC's strategic planning assumptions call for the early identification and resolution, at the staff level, of issues before the receipt of a potential LA to construct a geologic repository. The principal means for achieving this goal is through informal, pre-licensing consultation with DOE, the State of Nevada, Tribal Nations, and affected units of local government. This approach attempts to reduce the number of, and to better define, issues that will be litigated during a potential licensing hearing, by obtaining input and striving for consensus from the technical community, interested parties, or other targeted groups on such issues. Also see Section 1.

sufficient to meet the five technical and two programmatic acceptance criteria outlined for each ISI in this IRSR. The status of resolution for each of the subissues that provides input to this ISI is fully documented in the respective KTI IRSRs.

Table 16. Resolution summary for Total-system Performance Assessment and Integration key technical issue open items

Status of TSPAI KTI Open Items	Number
Resolved	27
Open	5

Table 17. 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 post-closure performance	
OAO030SEP1992C002	Resolved	Pre-closure potentially disruptive events used as examples of potential post-closure effects on performance	
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 17. 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	Holonich (1992)
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 as to how human intrusion will be handled	Holonich (1992, 1993), Roberts (1992)
OSC0000001347C111	Resolved	Inconsistencies in Total System Performance Section of SCP	
OSC0000001347C112	Resolved	There is a gap in the discussion of the treatment of state variables as constants or as random variables	
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	
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	
OAO028MAY1993C001	Resolved	PACs may not be appropriately considered in compliance demonstration with overall performance objectives	See discussion in Section 4.3.

Table 17. Summary of Total-system Performance Assessment and Integration key technical issue open item status (cont'd)

Item ID	Status	Title	Comment
OAO028MAY1993C002	Resolved	Consideration of present PAC/FACs may be inappropriately restricted to scenario development	See discussion in Section 4.3.
OSC0000001347C001	Resolved	Incomplete program for Issue Resolution Strategy	NRC (1989), DOE (1990), Bernero (1991). See discussion in Section 4.4.
OSC0000001347C002	Resolved	Deficiencies in performance allocation	See discussion in Section 4.4.
OSC0000001347C116	Resolved	Incorrect assumption that absence of significant sources of groundwater sources at site precludes consideration of environmental pathways for individual dose calculations	See discussion in Section 4.3.3.1.3.
OSC0000001347C117	Resolved	Current approach for C14 exposure will not provide the information needed to calculate residence time	See discussion in Section 4.3.2.3.2
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 discussion in Section 4.3.2.1.2.
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 discussion in Section 4.3.

Table 17. Summary of Total-system Performance Assessment and Integration key technical issue open item status (cont'd)

Item ID	Status	Title	Comment
OSC0000001347C009	Open	Lack of criteria for using expert judgment and lack of traceable and defendable procedures for expert judgment elicitation	See discussion in Section 4.3.
OSC0000001347C095	Open	Underlying logic for, and implementation of, scenario development and screening are deficient for generating a CCDF and deficient for guiding site characterization	NRC (1989), DOE (1990), Bernero (1991), Austin (1996). See discussion in Section 4.2.
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 4.3.
OSC0000001347C105	Open	Data, analyses, or justification should be provided to substantiate elimination of scenarios	NRC (1989), DOE (1990), Bernero (1991), Austin (1996). See discussion in Section 4.2.
OSC0000001347C007	Open	Clarification of role of subjective methods in performance assessment is needed	See discussion in Section 4.3.

Table 18. 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?	Section 4.3
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?	Section 4.3
TE3	How is DOE calibrating its use of abstracted data and response surfaces from process-level modeling results in the performance assessment calculations?	Section 4.3
TE4	What radionuclides will DOE use for its dose calculations? How has DOE screened radionuclides from inclusion into the dose calculation?	Section 4.3
TE5	How will DOE represent results from alternative conceptual models?	Section 4.3
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.	Section 4.3.2.1.1
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)?	Section 4.3.2.2.2
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?	Section 4.3.2.2.2
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).	Section 4.3.2.2.1

Table 18. Discussion points identified in recent U.S. Department of Energy/U.S. Nuclear Regulatory Commission performance assessment technical exchanges (cont'd)

	Questions	Discussion
TE10	How is the flow from the saturated zone being represented and treated in the flow and transport model? (See OSC0000001347C102).	Section 4.3.2.2.1
TE11	What is the significance of colloids on performance?	Section 4.3.1.1.4
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?	Section 4.3.2.1.1
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?	Section 4.3.2.1.1
TE14	What basis is DOE using to estimate radionuclide concentrations in the aquifer?	Section 4.3.3.1.1
TE15	What basis is DOE using to support its estimates of Neptunium solubility?	Section 4.3.1.1.4
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?	Section 4.3.1.1.1
TE17	If DOE is to take credit for galvanic protection, what basis will be used to support this?	Section 4.3.1.1.1
TE18	What data are DOE using to support its modeling of C-22 behavior (e.g., uniform corrosion rate and stress corrosion cracking susceptibility)?	Section 4.3.1.1.1
TE19	What basis is DOE using for establishing and applying the near-field environments for WP corrosion (e.g., corrosion potentials)?	Section 4.3.1.1.1
TE20	How is DOE integrating the interactions between the engineered barrier system and the natural system for radionuclide transport?	Section 4.3.1.1.3

Table 18. Discussion points identified in recent U.S. Department of Energy/U.S. Nuclear Regulatory Commission performance assessment technical exchanges (cont'd)

	Questions	Discussion
TE21	The primary objective of the concrete liner is to prevent pre-closure rock falls. Secondary effects, such as the modification of water chemistry during the post-closure period, could have both positive and negative performance implications. How does DOE plan to address the performance of the concrete lining on repository performance?	Section 4.3.1.1.3
TE22	How are the consequences of seismic events (i.e., vibratory ground motion and rockfall) on WPs going to be evaluated? (See also OSP0000831821Q001).	Section 4.3.1.1.2

Table 19. Summary of status of resolution of key technical issue subissues associated with the degradation of engineered barriers integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Container Life and Source Term (CLST)	CLST1: The effects of corrosion processes on the lifetime of the containers	Partially resolved: For dry-air oxidation, and humid-air corrosion and uniform aqueous corrosion, the criteria related to technical aspects have been met. Passive corrosion of resistant alloy, localized corrosion, microbially influenced corrosion, stress corrosion cracking, and hydrogen embrittlement remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 2, 3, and 5 - 7).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2
	CLST2: Effects of materials stability and mechanical failure on the lifetime of the containers and the release of radionuclides to the near-field environment	Partially resolved: Technical criteria for thermal embrittlement of carbon and low-alloy steel overpacks have been largely resolved. Technical criteria for thermal stability of Alloy 22 overpack and initial defects remain unresolved.	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2
	CLST6: The effects of alternate engineered barrier subsystem design features on container lifetime and radionuclide release from the engineered barrier subsystem	Partially resolved: For the ceramic coating, the criteria related to technical aspects have been met. Backfill, embrittlement of titanium drip shield, corrosion of titanium drip shield, and environmental cracking of titanium drip shield remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 1 and 4 - 8).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 &P2

Table 19. Summary of status of resolution of key technical issue subissues associated with the degradation of engineered barriers integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Evolution of the Near-Field Environment (ENFE)	ENFE2: Effects of coupled thermal-hydrologic-chemical processes on the waste package chemical environment	Open: All technical criteria (general criteria 1 - 5 and specific criteria 1 - 22) remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes have not been abstracted and no justification for their neglect has been provided. Quality assurance and expert elicitation acceptance criteria are unresolved. There are open quality assurance deficiency reports.	1 - 5 P1 & P2
Repository Design and Thermal-Mechanical Effects (RDTME)	RDTME3: Thermal-mechanical effects on underground facility design and performance	Open: The two technical criteria (3 & 4) are open because changes in drift shape and thermal-mechanical changes in hydrologic parameters have not been abstracted and may adversely affect repository performance. Resolution of programmatic criteria (1 & 2) are to be determined.	1 - 5 P1 & P2
Thermal Effects on Flow (TEF)	TEF1: Sufficiency of thermal-hydrologic testing program to assess thermal reflux	Largely resolved: Technical criteria 1.1 - 1.6, 1.8, 1.9, 2, and 3 are closed. Only technical criterion 1.7 remains open. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1 - 5 P1 & P2

Table 19. Summary of status of resolution of key technical issue subissues associated with the degradation of engineered barriers integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	TEF2: Sufficiency of thermal-hydrologic modeling to predict the nature and bounds on thermal effects on flow in the near field	Partially resolved: Technical criteria 1.1, 1.2, 2.1, 2.7, 2.12, 6, and 7 are closed. Technical criteria 2.2 - 2.6, 2.8 - 2.11, 2.13 - 2.16, and 3 - 5 remain open. Those criteria that remain unresolved primarily address features or processes that are inadequately addressed in DOE's coupled TH modeling efforts.	1 - 5
		Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	P1 & P2

Table 20. Summary of status of resolution of key technical issue subissues associated with the mechanical disruption of engineered barriers integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Repository Design and Thermal Mechnical Effects (RDTME)	RDTME2: Design of the geologic repository operations area for the effects of seismic events and direct fault disruption	Partial resolution achieved; full resolution through review of DOE TR3. Quality Assurance criteria is open. Expert Elicitation criteria is closed.	1 - 5 P1 & P2
	RDTME3: Thermal-mechanical effects on underground facility design and performance	Resolution through independent checking when DOE finalizes the LA design. AC 1-17 on effects of seismically induced rockfall on WP performance partially resolved	1 - 5 P1 & P2
Container Life and Source Term (CLST)	CLST1: Effects of corrosion on the lifetime of the containers and the release of radionuclides to the near-field environment	Both methodology and data under discussion with DOE; full resolution after DOE selects design, materials, and completes lab experiments; completes lab experiments and develops a detailed plan for the performance confirmation period. AC 1-16 partially resolved	1 - 5 P1 & P2
	CLST2: Effects of materials stability and mechnical failure on the lifetime of the containers and the release of radionuclides to the near-field environment	Both methodology and data under discussion with DOE; full resolution after DOE selects design, materials, and completes lab experiments; completes lab experiments and develops a detailed plan for the performance confirmation period. AC 1-17 partially resolved	1 - 5 P1 & P2

Table 20. Summary of status of resolution of key technical issue subissues associated with the mechanical disruption of engineered barriers integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	CLST 5: The effects of in-package criticality on waste package and engineered barrier subsystem performance	The methodology described in DOE's submittal (YMP/TR-004Q, Rev. 0) was reviewed and Request for Additional Information is about to be submitted to DOE.	1 - 5 P1 & P2
	CLST6: The effects of alternate engineering barrier subsystem design features on container lifetime and radionuclide release from the engineered barrier subsystem	Partial resolution in VA; full resolution after LA design established and reviewed; completes lab experiments and develops a detailed plan for the performance confirmation period. AC 1-17 partially resolved	1 - 5 P1 & P2
Igneous Activity (IA)	IA2: Consequences of igneous activity within the repository setting	No current questions on criteria 1-4. Criteria 5 is open, DOE has to reconcile the volcanological models with the tectonic models and geophysical data.	1 - 5 P1 & P2
Structural Deformation and Seismicity (SDS)	SDS1: Faulting	Resolved in principle; DOE expected to quantitatively demonstrate its assertion that faulting is not a significant contributor to dose. Quality Assurance criteria is open. Expert Elicitation criterion is resolved.	1 - 5 P1 & P2

Table 20. Summary of status of resolution of key technical issue subissues associated with the mechanical disruption of engineered barriers integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	SDS2: Seismicity	Partially resolved: Criterion 1 is resolved based on staff review of the DOE PSHA. Criteria 2-5 are open pending staff analysis of requested seismic data from DOE. Quality Assurance criteria is open. Quality Assurance criteria is resolved for this subissue. Resolution expected based on data to be provided by DOE. AC 1 resolved, 4-5 partially resolved	1 - 5 P1 & P2
	SDS3: Fracturing and structural framework of the geologic setting	Open: All technical criteria 1-5 remain unresolved for this subissue. Staff review of fracture data indicates that DOE's characterization of fracture characteristics may not be adequate. Quality Assurance acceptance criteria is open. Expert Elicitation criteria is not applicable.	1 - 5 P1 & P2
	SDS4: Tectonic Framework of the Geologic Setting	This subissue is resolved. DOE incorporated the full range of tectonic models in PSHA and TSPA-VA. Resolution of Quality Assurance criteria is open, while Expert Elicitation is closed	1 - 5 P1 & P2

Table 21. Summary of status of resolution of key technical issue subissues associated with the quantity and chemistry of water contacting the waste packages and waste forms integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Container Life and Source Term (CLST)	CLST1: The effects of corrosion processes on the lifetime of the containers	Partially resolved: For dry-air oxidation, and humid-air corrosion and uniform aqueous corrosion, the criteria related to technical aspects have been met. Passive corrosion of resistant alloy, localized corrosion, microbially influenced corrosion, stress corrosion cracking, and hydrogen embritlement remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 2, 3, and 5 - 7).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2
	CLST3: The rate at which radionuclides in spent nuclear fuel (SNF) are released from the engineered barrier subsystem through the oxidation and dissolution of spent fuel	Partially resolved: For SNF types, radionuclide inventory, dry air oxidation, and gaseous release, the criteria related to technical aspects have been met. Aqueous dissolution of SNF, solubility controlled radionuclide release, secondary minerals and colloids, and cladding remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 3 and 5 - 9).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2

Table 21. Summary of status of resolution of key technical issue subissues associated with the quantity and chemistry of water contacting the waste packages and waste forms integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	CLST4: The rate at which radionuclides in high-level waste (HLW) glass are released from the engineered barrier subsystem	Partially resolved: While long-term corrosion of HLW glass, secondary minerals formation, natural analog studies, and colloids and radionuclide transport remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 3 and 5 - 9), the importance to system performance may be limited.	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2
	CLST6: The effects of alternate engineered barrier subsystem design features on container lifetime and radionuclide release from the engineered barrier subsystem	Partially resolved: For the ceramic coating, the criteria related to technical aspects have been met. Backfill, embrittlement of titanium drip shield, corrosion of titanium dripshield, and environmental cracking of titanium dripshield remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 1 and 4 - 8).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2
Evolution of the Near-Field Environment (ENFE)	ENFE1: Effects of coupled thermal-hydrologic-chemical (THC) processes on seepage and flow	Open: All technical criteria (general criteria 1-5 and specific criteria 1 - 21) remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes on seepage and flow have not been abstracted and no justification for their neglect has been provided.	1 - 5
		Quality assurance and expert elicitation acceptance criteria are unresolved. There are open quality assurance deficiency reports.	P1 & P2

Table 21. Summary of status of resolution of key technical issue subissues associated with the quantity and chemistry of water contacting the waste packages and waste forms integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	ENFE2: Effects of coupled thermal-hydrologic-chemical processes on the waste package chemical environment	Open: All technical criteria (general criteria 1 - 5 and specific criteria 1 - 22) remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes have not been abstracted and no justification for their neglect has been provided. Quality assurance and expert elicitation acceptance criteria are unresolved. There are open quality assurance deficiency reports.	1 - 5 P1 & P2
	ENFE3: Effects of coupled thermal-hydrologic-chemical processes on the chemical environment for radionuclide release	Open: All technical criteria (general criteria 1-5 and specific criteria 1 - 22) remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes on radionuclide release have not been abstracted and no justification for their neglect has been provided. Quality assurance and expert elicitation acceptance criteria are unresolved, with open quality assurance deficiency reports.	1 - 5 P1 & P2
Repository Design and Thermal-Mechanical Effects (RDTME)	RDTME3: Thermal-mechanical effects on underground facility design and performance	Open: The two technical criteria (3 & 4) are open because changes in drift shape and thermal-mechanical changes in hydrologic parameters have not been abstracted and may adversely affect repository performance. Resolution of programmatic criteria (1 & 2) are to be determined.	1 - 5 P1 & P2

Table 21. Summary of status of resolution of key technical issue subissues associated with the quantity and chemistry of water contacting the waste packages and waste forms integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Thermal Effects on Flow (TEF)	TEF1: Sufficiency of thermal-hydrologic testing program to assess thermal reflux	Largely resolved: Technical criteria 1.1 - 1.6, 1.8, 1.9, 2, and 3 are closed. Only technical criterion 1.7 remains open. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1 - 5 P1 & P2
	TEF2: Sufficiency of thermal-hydrologic modeling to predict the nature and bounds on thermal effects on flow in the near field	Partially resolved: Technical criteria 1.1, 1.2, 2.1, 2.7, 2.12, 6, and 7 are closed. Technical criteria 2.2 - 2.6, 2.8 - 2.11, 2.13 - 2.16, and 3 - 5 remain open. Those criteria that remain unresolved primarily address features or processes that are inadequately addressed in DOE's coupled TH modeling efforts. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1 - 5 P1 & P2
Unsaturated and Saturated Zone Flow under Isothermal Conditions (USFIC)	USFIC4: Deep percolation (present and future)	Partially resolved: Technical criteria 1–4 are unresolved. Criterion 5 (expert elicitation) is closed, while criterion 6 (quality assurance) remains to be determined.	1 - 5 P1 & P2

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Structural Control and Seismicity (SDS)	SDS3: Fracturing and structural framework of the geologic setting	Open: Uncorrected sampling biases, unconstrained fracture-property parameters, and nonrepresentative data used in abstractions and models. All technical criteria (1 - 5) remain open.	1 - 5
		Resolution of programmatic criteria 6 & 7 is to be determined	P1 & P2

Table 22. **Summary of status of resolution of key technical issue subissues associated with the radionuclide release rates and solubility limits integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Container Life and Source Term (CLST)	CLST3: The rate at which radionuclides in spent nuclear fuel (SNF) are released from the engineered barrier subsystem through the oxidation and dissolution of spent fuel	Partially resolved: For SNF types, radionuclide inventory, dry air oxidation, and gaseous release, the criteria related to technical aspects have been met. Aqueous dissolution of SNF, solubility controlled radionuclide release, secondary minerals and colloids, and cladding remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 3 - 9).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2

Table 22. Summary of status of resolution of key technical issue subissues associated with the radionuclide release rates and solubility limits integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	CLST4: The rate at which radionuclides in HLW glass are released from the engineered barrier subsystem	Partially resolved: While long-term corrosion of HLW glass, secondary minerals formation, natural analog studies, and colloids and radionuclide transport remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 3 - 9), the importance to system performance may be limited. Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	1 - 5 P1 & P2
	CLST 5: The effects of in-package criticality on waste package and engineered barrier subsystem performance	Partially resolved: The "Disposal Criticality Analysis Methodology Topical Report" is currently under review. The review is expected to be completed prior to Rev 3 of CLST IRSR and will form basis for subissue resolution. Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	1 - 5 P1 & P2
	CLST6: The effects of alternate engineered barrier subsystem design features on container lifetime and radionuclide release from the engineered barrier subsystem	Partially resolved: For the ceramic coating, the criteria related to technical aspects have been met. Backfill, embrittlement of titanium drip shield, corrosion of titanium dripshield, and environmental cracking of titanium dripshield remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 1 and 4 - 8). Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	1 - 5 P1 & P2

Table 22. **Summary of status of resolution of key technical issue subissues associated with the radionuclide release rates and solubility limits integrated subissue (cont'd)**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Evolution of the Near-Field Environment (ENFE)	ENFE3: Effects of coupled thermal-hydrologic-chemical processes on the chemical environment for radionuclide release	Open: All technical criteria (general criteria 1-5 and specific criteria 1 - 22) remain unresolved for this subissue in the ENFE IRSR. Quality assurance (QA) and expert elicitation acceptance criteria are unresolved, with open QA deficiency reports.	1 - 5 P1 & P2
	ENFE4: Effects of coupled thermal-hydrologic-chemical processes on radionuclide transport through engineered and natural barriers	Open: All technical criteria (general criteria 1-5 and specific criteria 1 - 22) remain unresolved for this subissue in the ENFE IRSR. Quality assurance (QA) and expert elicitation acceptance criteria are unresolved, with open QA deficiency reports.	1 - 5 P1 & P2
	ENFE5: Effects of coupled thermal-hydrologic-chemical processes on potential nuclear criticality in the near field	Resolved: All technical criteria (general criteria 1-5 and specific criteria 1 - 18) are resolved for this subissue in the ENFE IRSR. Quality assurance (QA) and expert elicitation acceptance criteria are resolved.	1 - 5 P1 & P2

Table 23. **Summary of status of resolution of key technical issue subissues associated with the flow paths in the unsaturated zone integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Evolution of Near Field Environment (ENFE)	ENFE1: Effects of coupled thermal-hydrologic-chemical (THC) processes on seepage and flow	Open: All technical criteria (general criteria 1-21 and specific criteria 1-21) remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes have not been abstracted and no justification for their neglect has been provided. Quality assurance and expert elicitation acceptance criteria are unresolved.	1 - 5 P1 & P2
Structural Deformation and Seismicity (SDS)	SDS3: Fractures and other discontinuities affecting flow	Open: Uncorrected sampling biases, unconstrained fracture property parameters, and nonrepresentative data used in abstractions and models. All technical criteria remain open. Resolution of programmatic criteria 6 & 7 remain open.	1 - 5 P1 & P2
Thermal Effects on Flow (TEF)	TEF1: Sufficiency of thermal-hydrologic testing to assess thermal reflux in near-field	Largely resolved: Technical criteria 1.1 - 1.6, 1.8, 1.9, 2, and 3 are closed. Only technical criterion 1.7 remains open. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1-5 P1 & P2

Table 23. Summary of status of resolution of key technical issue subissues associated with the flow paths in the unsaturated zone integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	TEF2: Sufficiency of thermal-hydrologic modeling to predict the nature and bounds of thermal effects on flow in near-field	Partly resolved: Technical criteria 1.1, 1.2, 2.1, 2.7, 2.12, 6, and 7 are closed. Technical criteria 2.2 - 2.6, 2.8 - 2.11, 2.13 - 2.16, and 3 - 5 remain open. Those criteria that remain unresolved primarily address features or processes that are inadequately addressed in DOE's coupled TH modeling efforts. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1-5 P1 & P2
Unsaturated and Saturated Flow Under Isothermal Conditions (USFIC)	USFIC4: Rate of Deep Percolation (Present and Future [Post-Thermal Period])	All technical criteria (1 - 4) remain open. Multiple lines of evidence available, such as data from the ESF, ECRB, Busted Butte, and boreholes. Programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	1 - 5 P1 & P2

Table 24. Summary of status of resolution of key technical issue subissues associated with the spatial and temporal distribution of flow integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Evolution of Near Field Environment (ENFE)	ENFE1: Effects of coupled thermal, hydrologic, and chemical processes on seepage and flow	Open: All technical criteria (general criteria 1-21 and specific criteria 1-21) remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes have not been abstracted and no justification for their neglect has been provided.	1 - 5
		Quality assurance and expert elicitation acceptance criteria are unresolved.	P1 & P2
Repository Design and Thermal-Mechanical Effect (RDTME)	RDTME3: Design for thermal-mechanical effects	Open. Resolution through independent checking when DOE finalizes LA design	1 - 5
		Quality assurance and expert elicitation acceptance criteria are unresolved.	P1 & P2
Structural Deformation and Seismicity (SDS)	SDS2: Seismicity at Yucca Mountain	Partly resolved. Seismic sources resolved; ground motion parameters open. Acceptance criteria 1 resolved.	1 - 5
		Resolution of programmatic criteria 6 & 7 remain open.	P1 & P2
	SDS3: Fractures and other discontinuities affecting flow	Open: Uncorrected sampling biases, unconstrained fracture property parameters, and nonrepresentative data used in abstractions and models. All technical criteria remain open.	1 - 5
		Resolution of programmatic criteria 6 & 7 remain open.	P1 & P2

Table 24. Summary of status of resolution of key technical issue subissues associated with the spatial and temporal distribution of flow integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Thermal Effects on Flow (TEF)	TEF1: Sufficiency of thermal-hydrologic testing to assess thermal reflux in near-field	Largely resolved: Technical criteria 1.1 - 1.6, 1.8, 1.9, 2, and 3 are closed. Only technical criterion 1.7 remains open. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1 - 5 P1 & P2
	TEF2: Sufficiency of thermal-hydrologic modeling to predict the nature and bounds of thermal effects on flow in near-field	Partly resolved: Technical criteria 1.1, 1.2, 2.1, 2.7, 2.12, 6, and 7 are closed. Technical criteria 2.2 - 2.6, 2.8 - 2.11, 2.13 - 2.16, and 3 - 5 remain open. Those criteria that remain unresolved primarily address features or processes that are inadequately addressed in DOE's coupled TH modeling efforts. Programmatic criterion 2 on expert elicitation is closed, while programmatic criterion 1 on quality assurance remains open.	1-5 P1 & P2
Unsaturated and Saturated Flow Under Isothermal Conditions (USFIC)	USFIC1: Future climate change	Closed. Achieved resolution regarding methodology (paleoclimate), upper bound for pluvial precipitation, and likely depression of mean annual temperatures for pluvials. Although no expert elicitation was conduction for climate change, programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	1 - 5 P1 & P2

Table 24. Summary of status of resolution of key technical issue subissues associated with the spatial and temporal distribution of flow integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	USFIC2: Hydrologic effects of climate change	Largely resolved. Achieved resolution regarding the upper bound estimate of water table rise based on paleohydrology data.	1 - 5
		The SZ expert elicitation touched on water table rise and the DOE has a greater amount of water table rise. This criterion is closed. Programmatic criterion 6 on quality assurance remains open	P1 & P2
	USFIC3: Present-Day Shallow Infiltration	Largely resolved: Technical criteria 1, 2, and 4 are closed (estimated present-day shallow infiltration, spatial and temporal distribution of infiltration for PA, and infiltration sensitivity.) Criterion 3 remains open regarding the upper bound estimates of infiltration.	1 - 5
		Programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	P1 & P2
	USFIC4: Rate of Deep Percolation (Present and Future [Post-Thermal Period])	All technical criteria (1 - 4) remain open. Multiple lines of evidence available, such as data from the ESF, ECRB, Busted Butte, and boreholes.	1 - 5
		Programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	P1 & P2

Table 25. Summary of status of resolution of key technical issue subissues associated with the radionuclide transport in the unsaturated zone integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Radionuclide Transport (RT)	RT1: Radionuclide transport through porous rock	Partially resolved: Some acceptance criteria for some radionuclides have been met	1 - 5 P1 & P2
	RT3: Radionuclide transport through fractured rock	Open: Acceptance criteria have been developed in the RT IRSR Rev. 1, Sept. 99 Programmatic criteria open	1 - 5 P1 & P2
	RT4: Nuclear criticality in the far-field	Resolved: No further questions at this time	1 - 5 P1 & P2
Structural Control and Seismicity (SDS)	SDS3: Fracture framework	Open: Uncorrected sampling biases, unconstrained fracture-property parameters, and non-representative data used in abstractions and models. All technical criteria (1 - 5) remain open. Resolution of programmatic criteria 6 & 7 is to be determined	1 - 5 P1 & P2
Evolution of the Nearfield Environment (ENFE)	ENFE4: Effects of thermal-hydrologic-chemical processes on radionuclide transport through engineered and natural barriers	Open: All technical criteria (general criteria 1-5 and specific criteria 1 - 22 remain unresolved for this subissue in the ENFE IRSR. The effects of coupled THC processes on transport have not been abstracted and no justification for their neglect has been provided. Quality assurance (QA) and expert elicitation acceptance criteria are unresolved, with open QA deficiency reports	1 - 5 P1 & P2

Table 25. Summary of status of resolution of key technical issue subissues associated with the radionuclide transport in the unsaturated zone integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Unsaturated and Saturated Flow under Isothermal Conditions (USFIC)	USFIC4: Deep percolation	All technical criteria (1 - 4) remain open. Multiple lines of evidence available for evidence, such as data from the ESF, ECRB, Busted Butte, and boreholes. Programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	1 - 5 P1 & P2
	USFIC6: Matrix diffusion	Unresolved: Technical criterion 2 pertinent to this subissue in the USFIC IRSR is open. Programmatic criterion 3 (EE) is not applicable; and programmatic criterion 4 (QA) is to be determined.	1 - 5 P1 & P2

Table 26. Summary of status of resolution of key technical issue subissues associated with the flow paths in the saturated zone integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Unsaturated and Saturated Zone Flow under Isothermal Conditions (USFIC)	USFIC2: Hydraulic effects of climate change	Largely resolved: Technical criteria (1-4) pertinent to this subissue in the USFIC IRSR are resolved.	1 - 5
		Resolution of programmatic criteria 5 (QA) is to be determined.	P1
	USFIC5: Saturated zone ambient flow conditions and dilution processes	Largely Open: Technical criteria 1,2,3,4,5,6,8, and 9 pertinent to this subissue in the USFIC IRSR are open, except that criterion 2 is considered partly resolved.	1 - 5
		Programmatic criterion 10 (EE) is resolved.	P2
		Resolution of programmatic criterion 11 (QA) is to be determined.	P1
	USFIC6: Matrix diffusion	Unresolved: Technical criterion 2 pertinent to this subissue in the USFIC IRSR is open.	1 - 5
		Programmatic criterion 3 (EE) is not applicable; and programmatic criterion 4 (QA) is to be determined.	P1 & P2
Structural Control and Seismicity (SDS)	SDS1: Faulting	Partly resolved: Technical criteria (1-5) pertaining to faulting in the SDS IRSR are largely resolved, except that the DOE still needs to demonstrate that faulting is of no significance to PA and ISA (Integrated Safety Assessment).	1 - 5
		Resolution of programmatic criteria (6 & 7) is to be determined.	P1 & P2

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	SDS3: Fracturing and structural framework of the geologic setting	Open: Uncorrected sampling biases, unconstrained fracture-property parameters, nonrepresentative data used in abstractions and models. Resolution of programmatic criteria (6 & 7) is to be determined.	1 - 5 P1 & P2

Table 27. Summary of status of resolution of key technical issue subissues associated with the radionuclide transport in the saturated zone integrated subissue

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Radionuclide Transport (RT)	RT1: Radionuclide transport through porous rock	Partially resolved: Some acceptance criteria for some radionuclides have been met	1 - 5 P1 & P2
	RT2: Radionuclide transport through alluvium	Open: The alluvium has not been characterized	1 - 5 P1 & P2
	RT3: Radionuclide transport through fractured rock	Open: Acceptance criteria have been developed in the RT IRSR Rev. 1, Sept. 99 Programmatic criteria open	1 - 5 P1 & P2
	RT4: Nuclear criticality in the far-field	Resolved: No further questions at this time	1 - 5 P1 & P2

Table 27. Summary of status of resolution of key technical issue subissues associated with the radionuclide transport in the saturated zone integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Structural Control and Seismicity (SDS)	SDS3: Fracture framework	Open: Uncorrected sampling biases, unconstrained fracture-property parameters, and non-representative data used in abstractions and models. All technical criteria (1 - 5) remain open.	1 - 5
		Resolution of programmatic criteria 6 & 7 is to be determined	P1 & P2
Unsaturated and Saturated Flow under Isothermal Conditions (USFIC)	USFIC5: Saturated zone ambient flow conditions and dilution processes	Largely Open: Technical criteria 1,2,3,4,5,6,8, and 9 pertinent to this subissue in the USFIC IRSR are open, except that criterion 2 is considered partly resolved.	1 - 5
		Programmatic criterion 10 (EE) is resolved.	P2
		Resolution of programmatic criterion 11 (QA) is to be determined.	P1
	USFIC6: Matrix diffusion	Unresolved: Technical criterion 2 pertinent to this subissue in the USFIC IRSR is open.	1 - 5
		Programmatic criterion 3 (EE) is not applicable; and programmatic criterion 4 (QA) is to be determined.	P1 & P2

Table 28. **Summary of status of resolution of key technical issue subissues associated with the volcanic disruption of waste packages integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Igneous Activity (IA)	IA1: Probability of igneous activity	No current questions on 2 of 7 Technical Criterion.	1 - 5
		Questions on both programmatic criterion.	P1 & P2
	IA2: Consequences of igneous activity	No current questions on 1 of 5 technical criterion.	1 - 5
		Questions on both programmatic criterion.	P1 & P2
Structural Control and Seismicity (SDS)	SDS1: Faulting	Partly resolved: Technical criteria (1-5) pertaining to faulting in the SDS IRSR are largely resolved, except that the DOE still needs to demonstrate that faulting is of no significance to PA and ISA (Integrated Safety Assessment).	1 - 5
		Resolution of programmatic criteria (6 & 7) is to be determined.	P1 & P2
	SDS4: Tectonics and Crustal Conditions	Partially resolved. Question consistent use of updated strain data in PS and ISA. Acceptance criteria 1-4 resolved.	1 - 5
		Resolution of programmatic criteria is to be determined.	P1 & P2

Table 28. Summary of status of resolution of key technical issue subissues associated with the volcanic disruption of waste packages integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Container Life and Source Term (CLST)	CLST1: The effects of corrosion processes on the lifetime of the containers	Partially resolved: For dry-air oxidation, and humid-air corrosion and uniform aqueous corrosion, the criteria related to technical aspects have been met. Passive corrosion of resistant alloy, localized corrosion, microbially influenced corrosion, stress corrosion cracking, and hydrogen embritlement remain unresolved for technical criteria (general criteria 3 - 9 and specific criteria 2, 3, and 5 - 7).	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2
	CLST2: Effects of materials stability and mechanical failure on the lifetime of the containers and the release of radionuclides to the near-field environment	Partially resolved: Technical criteria for thermal embrittlement of carbon and low-alloy steel overpacks have been largely resolved. Technical criteria for thermal stability of Alloy 22 overpack and initial defects remain unresolved.	1 - 5
		Resolution of general criteria 1 & 2 in the CLST IRSR is to be determined	P1 & P2

Table 29. **Summary of Status of resolution of key technical issue subissues associated with the airborne transport of radionuclides integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Igneous Activity (IA)	IA2: Consequences of igneous activity	No current questions on 1 of 5 technical criterion. Questions on both programmatic criterion.	1 - 5 P1 & P2

Table 30. **Summary of status of resolution of key technical issue subissues associated with the dilution of radionuclides in groundwater due to well pumping integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Unsaturated and Saturated Zone Flow under Isothermal Conditions (USFIC)	USFIC5: Saturated zone ambient flow conditions and dilution processes	Resolved: To the extent that DOE was conservative and did not take credit for RN dilution in groundwater due to well pumping in the VA, this ISI is considered resolved for the time being. Technical acceptance criteria pertaining to this subissue in the USFIC IRSR (mainly criterion 7) are considered resolved for the time being. Programmatic criteria pertaining to this subissue in the USFIC IRSR (criteria 10 and 11) are also considered resolved for the time being as far as this subissue is concerned.	 1 - 5 P1 & P2

Table 31. **Summary of status of resolution of key technical issue subissues associated with the redistribution of radionuclides in soil integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Igneous Activity (IA)	IA2: Consequences of igneous activity	No current questions on 1 of 5 technical criterion	1 - 5
		Questions on both programmatic criteria	P1 & P2

Table 32. **Summary of status of resolution of key technical issue subissues associated with the lifestyle of the critical group integrated subissue**

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
Unsaturated and Saturated Zone Flow under Isothermal Conditions (USFIC)	USFIC1: Future climate change	Closed. Achieved resolution regarding methodology (paleoclimate), upper bound for pluvial precipitation, and likely depression of mean annual temperatures for pluvials.	1 - 5
		Although no expert elicitation was conducted for climate change, programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	P1 & P2
	USFIC2: Hydraulic effects of climate change	Largely resolved: Technical criteria (1–4) pertinent to this subissue in the USFIC IRSR are resolved.	1 - 5
		Resolution of programmatic criterion 5 (QA) is to be determined.	P1

Table 32. Summary of status of resolution of key technical issue subissues associated with the lifestyle of the critical group integrated subissue (cont'd)

KTI	KTI SUBISSUES PERTINENT TO ISI	STATUS OF RESOLUTION RELATIVE TO PERTINENT KTI IRSR	RELATIONSHIP TO TSPA ACCEPTANCE CRITERIA
	USFIC3: Present-Day Shallow Infiltration	Largely resolved: Technical criteria 1, 2, and 4 are closed (estimated present-day shallow infiltration, spatial and temporal distribution of infiltration for PA, and infiltration sensitivity.) Criterion 3 remains open regarding the upper bound estimates of infiltration. Programmatic criterion 5 on expert elicitation is closed, while programmatic criterion 6 on quality assurance remains open.	1 - 5 P1 & P2
	USFIC5: Saturated zone ambient flow conditions and dilution processes	Largely Open: Technical criteria 1,2,3,4,5,6,8, and 9 pertinent to this subissue in the USFIC IRSR are open, except that criterion 2 is considered partly resolved. Programmatic criterion 10 (EE) is resolved. Resolution of programmatic criterion 11 (QA) is to be determined.	1 - 5 P2 P1
Radionuclide Transport	RT3: Radionuclide transport through fractured rock	Open: Acceptance criteria are currently being developed Programmatic criteria open	1 - 5 P1 & P2
Igneous Activity (IA)	IA2: Consequences of igneous activity	No current questions on 1 of 5 technical criterion. Questions on both programmatic criteria.	1 - 5 P1 & P2

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APPENDIX B:

LIST OF SUBISSUES IN NRC 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 WP 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 (RT) through engineered and natural barriers
ENFE5	Coupled thermal-hydrologic-chemical processes affecting potential nuclear criticality in the near field

Container Life and Source Term (CLST)

CLST1	Effects of corrosion on the lifetime of the containers and the release of RNs to the near-field environment

CLST2	Effects of materials stability and mechanical failure on the lifetime of the containers and the release of RNs to the near-field environment
CLST3	Rate of degradation of spent nuclear fuel and the rate at which RNs in spent nuclear fuel are released to the near field environment
CLST4	Rate of degradation of high-level waste glass and the rate at which RNs in high-level waste glass are released to the near field environment
CLST5	Design of WP and other components of the engineered barrier system for prevention of nuclear criticality
CLST6	Effect of alternate design features on container lifetime and RN release

Radionuclide Transport (RT)

RT1	RT through porous rock
RT2	RT through alluvium
RT3	RT through fractured rock
RT4	Nuclear criticality in the far field

Total System Performance Assessment and Integration

TSPAI1	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 since rulemaking is the product).

Igneous Activity (IA)

IA1	Probability of future igneous activity
IA2	Consequences of igneous activity within the repository setting

Structural Deformation and Seismicity (SDS)

SDS1	Faulting
SDS2	Seismicity
SDS3	Fracturing and structural framework of the geologic setting
SDS4	Tectonics and crustal conditions

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 post-closure performance objectives

APPENDIX C:

TECHNICAL BASIS FOR U.S. NUCLEAR REGULATORY COMMISSION'S REVIEW OF THE INTEGRATED SUBISSUES

This section provides a synopsis of the technical basis for the U.S. Nuclear Regulatory Commission's (NRC's) review of the U.S. Department of Energy (DOE) approach. The bulk of the technical work supporting the NRC's position for review of an integrated subissue (ISI) is currently contained in the Issue Resolution Status Reports (IRSR) for the pertinent Key Technical Issues (KTIs) (U.S. Nuclear Regulatory Commission, 1999a–f,h). It is anticipated that the technical basis sections that follow will evolve toward a level of greater detail in future revisions of the Total-System Performance Assessment and Integration (TSPAI) IRSR.

This section also provides the initial attempt of the NRC to evaluate DOE's features, events, and processes (FEPs) database. The preliminary evaluation is an assignment of the 310 primary FEPs (U.S. Department of Energy, 1999) to relevant ISIs. It is expected that the documentation provided in this section will evolve to include the secondary FEPs. Also, the assignment of FEPs to ISIs is a dynamic process as a result of the evolution of the FEPs database and evaluation of FEPs at the ISI-level. Some FEPs have been evaluated to potentially cross between multiple ISIs.

Eventually, DOE's Performance Assessment (PA) will be reviewed to determine if DOE has adequately identified and addressed those events that have $>10^{-8}$ probability of occurrence. 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) through (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. NRC currently has plans to review (within the FY2000 revisions of the KTI IRSRs) the DOE's analyses of FEPs that have been screened out.

Engineered Barrier Degradation

Container lifetimes and dose to the receptor group have been independently calculated using Version 3.2 of the NRC Total-system Performance Assessment (TPA) code for the repository and waste package (WP) design presented in the Viability Assessment (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 E_{corr} is dependent on the partial pressure of oxygen, temperature, pH, the presence of other redox species, and the passive current density. The E_{rp} is dependent on the logarithm of the chloride concentration and temperature. Recent work also shows that the E_{rp} of the alloy can be reduced, and thus 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 millimeters 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 (RN) 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. Although carbon steel is not used in either the site recommendation or the Enhanced Design Alternative (EDA) II WP designs, E_{rp} measurements conducted with Alloy 22 specimens indicate that localized corrosion in the modeling 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 was also a factor having 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 5.9×10^{-4} to 1.9×10^{-3} millimeters per year, the first WP failure (VA design) occurs in approximately 10,000 years and all WPs fail in 46,000 years. Using experimentally determined passive corrosion rates, the first WP failure occurs 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.

Table C-1 is a compilation of DOE's primary FEPs assigned to the engineered barrier degradation ISI. KTI subissues pertinent to the ISI and all listed FEPs (CLST1, CLST2, CLST6, ENFE2, TEF1, TEF2, RDTME3) are identified.

Mechanical Disruption of Engineered Barriers

Yucca Mountain (YM) 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 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 barrier systems (EBSs) and pose a potential risk of noncompliance with radiological safety, health, and environmental protection standards.

Detailed technical bases for abstractions of mechanical disruption for EBSs are presented in the SDS, RDTME, and CLST IRSRs (U.S. Nuclear Regulatory Commission, 1999a,b,e). 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 PA 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, 1997) 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 PA. 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 analysis based on the North Ramp Geotechnical (NRG) 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.

Possibility of Simultaneous Rockfall and Vertical Extent of Potential Rockfall

TM 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; Civilian Radioactive Waste Management System Management and Operating Contractor, 1995). 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 under 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, 1999d). 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 meters per second^{-1}), 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 meters below the surface commonly are at least 1 kilometer 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 3×10^6 cubic meters) is smaller than most YMR basaltic eruptions (about 10^6–10^8 cubic meters), 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 breeched.

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-meter 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,b), staff conclude that WP failure on contact with basaltic magma is a reasonably conservative assumption (U.S. Nuclear Regulatory Commission, 1999d). Available data and models also have not evaluated high-level radioactive waste (HLW) behavior under appropriate igneous conditions (e.g., U.S. Department of Energy, 1998b). 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, 1999d). This will affect subsequent remobilization of RNs in aqueous solutions.

Corrosion Degradation

The NRC has 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 hydrogen embrittlement. 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 hydrogen embrittlement. 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.

Table C-2 is a compilation of primary FEPs assigned to the mechanical disruption of engineered barriers ISI. KTI subissues pertinent to the ISI and all listed FEPs (CLST1, CLST2, CLST5, CLST6, IA2, SDS1, SDS2, SDS3, SDS4, RDTME2, RDTME3) are identified.

Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms

The quantity of water contacting WPs plays an important role in determining the lifetime of the WP and the release rates of RNs 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 RNs are also dependent on the quantity of water contacting the waste forms. RN 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 RN, the rate of release of the RNs is dissolution limited. In this case, RN releases in PA are usually calculated by multiplying the WP RN inventory by a maximum fractional release rate for that RN (Mohanty et al., 1997). In the solubility-limited regime, there is sufficient RN release to saturate the water with a given RN. In either case, it is necessary to estimate the quantity of water contacting the waste. Maximum fractional release rates and RN 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 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 spent nuclear fuel (SNF) (U.S. Nuclear Regulatory Commission, 1999e,f). Also, parameters such as pH and the redox state of the water are important for estimating RN 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.*, 1993), uncertainties in YM groundwater pH are characterized as providing one of the major sources of uncertainty for predicting RN solubilities. Distribution coefficients for RNs 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, 1999f).

Table C-3 is a compilation of DOEs primary FEPs assigned to the quantity and chemistry of water contacting the WPs and waste forms ISI. Pertinent KTI subissues (USFIC4, TEF1, TEF2, ENFE1, ENFE2, ENFE3, CLST1, CLST3, CLST4, CIST6, SDS3, RDTME3) are listed.

Radionuclide Release Rates and Solubility Limits

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

A typical approach to analyze the RN 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 RN 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, RN concentrations are truncated to the solubility limits (U.S. Nuclear Regulatory Commission, 1999e). In this manner, both RN solubilities and the waste matrix solubility (determining the release rate for RNs) contribute to estimates of repository performance.

PA 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, 1999g) 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 RN concentrations in the water contained within the WP. In advective release, the rate at which water exits the WP is multiplied by the RN concentration to obtain an exit rate for RNs from the WP (U.S. Nuclear Regulatory Commission, 1999e). In diffusive release, the concentration of RNs in WP waters is used to estimate the concentration gradient necessary for calculating the diffusive flux of RNs from the WP. To estimate time-dependent RN concentrations inside a breached WP, alternative expressions for the dissolution rate of RNs in the SNF are used (U.S. Nuclear Regulatory Commission, 1999e,f). Then, a mass balance is performed for the RN concentration in the WP water. The total release rate of RNs to WP waters is the dissolution rate multiplied by the RN inventory in the WPs (U.S. Nuclear Regulatory Commission, 1999e).

The RNs 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, 1999f). These materials could sorb the RNs 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, 1999f). The physical properties and sorptive capabilities of these materials may change as a result of coupled thermal-hydrologic-chemical processes (U.S. Nuclear Regulatory Commission, 1999f).

Both the RN 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, 1999f). The chemistry of water contacting the waste affects the oxidation state in which RNs exist and ultimately, the solubility and release rate of the RNs (U.S. Nuclear Regulatory Commission, 1999f). 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, 1999f). Similarly, Tc is generally considered to be very soluble under oxidizing conditions but relatively insoluble under reducing conditions (U.S. Nuclear Regulatory Commission, 1999f). 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 RNs 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, 1999f). The secondary minerals may mitigate RN 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 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 PA could be significant if the RN release rate is higher than the RN release rate from SNF (e.g., RN release in colloidal form or pulse release of RNs 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 RNs by the increased production of organic acids (U.S. Nuclear Regulatory Commission, 1999f).

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

Table C-4 is a compilation of DOE primary FEPs assigned to the radionuclide release rates and solubility limits ISI. Pertinent KTI subissues (ENFE3, ENFE4, ENFE5, CLST3, CLST4, CLST5, CLST6) are listed.

Spatial and Temporal Distribution of Flow

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 Mean Annual Infiltration (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 solar load.

The themal-hydrologic-chemical (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 need not be considered in the TSPA.

Table C-5 is a compilation of DOE's primary FEPs assigned to the spatial and temporal distribution of flow ISI. KTI subissues pertinent to the ISI and all listed FEPs (USFIC1, USFIC3, USFIC4, TEF1, TEF2, ENFE1, SDS2, SDS3, RDTME3) are identified.

Flow Paths in the Unsaturated Zone

Flow in the unsaturated zone (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 saturated zone (SZ). In contrast, both geochemical evidence and transient-flow modeling have suggested that a significant amount of groundwater flux occurs in the fracture system and that these fluxes can travel at much faster rates than 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 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. The disparity in velocity between matrix and fracture flow is so dominant that the NRC staff are examining the accuracy of its UZ flow and transport module in TPA Version 3.2.

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 need not be considered in the TSPA.

Table C-6 is a compilation of DOE's primary FEPs assigned to the flow paths in the UZ ISI. KTI subissues pertinent to the ISI and all listed FEPs (USFIC4, TEF1, TEF2, ENFE1, SDS3) are identified.

Radionuclide Transport in the Unsaturated Zone

Calculation of the RN velocity field in the UZ involves using an equation first proposed by Vermuelen and Hiester (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 dissolved 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 1D flow system (termed "fingering ratio"), the rate of radionuclide transport (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, Volume 1, Appendix C) planned at the UZ Transport Test Facility on Busted Butte, located about 5 kilometers south of the potential repository, that are 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 and,

- 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 (13 to 18 months) reactive and nonreactive tracer tests in a 10 × 10 × 6 meter 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 as analogs for RT. 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 hydrologic pump tests to demonstrate 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 as follows:

- 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 RN within the fracture. It must be resolved whether or not this assumption is valid 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 YMR 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 RNs, 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. Retardation in this case is primarily achieved by filtering. The potential for significant colloid/particulate transport of a given RN should be considered when modeling retardation.

- The retardation factor assigned to a given stratum for a particular RN 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.

Table C-7 is a compilation of DOE's primary FEPs assigned to the RT in the UZ ISI. KTI subissues pertinent to the ISI and all listed FEPs (USFIC4, USFIC6, ENFE4, RT1, RT3, RT4,SDS3) are identified.

Flow Paths in the Saturated Zone

The presence of alluvium along the groundwater flow path is expected to significantly delay the arrival of RNs 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 RNs, such as neptunium, in the alluvium (U.S. Department of Energy, 1998a, Volume 3, pp. 6-24, 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 and/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 down gradient of YM may result in more southerly-directed flow paths than currently modeled by the DOE. The RNs in this southerly flow path could remain in the volcanic tuff aquifer nearly all the way to receptor locations at 20 kilometers, 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 utilizes the collective work of all relevant parties as the technical bases for its review. The Civilian Radioactive Waste Management Systems Management and Operating Contractor (1998) and the U.S. Department of Energy (1998a) suggest that the groundwater flow system in the YM vicinity has not yet been adequately characterized. There are very limited field data to characterize SZ flow between about 5 and 20 kilometers downgradient from the repository (U.S. Department of Energy, 1998a, Volume 4, p 2-38). Limited data exists 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'Agnes, et al., 1997; U.S. Department of Energy, 1998a; Geomatrix Consultants, Inc., 1998; Gelhar, 1998; 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, 1998c). 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 RNs.

Table C-8 is a compilation of DOE's primary FEPs assigned to the flow paths in the SZ ISI. KTI subissues pertinent to the ISI and all listed FEPs (USFIC1, USFIC4, USFIC5, SDS3, SDS4) are identified.

Radionuclide Transport in the Saturated Zone

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 meters 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, since the proposed draft 10 CFR Part 63 is dose based, concentrations of RNs 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 RNs would be reduced, by some unknown amount.

The PA of the high-level nuclear waste 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 PA.

It is anticipated that for DOE to demonstrate a capability to <u>predict</u> breakthrough curves in the field, the following is required

- Laboratory experimentation to determine parameters to be used in process modeling (K_ds, 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

Table C-9 is a compilation of DOE's primary FEPs assigned to the RT in the SZ ISI. KTI subissues pertinent to the ISI and all listed FEPs (USFIC5, USFIC6, RT1, RT2, RT3, RT4, SDS3) are identified.

Volcanic Disruption of Waste Packages

This section presents an overview of the technical basis for the abstraction of volcanic disruption of WPs in repository PAs. Details of these abstractions are presented in NRC (1999d).

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, 1999d), 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 meters, 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, 1999d).

Other parameters necessary for volcanism risk calculations, primarily related to interactions between basaltic magma and EBSs, are difficult to constrain. 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 reasonably conservative assumption (U.S. Nuclear Regulatory Commission, 1999d). 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, 1999d).

Current staff modeling assumes that during the first 10,000 years of repository closure, volcanism is the only process that could lead to direct release of RNs from the proposed repository and cause significant (relative to base-case dose) radiological dose to individuals located 20 kilometers away. Considering both the annual probability of volcanic disruption and the dose consequences of the event, current analyses show the maximum expected annual dose (i.e., risk) from volcanism is about 1 mrem per year and occurs around 1,000 years after repository closure. Although this value is demonstrably below the proposed performance standard of 25 mrem per year, these analyses demonstrate that DOE's license application (LA) will need a clear and credible treatment of igneous activity disruptive processes.

Table C-10 is a compilation of DOE's primary FEPs assigned to the disruption of WPs ISI. KTI subissues pertinent to the ISI and all listed FEPs (CLST1, CLST2, IA1, IA2, SDS1, SDS4) are identified.

Airborne Transport of Radionuclides

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; Woods, 1993; 1995; Sparks et al., 1997). 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 PA 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 signifcantly the amount of HLW dispersed during some eruptions. An important conclusion from initial analyses (U.S. Nuclear Regulatory Commission, 1999d) 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 kilometers above ground level, which is observed for most violent-strombolian basaltic eruptions (U.S. Nuclear Regulatory Commission, 1999d). 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-kilometers-high eruption columns (e.g., U.S. Department of Energy, 1997b). The nearest available high-altitude wind data are from the Desert Rock airstrip, which is located about 50 kilometers southeast of YM. Based on data in U.S. Department of Energy (1997b), average wind speeds at about 2 kilometers above ground level (i.e., 700 mbar) are 6 meters s^{-1}. These average wind speeds increase to about 12 meters s^{-1} at altitudes of about 4 kilometers above ground level (i.e., 500 mbar). Staff conclude that an average wind speed of 12 meters 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).

Table C-11 is a compilation of DOE's primary FEPs assigned to the airborne transport of RNs ISI. KTI subissues pertinent to the ISI and all listed FEPs (IA2) are identified.

Dilution of Radionuclides Caused By Well Pumping

This section describes the technical basis for the abstraction of dilution of RNs caused by well pumping in repository PAs. Specifically, the effects of pumping on plume capture are discussed.

RNs 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 RNs 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 RNs within the capture zone that may homogenize the RN 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 down gradient 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 RNs migrating down gradient from the proposed repository. Depending on the relative volumes of contaminated and uncontaminated waters drawn into the cone of depression, significant reductions in RN concentrations may result, thus reducing RN concentrations reaching the biosphere. Hence, in a qualitative sense, this mixing or dilution can have a significant impact on repository performance. However, for PA analyses, quantitative estimates of dilution within the cone of depression are required. At this time, no standard methodology exists for quantifying dilution caused by pumping, and as a result approaches tend to be tailored to the approach used to simulate mass transport. It is clear, however, that 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.

RN dilution caused by pumping depends on the relative geometries of the well capture zone and the plume of dissolved RNs. If the capture zone is sufficiently large to capture the entire plume of dissolved RNs, the borehole concentration is computed by integrating the spatial distribution of RN concentrations to obtain the total RN 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 RN 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 PA 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.

Table C-12 is a compilation of DOE's primary FEPs assigned to the dilution of RNs caused by well pumping ISI. The KTI subissue pertinent to the ISI and all listed FEPs (USFIC5) are identified.

Redistribution of Radionuclides in Soil

This section describes the technical basis for the abstraction of redistribution of RNs in soil to repository PAs. 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 RNs that exist fairly close to the surface are capable of exposing members of a receptor population to radiation. The depth beyond which RNs 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 centimeters 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 RNs 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 RNs and are thus more penetrating than most gamma-ray emissions. The dose rate at 1 meter above the soil due to contamination in the uppermost 15 centimeters is 7.25×10^{-17} [Sv/s]/[Bq/m^3], however, the dose rate at 1 meter above the soil due to contamination from all the soil deeper than 15 cm is only 1.43×10^{-17} [Sv/s]/[Bq/m^3] (Eckerman and Ryman, 1993) (i.e., contamination in the uppermost 15 centimeters of soil accounts for 84 percent of the exposure) (Note: 1 Sv = 100 rem and 3.7 × 10^{10} Bq = 1 Ci). The degree of self-shielding would increase for RNs whose gamma ray emissions are less energetic.

There are at least two processes by which RNs 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 RNs 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 RN solubility and distribution coefficient. It is noted that these processes may work in conjunction, meaning that RNs 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 RNs 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.

If a volcano should erupt through a repository at YM, the majority of volcanic material will 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 1,000 years (U.S. Nuclear Regulatory Commission, 1999d), during the first 1,000 years after the eruption approximately 10^7 cubic meters 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. Although some of the contaminated material could be deposited on fields, it is not likely that the immediate fan area would be used for straight agricultural purposes. However, it could be a source of grazing land. 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 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 RNs 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.

Staff from NRC, CNWRA, DOE, and the State of Nevada have conducted numerous investigations regarding the probability and likely consequences of repository disruption by basaltic igneous activity. Results of these investigations demonstrate that the probability and likely consequences of future igneous activity are sufficiently large, such that basaltic igneous activity needs to be considered in repository PAs. 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-millimeter diameter at least 30 kilometers from the vent, resulting in 1- to 100-millimeters thick deposits (Hill et al., 1996). The redistribution of these RNs 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 RNs in soil are important in determining the risk associated with igneous activity disrupting the repository.

U.S. Nuclear Regulatory Commission (1999d) demonstrates that the expected annual dose from igneous activity may be the dominant contributor to total-system expected annual dose during the first 10,000 years of post-closure repository operations. 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. Under 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 post-closure 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. The maximum expected annual dose from volcanic disruption is calculated in NRC (1999d) to be around 1 mrem per year. The timing and magnitude of this maximum expected annual dose is relatively insensitive to assumptions of tephra-fall deposit half-life, requiring a half-life of 100 years (i.e., assumed deposit lifetime of 1,000 years) to lower the maximum expected annual dose significantly.

Table C-13 is a compilation of DOE's primary FEPs assigned to the redistribution of RNs in soil ISI. The KTI subissues pertinent to the ISI and all listed FEPs (IA2) are identified.

Lifestyle of the Critical Group

The scope of the ISI of lifestyle of the critical group encompasses key aspects of critical group dose calculations based on estimated RN concentrations in the biosphere. In PA calculations, when modeled groundwater or air contaminants reach the location of the critical group, the fate and human health consequences must be estimated considering characteristics of the biosphere and critical group. This section describes the technical basis for the critical group abstraction to repository PAs and the basis for relevant acceptance criteria.

In their recommendations to the EPA for developing HLW standards for YM, 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 (International Council on Radiation Protection, 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 RNs. 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). 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 has 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 that are 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 a number of 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 (U.S. Nuclear Regulatory Commission, 1999g). 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 PAs. 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 semi-arid 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.

Table C-14 is a compilation of DOE's primary FEPs assigned to lifestyle of the critical group ISI. KTI subissues pertinent to the ISI and all listed FEPs (USFIC1, USFIC2, USFIC3, USFIC5, RT3, IA2) are identified.

Table C-1. List of features, events, and processes related to the degradation of engineered barriers integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Degradation of engineered barriers KTI subissues TEF1 TEF2 ENFE2 CLST1 CLST2 CLST6 RDTME3	1.1.02.03.00	Undesirable materials left	
	1.1.07.00.00	Repository design	
	1.1.08.00.00	Quality control	
	1.1.12.01.00	Accidents and unplanned events during operation	
	1.2.04.04.00	Magma interacts with waste	
	2.1.01.02.00	Co-disposal/colocation of waste	
	2.1.02.08.00	Pyrophoricity	
	2.1.03.01.00	Corrosion of waste containers	
	2.1.03.02.00	Stress corrosion cracking of waste containers	
	2.1.03.03.00	Pitting of waste containers	
	2.1.03.04.00	Hydride cracking of waste containers	
	2.1.03.05.00	Microbially mediated corrosion of waste container	
	2.1.03.06.00	Internal corrosion of waste container	
	2.1.03.08.00	Juvenile and early failure of waste containers	
	2.1.03.10.00	Container healing	
	2.1.03.11.00	Container form	
	2.1.03.12.00	Container failure (long term)	
	2.1.06.07.00	Effects at material interfaces	
	2.1.09.03.00	Volume increase of corrosion products	
	2.1.09.06.00	Reduction-oxidation potential in waste and EBS	
	2.1.09.07.00	Reaction kinetics in waste and EBS	
	2.1.09.08.00	Chemical gradients/enhanced diffusion in waste and EBS	
	2.1.09.09.00	Electrochemical effects (electrophoresis, galvanic coupling) in waste and EBS	
	2.1.10.01.00	Biological activity in waste and EBS	
	2.1.11.01.00	Heat output/temperature in waste and EBS	
	2.1.11.04.00	Temperature effects/coupled processes in waste and EBS	
	2.1.11.06.00	Thermal sensitization of waste containers increases fragility	
	2.1.12.01.00	Gas generation	
	2.1.12.03.00	Gas generation (H^2) from metal corrosion	
	2.1.12.04.00	Gas generation (CO^2, CH^4, H^2S) from microbial degradation	
	2.1.13.01.00	Radiolysis	
	2.1.13.02.00	Radiation damage in waste and EBS	

Table C-2. List of features, events, and processes related to the mechanical disruption of engineered barriers integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Mechanical disruption of engineered barriers	1.1.02.00.00	Excavation/construction	
	1.1.07.00.00	Repository design	
	1.1.08.00.00	Quality control	
	1.1.12.01.00	Accidents and unplanned events during operation	
	1.2.01.01.00	Tectonic activity - large scale	
KTI subissues	1.2.02.01.00	Fractures	
CLST1	1.2.02.02.00	Faulting	
CLST2	1.2.02.03.00	Fault movement shears waste container	
CLST6	1.2.03.01.00	Seismic activity	
IA2	1.2.03.02.00	Seismic vibration causes container failure	
SDS1	1.2.03.03.00	Seismicity associated with igneous activity	
SDS2	1.2.04.04.00	Magma interacts with waste	
SDS3	2.1.03.02.00	Stress corrosion cracking of waste containers	
SDS4	2.1.03.07.00	Mechanical impact on waste container	
RDTME2	2.1.03.08.00	Juvenile and early failure of waste containers	
RDTME3	2.1.03.11.00	Container form	
	2.1.03.12.00	Container failure (long term)	
	2.1.04.02.00	Physical and chemical properties of backfill	
	2.1.04.03.00	Erosion or dissolution of backfill	
	2.1.04.04.00	Mechanical effects of backfill	
	2.1.04.05.00	Backfill evolution	
	2.1.06.01.00	Degradation of cementitious materials in drift	
	2.1.06.02.00	Effects of rock reinforcement materials	
	2.1.06.03.00	Degradation of the liner	
	2.1.06.05.00	Degradation of invert and pedestal	
	2.1.06.06.00	Effects and degradation of drip shield	
	2.1.07.01.00	Rockfall (large block)	
	2.1.07.02.00	Mechanical degradation or collapse of drift	
	2.1.07.03.00	Movement of containers	
	2.1.07.04.00	Hydrostatic pressure on the container	
	2.1.07.05.00	Creeping of metallic materials in the EBS	
	2.1.07.06.00	Floor buckling	
	2.1.09.03.00	Volume increase of corrosion products	
	2.1.09.12.00	Rind (altered zone) formation in waste, EBS, and adjacent rock	
	2.1.11.05.00	Differing thermal expansion of repository components	
	2.1.11.06.00	Thermal sensitization of waste containers increases fragility	
	2.1.11.07.00	Thermally induced stress changes in waste and EBS	
	2.1.13.02.00	Radiation damage in waste and EBS	
	2.2.01.01.00	Excavation and construction-related changes in the adjacent host rock	
	2.2.01.02.00	Thermal and other waste and EBS-related changes in the adjacent host rock	
	2.2.03.02.00	Rock properties of host rock and other units	
	2.2.10.04.00	Thermo-mechanical alteration of fractures near repository	

Table C-3. List of features, events, and processes related to the quantity and chemistry of water contacting waste packages and waste forms integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Quantity and hemistry of ater ontacting WPs and aste forms	1.1.02.00.00	Excavation/construction	
	1.1.02.01.00	Site flooding (during construction and operation)	
	1.1.02.02.00	Effects of pre-closure ventilation	
	1.1.03.01.00	Error in waste or backfill emplacement	
	1.1.07.00.00	Repository design	
	1.1.08.00.00	Quality control	
	1.1.12.01.00	Accidents and unplanned events during operation	
KTI subissues	1.2.02.01.00	Fractures	
USFIC3	1.2.06.00.00	Hydrothermal activity	
USFIC4	1.2.10.01.00	Hydrological response to seismic activity	
TEF1	2.1.01.01.00	Waste inventory	
TEF2	2.1.01.02.00	Co-disposal/co-location of waste	
ENFE1	2.1.01.03.00	Heterogeneity of waste forms	
ENFE2	2.1.02.01.00	DSNF degradation, alteration, and dissolution	
ENFE3	2.1.02.02.00	CSNF alteration, dissolution, and radionuclide release	
CLST1	2.1.02.03.00	Glass degradation, alteration, and dissolution	
CLST3	2.1.02.05.00	Glass cracking and surface area	
CLST4	2.1.02.08.00	Pyrophoricity	
CLST6	2.1.02.09.00	Void space (in glass container)	
SDS3	2.1.02.10.00	Cellulosic degradation	
RDTME3	2.1.02.11.00	Waterlogged rods	
	2.1.02.12.00	Cladding degradation before YMP receives it	
	2.1.02.13.00	General corrosion of cladding	
	2.1.02.14.00	Microbial corrosion (MIC) of cladding	
	2.1.02.15.00	Acid corrosion of cladding from radiolysis	
	2.1.02.16.00	Localized corrosion (pitting) of cladding	
	2.1.02.17.00	Localized corrosion (crevice corrosion) of cladding	
	2.1.02.18.00	High dissolved silica content of waters enhances corrosion of cladding	
	2.1.02.19.00	Creep rupture of cladding	
	2.1.02.20.00	Pressurization from He production causes cladding failure	
	2.1.02.21.00	Stress corrosion cracking (SCC) of cladding	
	2.1.02.22.00	Hydride embrittlement of cladding	
	2.1.02.23.00	Cladding unzipping	
	2.1.02.24.00	Mechanical failure of cladding	
	2.1.02.25.00	DSNF cladding degradation	
	2.1.03.05.00	Microbially mediated corrosion of waste container	
	2.1.03.06.00	Internal corrosion of waste container	
	2.1.03.08.00	Juvenile and early failure of waste containers	
	2.1.03.10.00	Container healing	
	2.1.03.11.00	Container form	
	2.1.03.12.00	Container failure (long term)	
	2.1.04.01.00	Preferential pathways in the backfill	

Table C-3. List of features, events, and processes related to the quantity and chemistry of water contacting waste packages and waste forms integrated subissue (cont'd)

ISI	Primary FEP No.	FEP Description	NRC Review
Quantity and chemistry of water contacting WPs and waste forms (continued)	2.1.04.02.00	Physical and chemical properties of backfill	
	2.1.04.03.00	Erosion or dissolution of backfill	
	2.1.04.05.00	Backfill evolution	
	2.1.04.08.00	Diffusion in backfill	
	2.1.06.01.00	Degradation of cementitious materials in drift	
	2.1.06.02.00	Effects of rock reinforcement materials	
	2.1.06.03.00	Degradation of the liner	
	2.1.06.04.00	Flow through the liner	
	2.1.06.05.00	Degradation of invert and pedestal	
	2.1.06.06.00	Effects and degradation of drip shield	
	2.1.06.07.00	Effects at material interfaces	
	2.1.07.06.00	Floor buckling	
	2.1.08.01.00	Increased unsaturated water flux at the repository	
	2.1.08.02.00	Enhanced influx (Philip's drip)	
	2.1.08.03.00	Repository dry-out due to waste heat	
	2.1.08.04.00	Condensation forms on backs of drifts	
	2.1.08.06.00	Wicking in waste and EBS	
	2.1.08.07.00	Pathways for unsaturated flow and transport in the waste and EBS	
	2.1.08.08.00	Induced hydrological changes in the waste and EBS	
	2.1.08.09.00	Saturated groundwater flow in waste and EBS	
	2.1.08.10.00	Desaturation/dewatering of the repository	
	2.1.08.11.00	Resaturation of repository	
	2.1.09.01.00	Properties of the potential carrier plume in the waste and EBS	
	2.1.09.04.00	Radionuclide solubility, solubility limits, and speciation in the waste form and EBS	
	2.1.09.06.00	Reduction-oxidation potential in waste and EBS	
	2.1.09.07.00	Reaction kinetics in waste and EBS	
	2.1.09.08.00	Chemical gradients/enhanced diffusion in waste and EBS	
	2.1.09.09.00	Electrochemical effects (electrophoresis, galvanic coupling) in waste and EBS	
	2.1.09.10.00	Secondary phase effects on dissolved radionuclide concentrations at the waste form	
	2.1.09.11.00	Waste-rock contact	
	2.1.09.12.00	Rind (altered zone) formation in waste, EBS, and adjacent rock	
	2.1.10.01.00	Biological activity in waste and EBS	
	2.1.11.01.00	Heat output/temperature in waste and EBS	
	2.1.11.02.00	Nonuniform heat distribution/edge effects in repository	
	2.1.11.03.00	Exothermic reactions in waste and EBS	
	2.1.11.04.00	Temperature effects/coupled processes in waste and EBS	
	2.1.11.08.00	Thermal effects: chemical and microbiological changes in the waste and EBS	
	2.1.11.09.00	Thermal effects on liquid or two-phase fluid flow in the waste and EBS	
	2.1.11.10.00	Thermal effects on diffusion (Soret effect) in waste and EBS	

Table C-3. List of features, events, and processes related to the quantity and chemistry of water contacting waste packages and waste forms integrated subissue (cont'd)

ISI	Primary FEP No.	FEP Description	NRC Review
Quantity and chemistry of water contacting WPs and waste forms (cont'd)	2.1.12.01.00	Gas generation	
	2.1.12.02.00	Gas generation (He) from fuel decay	
	2.1.12.03.00	Gas generation (H^2) from metal corrosion	
	2.1.12.04.00	Gas generation (CO^2, CH^4, H^2S) from microbial degradation	
	2.1.12.05.00	Gas generation from concrete	
	2.1.13.01.00	Radiolysis	
	2.2.01.01.00	Excavation and construction-related changes in the adjacent host rock	
	2.2.01.02.00	Thermal and other waste and EBS-related changes in the adjacent host rock	
	2.2.01.03.00	Changes in fluid saturations in the excavation disturbed zone	
	2.2.07.10.00	Condensation zone forms around drifts	
	2.2.07.11.00	Return flow from condensation cap/resaturation of dry-out zone	
	2.2.08.01.00	Groundwater chemistry/composition in UZ and SZ	
	2.2.08.04.00	Redissolution of precipitates directs more corrosive fluids to containers	
	2.2.10.01.00	Repository-induced thermal effects in geosphere	
	2.2.10.04.00	Thermo-mechanical alteration of fractures near repository	
	2.2.10.05.00	Thermo-mechanical alteration of rocks above and below the repository	
	2.2.10.06.00	Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution)	
	2.2.10.10.00	Two-phase bouyant flow/heat pipes	
	2.2.10.12.00	Geosphere dry-out due to waste heat	
	2.2.11.01.00	Naturally-occurring gases in geosphere	

Table C-4. List of features, events, and processes related to the radionuclide release rates and solubility limits integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Radionuclide release rates and solubility limits KTI subissues ENFE3 ENFE4 ENFE5 CLST3 CLST4 CLST5 CLST6	1.1.02.03.00	Undesirable materials left	
	1.1.07.00.00	Repository design	
	1.1.08.00.00	Quality control	
	1.1.12.01.00	Accidents and unplanned events during operation	
	1.2.04.04.00	Magma interacts with waste	
	2.1.01.01.00	Waste inventory	
	2.1.01.02.00	Co-disposal/co-location of waste	
	2.1.01.03.00	Heterogeneity of waste forms	
	2.1.02.01.00	DSNF degradation, alteration, and dissolution	
	2.1.02.02.00	CSNF alteration, dissolution, and radionuclide release	
	2.1.02.03.00	Glass degradation, alteration, and dissolution	
	2.1.02.04.00	Alpha recoil enhances dissolution	
	2.1.02.05.00	Glass cracking and surface area	
	2.1.02.06.00	Glass recrystallization	
	2.1.02.07.00	Gap and grain relelase of Cs, I	
	2.1.02.08.00	Pyrophoricity	
	2.1.02.09.00	Void space (in glass container)	
	2.1.04.02.00	Physical and chemical properties of backfill	
	2.1.04.03.00	Erosion or dissolution of backfill	
	2.1.04.05.00	Backfill evolution	
	2.1.04.08.00	Diffusion in backfill	
	2.1.04.09.00	Radionuclide transport through backfill	
	2.1.06.03.00	Degradation of the liner	
	2.1.06.04.00	Flow through the liner	
	2.1.06.05.00	Degradation of invert and pedestal	
	2.1.06.07.00	Effects at material interfaces	
	2.1.08.05.00	Flow through invert	
	2.1.08.07.00	Pathways for unsaturated flow and transport in the waste and EBS	
	2.1.08.08.00	Induced hydrological changes in the waste and EBS	
	2.1.08.09.00	Saturated groundwater flow in waste and EBS	
	2.1.09.01.00	Properties of the potential carrier plume in the waste and EBS	
	2.1.09.02.00	Interaction with corrosion products	
	2.1.09.04.00	Radionuclide solubility, solubility limits, and speciation in the waste form and EBS	
	2.1.09.05.00	In-drift sorption	
	2.1.09.06.00	Reduction-oxidation potential in waste and EBS	
	2.1.09.07.00	Reaction kinetics in waste and EBS	
	2.1.09.08.00	Chemical gradients/enhanced diffusion in waste and EBS	
	2.1.09.10.00	Secondary phase effects on dissolved radionuclide concentrations at the waste form	
	2.1.09.11.00	Waste-rock contact	
	2.1.09.12.00	Rind (altered zone) formation in waste, EBS, and adjacent rock	
	2.1.09.13.00	Complexation by organics in waste and EBS	

Table C-4. List of features, events, and processes related to the radionuclide release rates and solubility limits integrated subissue (cont'd)

ISI	Primary FEP No.	FEP Description	NRC Review
Radionuclide release rates and solubility limits (continued)	2.1.09.14.00	Colloid formation in waste and EBS	
	2.1.09.15.00	Formation of true colloids in waste and EBS	
	2.1.09.16.00	Formation of pseudo-colloids (natural) in waste and EBS	
	2.1.09.17.00	Formation of pseudo-colloids (corrosion products) in waste and EBS	
	2.1.09.18.00	Microbial colloid transport in the waste and EBS.	
	2.1.09.19.00	Colloid transport and sorption in the waste and EBS.	
	2.1.09.20.00	Colloid filtration in the waste and EBS	
	2.1.09.21.00	Suspensions of particles larger than colloids	
	2.1.10.01.00	Biological activity in waste and EBS	
	2.1.11.01.00	Heat output/temperature in waste and EBS	
	2.1.11.02.00	Nonuniform heat distribution/edge effects in repository	
	2.1.11.03.00	Exothermic reactions in waste and EBS	
	2.1.11.04.00	Temperature effects/coupled processes in waste and EBS	
	2.1.11.08.00	Thermal effects: chemical and microbiological changes in the waste and EBS	
	2.1.11.09.00	Thermal effects on liquid or two-phase fluid flow in the waste and EBS	
	2.1.11.10.00	Thermal effects on diffusion (Soret effect) in waste and EBS	
	2.1.12.01.00	Gas generation	
	2.1.12.02.00	Gas generation (He) from fuel decay	
	2.1.12.03.00	Gas generation (H^2) from metal corrosion	
	2.1.12.04.00	Gas generation (CO^2, CH^4, H^2S) from microbial degradation	
	2.1.12.06.00	Gas transport in waste and EBS	
	2.1.12.07.00	Radioactive gases in waste and EBS	
	2.1.12.08.00	Gas explosions	
	2.1.13.01.00	Radiolysis	
	2.1.13.02.00	Radiation damage in waste and EBS	
	2.1.14.01.00	Criticality in waste and EBS	
	2.1.14.02.00	Criticality *in-situ*, nominal configuration, top breach	
	2.1.14.03.00	Criticality *in-situ*, WP internal structures degrade faster than waste form, top breach	
	2.1.14.04.00	Criticality *in-situ*, WP internal structures degrade at same rate as waste form, top breach	
	2.1.14.05.00	Criticality *in-situ*, WP internal structures degrade slower than waste form, top breach	
	2.1.14.06.00	Criticality *in-situ*, waste form degrades in place and swells, top breach	
	2.1.14.07.00	Criticality *in-situ*, bottom breach allows flow through WP, fissile material collects at bottom of WP	
	2.1.14.08.00	Criticality *in-situ*, bottom breach allows flow through WP, waste form degrades in place	
	2.1.14.09.00	Near-field criticality, fissile material deposited in near-field pond	
	2.1.14.10.00	Near-field criticality, fissile solution flows into drift lowpoint	
	2.1.14.11.00	Near-field criticality, fissile solution is adsorbed or reduced in invert	
	2.1.14.12.00	Near-field criticality, filtered slurry or colloidal stream collects on invert surface	
	2.1.14.13.00	Near-field criticality associated with colloidal deposits	
	2.2.01.02.00	Thermal and other waste and EBS-related changes in the adjacent host rock	
	2.2.01.04.00	Elemental solubility in excavation disturbed zone	
	2.2.01.05.00	Radionuclide transport in excavation disturbed zone	
	2.2.07.06.00	Episodic/pulse release from repository	
	2.2.08.07.00	Radionuclide solubility limits in the geosphere	
	3.1.01.01.00	Radioactive decay and ingrowth	

Table C-5. List of features, events, and processes related to the spatial and temporal distribution of flow integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Spatial and temporal distribution of flow KTI Subissues USFIC1 USFIC3 USFIC4 TEF1 TEF2 ENFE1 SDS2 SDS3 RDTME3	1.1.01.01.00	Open site investigation boreholes	
	1.1.01.02.00	Loss of integrity of borehole seals	
	1.1.02.01.00	Site flooding (during construction and operation)	
	1.1.02.02.00	Effects of pre-closure ventilation	
	1.2.02.01.00	Fractures	
	1.2.02.02.00	Faulting	
	1.2.04.02.00	Igneous activity causes changes to rock properties	
	1.2.06.00.00	Hydrothermal activity	
	1.2.07.01.00	Erosion/denudation	
	1.2.07.02.00	Deposition	
	1.2.09.02.00	Large-scale dissolution	
	1.2.10.01.00	Hydrological response to seismic activity	
	1.2.10.02.00	Hydrological response to igneous activity	
	1.3.01.00.00	Climate change, global	
	1.3.04.00.00	Periglacial effects	
	1.3.05.00.00	Glacial and ice sheet effects, local	
	1.4.01.00.00	Human influences on climate	
	1.4.01.01.00	Climate modification increases recharge	
	1.4.01.02.00	Greenhouse gas effects	
	1.4.01.03.00	Acid rain	
	1.4.01.04.00	Ozone layer failure	
	1.4.04.02.00	Abandoned and undetected boreholes	
	2.1.02.03.00	Glass degradation, alteration, and dissolution	
	2.1.04.02.00	Physical and chemical properties of backfill	
	2.1.04.03.00	Erosion or dissolution of backfill	
	2.1.04.05.00	Backfill evolution	
	2.1.05.01.00	Seal physical properties	
	2.1.05.02.00	Groundwater flow and radionuclide transport in seals	
	2.1.05.03.00	Seal degradation	
	2.1.08.01.00	Increased unsaturated water flux at the repository	
	2.1.08.03.00	Repository dry-out due to waste heat	
	2.1.08.10.00	Desaturation/dewatering of the repository	
	2.1.08.11.00	Resaturation of the repository	
	2.1.11.02.00	Nonuniform heat distribution/edge effects in repository	
	2.2.01.03.00	Changes in fluid saturations in the excavation disturbed zone	
	2.2.03.01.00	Stratigraphy	
	2.2.03.02.00	Rock properties of host rock and other units	
	2.2.06.01.00	Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock	
	2.2.06.02.00	Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults	
	2.2.06.03.00	Changes in stress (due to seismic or tectonic effects) alter perched water zones	
	2.2.06.04.00	Effects of subsidence	
	2.2.07.01.00	Locally saturated flow at bedrock/alluvium contact	

Table C-5. List of features, events, and processes related to the spatial and temporal distribution of flow integrated subissue (cont'd)

ISI	Primary FEP No.	FEP Description	NRC Review
Spatial and temporal distribution of flow (cont'd)	2.2.07.02.00	Unsaturated groundwater flow in geosphere	
	2.2.07.04.00	Focusing of unsaturated flow (fingers, weeps)	
	2.2.07.05.00	Flow and transport in the UZ from episodic infiltration	
	2.2.07.07.00	Perched water develops	
	2.2.07.10.00	Condensation zone forms around drifts	
	2.2.07.11.00	Return flow from condensation cap/resaturation of dry-out zone	
	2.2.10.01.00	Repository-induced thermal effects in geosphere	
	2.2.10.04.00	Thermo-mechanical alteration of fractures near repository	
	2.2.10.05.00	Thermo-mechanical alteration of rocks above and below the repository	
	2.2.10.09.00	Thermo-chemical alteration of the Topopah Spring basal vitrophyre	
	2.2.10.10.00	Two-phase bouyant flow/heat pipes	
	2.2.10.11.00	Natural air flow in UZ	
	2.2.10.12.00	Geosphere dry-out due to waste heat	
	2.2.10.13.00	Density-driven groundwater flow (thermal)	
	2.2.11.02.00	Gas pressure effects	
	2.2.12.00.00	Undetected features (in geosphere)	
	2.3.01.00.00	Topography and morphology	
	2.3.11.01.00	Precipitation	
	2.3.11.02.00	Surface runoff and flooding	
	2.3.11.03.00	Infiltration and recharge (hydrologic and chemical effects)	
	2.3.13.01.00	Biosphere characteristics	
	2.3.13.03.00	Effects of repository heat on biosphere	

Table C-6. List of features, events, and processes related to the flow paths in the unsaturated zone integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Flow paths in the UZ	1.2.02.01.00	Fractures	
	1.2.04.02.00	Igneous activity causes changes to rock properties	
	1.2.08.00.00	Diagenesis	
	1.2.10.02.00	Hydrological response to igneous activity	
	1.4.01.01.00	Climate modification increases recharge	
	2.1.02.03.00	Glass degradation, alteration, and dissolution	
KTI subissues USFIC4 TEF1 TEF2 ENFE1 SDS3	2.1.04.02.00	Physical and chemical properties of backfill	
	2.1.04.03.00	Erosion or dissolution of backfill	
	2.1.04.05.00	Backfill evolution	
	2.1.06.01.00	Degradation of cementitious materials in drift	
	2.1.06.04.00	Flow through the liner	
	2.1.06.05.00	Degradation of invert and pedestal	
	2.1.09.12.00	Rind (altered zone) formation in waste, EBS, and adjacent rock	
	2.1.11.02.00	Nonuniform heat distribution/edge effects in repository	
	2.2.01.02.00	Thermal and other waste and EBS-related changes in the adjacent host rock	
	2.2.03.01.00	Stratigraphy	
	2.2.03.02.00	Rock properties of host rock and other units	
	2.2.06.01.00	Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock	
	2.2.06.03.00	Changes in stress (due to seismic or tectonic effects) alter perched water zones	
	2.2.07.02.00	Unsaturated groundwater flow in geosphere	
	2.2.07.04.00	Focusing of unsaturated flow (fingers, weeps)	
	2.2.07.05.00	Flow and transport in the UZ from episodic infiltration	
	2.2.07.08.00	Fracture flow in the UZ	
	2.2.07.09.00	Matrix imbibition in the UZ	
	2.2.08.08.00	Matrix diffusion in geosphere	
	2.2.10.01.00	Repository-induced thermal effects in geosphere	
	2.2.10.04.00	Thermo-mechanical alteration of fractures near repository	
	2.2.10.05.00	Thermo-mechanical alteration of rocks above and below the repository	
	2.2.10.06.00	Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution)	
	2.2.10.07.00	Thermo-chemical alteration of the Calico Hills unit	
	2.2.10.08.00	Thermo-chemical alteration of the saturated zone	
	2.2.10.09.00	Thermo-chemical alteration of the Topopah Spring basal vitrophyre	
	2.2.10.11.00	Natural air flow in UZ	

Table C-7. List of features, events, and processes related to the radionuclide transport in the unsaturated zone integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Radionuclide transport in the UZ	1.1.02.03.00	Undesirable materials left	
	1.2.04.02.00	Igneous activity causes changes to rock properties	
	1.2.08.00.00	Diagenesis	
	1.2.09.02.00	Large-scale dissolution	
KTI subissues USFIC4 USFIC6 ENFE4 RT1 RT3 RT4 SDS3	2.1.06.01.00	Degradation of cementitious materials in drift	
	2.1.06.03.00	Degradation of the liner	
	2.1.06.05.00	Degradation of invert and pedestal	
	2.1.09.01.00	Properties of the potential carrier plume in the waste and EBS	
	2.1.09.12.00	Rind (altered zone) formation in waste, EBS, and adjacent rock	
	2.1.09.21.00	Suspensions of particles larger than colloids	
	2.1.12.05.00	Gas generation from concrete	
	2.2.01.02.00	Thermal and other waste and EBS-related changes in the adjacent host rock	
	2.2.01.05.00	Radionuclide transport in excavation disturbed zone	
	2.2.03.01.00	Stratigraphy	
	2.2.03.02.00	Rock properties of host rock and other units	
	2.2.07.15.00	Advection and dispersion	
	2.2.08.01.00	Groundwater chemistry/composition in UZ and SZ	
	2.2.08.02.00	Radionuclide transport occurs in a carrier plume in geosphere	
	2.2.08.03.00	Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport	
	2.2.08.05.00	Osmotic processes	
	2.2.08.06.00	Complexation in geosphere	
	2.2.08.07.00	Radionuclide solubility limits in the geosphere	
	2.2.08.08.00	Matrix diffusion in geosphere	
	2.2.08.09.00	Sorption in UZ and SZ	
	2.2.08.10.00	Colloidal transport in geosphere	
	2.2.09.01.00	Microbial activity in geosphere	
	2.2.10.01.00	Repository-induced thermal effects in geosphere	
	2.2.10.06.00	Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution)	
	2.2.10.07.00	Thermo-chemical alteration of the Calico Hills unit	
	2.2.10.09.00	Thermo-chemical alteration of the Topopah Spring basal vitrophyre	
	2.2.11.01.00	Naturally-occurring gases in geosphere	
	2.2.11.03.00	Gas transport in geosphere	
	2.2.14.01.00	Critical assembly forms away from repository	
	2.2.14.02.00	Far-field criticality, precipitation in organic reducing zone in or near water table	
	2.2.14.03.00	Far-field criticality, sorption on clay/zeolite in TSbv	
	2.2.14.04.00	Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ	
	2.2.14.05.00	Far-field criticality, precipitation in perched water above TSbv	
	2.2.14.06.00	Far-field criticality, precipitation in fractures of TSw rock	
	2.2.14.07.00	Far-field criticality, dryout produces fissile salt in a perched water basin	
	2.2.14.08.00	Far-field criticality associated with colloidal deposits	

Table C-8. List of features, events, and processes related to the flow paths in the saturated zone integrated subissue radionuclide transport in the saturated zone

ISI	Primary FEP No.	FEP Description	NRC Review
Flow paths in the SZ	1.2.02.01.00	Fractures	
	1.2.02.02.00	Faulting	
	1.2.06.00.00	Hydrothermal activity	
	1.2.09.02.00	Large-scale dissolution	
	1.2.10.01.00	Hydrological response to seismic activity	
KTI subissues	1.2.10.02.00	Hydrologic response to igneous activity	
USFIC1	1.3.07.01.00	Drought/water table decline	
USFIC4	1.3.07.02.00	Water table rise	
USFIC5	1.4.01.01.00	Climate modification increases recharge	
SDS3	1.4.07.01.00	Water management activities	
SDS4	1.4.07.02.00	Wells	
	1.5.03.02.00	Earth tides	
	2.2.03.01.00	Stratigraphy	
	2.2.03.02.00	Rock properties of host rock and other units	
	2.2.06.01.00	Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock	
	2.2.06.02.00	Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults	
	2.2.07.12.00	Saturated groundwater flow	
	2.2.07.13.00	Water-conducting features in the saturated zone	
	2.2.07.14.00	Density effects on groundwater flow	
	2.2.07.15.00	Advection and dispersion	
	2.2.07.16.00	Dilution of radionuclides in groundwater	
	2.2.10.01.00	Repository-induced thermal effects in geosphere	
	2.2.10.02.00	Thermal convection cell develops in SZ	
	2.2.10.03.00	Natural geothermal effects	
	2.2.10.06.00	Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution)	
	2.2.10.08.00	Thermo-chemical alteration of the saturated zone	
	2.2.10.13.00	Density-driven groundwater flow (thermal)	
	2.2.11.03.00	Gas transport in geosphere	
	2.2.12.00.00	Undetected features (in geosphere)	
	2.3.11.04.00	Groundwater discharge to surface	

Table C-9. List of features, events, and processes related to the radionuclide transport in the saturated zone integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Radionuclide transport in the saturated zone	1.2.02.01.00	Fractures	
	1.2.04.02.00	Igneous activity causes changes to rock properties	
	1.4.06.01.00	Altered soil or surface water chemistry	
	2.1.09.21.00	Suspensions of particles larger than colloids	
	2.2.03.01.00	Stratigraphy	
	2.2.03.02.00	Rock properties of host rock and other units	
KTI subissues	2.2.07.15.00	Advection and dispersion	
USFIC5	2.2.07.16.00	Dilution of radionuclides in groundwater	
USFIC6	2.2.07.17.00	Diffusion in the saturated zone	
RT1	2.2.08.01.00	Groundwater chemistry/composition in UZ and SZ	
RT2	2.2.08.02.00	Radionuclide transport occurs in a carrier plume in geosphere	
RT3	2.2.08.03.00	Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport	
RT4	2.2.08.05.00	Osmotic processes	
SDS3	2.2.08.06.00	Complexation in geosphere	
	2.2.08.07.00	Radionuclide solubility limits in the geosphere	
	2.2.08.08.00	Matrix diffusion in geosphere	
	2.2.08.09.00	Sorption in UZ and SZ	
	2.2.08.10.00	Colloidal transport in geosphere	
	2.2.09.01.00	Microbial activity in geosphere	
	2.2.10.01.00	Repository-induced thermal effects in geosphere	
	2.2.10.02.00	Thermal convection cell develops in SZ	
	2.2.10.03.00	Natural geothermal effects	
	2.2.10.06.00	Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution)	
	2.2.10.08.00	Thermo-chemical alteration of the saturated zone	
	2.2.10.13.00	Density-driven groundwater flow (thermal)	
	2.2.11.01.00	Naturally-occurring gases in geosphere	
	2.2.11.03.00	Gas transport in geosphere	
	2.2.12.00.00	Undetected features (in geosphere)	
	2.2.14.01.00	Critical assembly forms away from repository	
	2.2.14.02.00	Far-field criticality, precipitation in organic reducing zone in or near water table	
	2.2.14.03.00	Far-field criticality, sorption on clay/zeolite in TSbv	
	2.2.14.04.00	Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the SZ	
	2.2.14.05.00	Far-field criticality, precipitation in perched water above TSbv	
	2.2.14.06.00	Far-field criticality, precipitation in fractures of TSw rock	
	2.2.14.07.00	Far-field criticality, dryout produces fissile salt in a perched water basin	
	2.2.14.08.00	Far-field criticality associated with colloidal deposits	

Table C-10. List of features, events, and processes related to the volcanic disruption of waste packages integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Volcanic disruption of waste packages KTI subissues CLST1 CLST2 IA1 IA2 SDS1 SDS4	1.1.02.00.00	Excavation/construction	
	1.1.02.02.00	Effects of pre-closure ventilation	
	1.1.03.01.00	Error in waste or backfill emplacement	
	1.1.04.01.00	Incomplete closure	
	1.1.07.00.00	Repository design	
	1.2.01.01.00	Tectonic activity–large scale	
	1.2.02.02.00	Faulting	
	1.2.04.01.00	Igneous activity	
	1.2.04.02.00	Igneous activity causes changes to rock properties	
	1.2.04.03.00	Igneous intrusion into repository	
	1.2.04.04.00	Magma interacts with waste	
	1.2.04.05.00	Magmatic transport of waste	
	1.2.04.06.00	Basaltic cinder cone erupts through the repository	
	2.1.01.01.00	Waste inventory	
	2.1.03.11.00	Container form	
	2.1.03.12.00	Container failure (long-term)	
	2.1.04.04.00	Mechanical effects of backfill	
	2.1.07.02.00	Mechanical degradation or collapse of drift	
	2.2.03.01.00	Stratigraphy	
	2.3.01.00.00	Topography and morphology	

Table C-11. List of Features, Events, and Publications Related to the Airborne Transport of Radionuclides Integrated Subissue

ISI	Primary FEP #	FEP description	NRC Review
Airborne transport of radionuclides KTI subissues IA2	1.2.04.07.00	Ashfall	
	1.2.04.06.00	Basaltic cinder cone erupts through the repository	
	3.2.10.00.00	Atmospheric transport of contaminants	

Table C-12. List of features, events, and processes related to the dilution of radionuclides due to well pumping integrated subissue redistribution of radionuclides in soil

ISI	Primary FEP No.	FEP Description	NRC Review
Dilution of radionuclides in GW due to well pumping	1.3.07.01.00	Drought/water table decline	
	1.3.07.02.00	Water table rise	
	1.4.07.01.00	Water management activities	
	1.4.07.02.00	Wells	
	2.1.09.21.00	Suspensions of particles larger than colloids	
KTI subissues USFIC5	2.2.07.12.00	Saturated groundwater flow	
	2.2.07.13.00	Water-conducting features in the saturated zone	
	2.2.07.14.00	Density effects on groundwater flow	
	2.2.07.16.00	Dilution of radionuclides in groundwater	
	2.2.08.06.00	Complexation in geosphere	
	2.2.08.07.00	Radionuclide solubility limits in the geosphere	
	2.2.08.10.00	Colloidal transport in geosphere	
	2.2.08.11.00	Distribution and release of nuclides from the geosphere	
	2.2.12.00.00	Undetected features (in geosphere)	
	2.3.11.04.00	Groundwater discharge to surface	
	2.3.13.01.00	Biosphere characteristics	
	2.4.04.01.00	Human lifestyle	
	2.4.08.00.00	Wild and natural land and water use	
	2.4.09.01.00	Agricultural land use and irrigation	
	2.4.09.02.00	Animal farms and fisheries	
	2.4.10.00.00	Urban and industrial land and water use	

Table C-13. List of features, events, and processes related to the redistribution of radionuclides in soil integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Redistribution of radionuclides in soil KTI subissues IA2	1.2.04.07.00	Ashfall	
	1.2.07.01.00	Erosion/denudation	
	1.2.07.02.00	Deposition	
	1.4.07.01.00	Water management activities	
	2.3.02.01.00	Soil type	
	2.3.02.02.00	Radionuclide accumulation in soils	
	2.3.02.03.00	Soil and sediment transport	
	2.3.04.01.00	Surface water transport and mixing	
	2.3.11.01.00	Precipitation	
	2.3.11.02.00	Surface runoff and flooding	
	2.3.11.03.00	Infiltration and recharge (hydrologic and chemical effects)	
	2.3.11.04.00	Groundwater discharge to surface	
	2.4.08.00.00	Wild and natural land and water use	
	2.4.09.01.00	Agricultural land use and irrigation	
	2.4.10.00.00	Urban and industrial land and water use	
	3.1.01.01.00	Radioactive decay and ingrowth	
	3.2.07.01.00	Isotopic dilution	
	1.3.07.01.00	Drought/water table decline	
	1.3.07.02.00	Water table rise	
	2.2.08.09.00	Sorption in UZ and SZ	
	2.2.08.11.00	Distribution and release of nuclides from the geosphere	
	2.3.01.00.00	Topography and morphology	
	2.3.09.01.00	Animal burrowing/intrusion	

Table C-14. List of features, events, and processes related to the lifestyle of the critical group integrated subissue

ISI	Primary FEP No.	FEP Description	NRC Review
Lifestyle of the	1.1.05.00.00	Records and markers, repository	
critical group	1.2.04.07.00	Ashfall	
	1.2.07.01.00	Erosion/denudation	
KTI subissues	1.2.07.02.00	Deposition	
USFIC1	1.3.01.00.00	Climate change, global	
USFIC2	1.3.05.00.00	Glacial and ice sheet effects, local	
USFIC3	1.3.07.01.00	Drought/water table decline	
USFIC5	1.3.07.02.00	Water table rise	
RT3	1.4.01.01.00	Climate modification increases recharge	
IA2	1.4.01.04.00	Ozone layer failure	
	1.4.06.01.00	Altered soil or surface water chemistry	
	1.4.07.01.00	Water management activities	
	1.4.07.02.00	Wells	
	1.5.02.00.00	Species evolution	
	2.1.01.01.00	Waste inventory	
	2.2.07.12.00	Saturated groundwater flow	
	2.2.07.16.00	Dilution of radionuclides in groundwater	
	2.2.08.01.00	Groundwater chemistry/composition in UZ and SZ	
	2.2.08.07.00	Radionuclide solubility limits in the geosphere	
	2.2.08.09.00	Sorption in UZ and SZ	
	2.2.08.11.00	Distribution and release of nuclides from the geosphere	
	2.3.02.01.00	Soil type	
	2.3.02.02.00	Radionuclide accumulation in soils	
	2.3.02.03.00	Soil and sediment transport	
	2.3.04.01.00	Surface water transport and mixing	
	2.3.11.01.00	Precipitation	
	2.3.11.02.00	Surface runoff and flooding	
	2.3.13.01.00	Biosphere characteristics	
	2.3.13.02.00	Biosphere transport	
	2.3.13.03.00	Effects of repository heat on biosphere	
	2.4.01.00.00	Human characteristics (physiology, metabolism)	
	2.4.03.00.00	Diet and fluid intake	
	2.4.04.01.00	Human lifestyle	

Table C-14. List of features, events, and processes related to the lifestyle of the critical group integrated subissue (cont'd)

ISI	Primary FEP No.	FEP Description	NRC Review
Lifestyle of the critical group (continued)	2.4.07.00.00	Dwellings	
	2.4.08.00.00	Wild and natural land and water use	
	2.4.09.01.00	Agricultural land use and irrigation	
	2.4.09.02.00	Animal farms and fisheries	
	2.4.10.00.00	Urban and industrial land and water use	
	3.1.01.01.00	Radioactive decay and ingrowth	
	3.2.07.01.00	Isotopic dilution	
	3.2.10.00.00	Atmospheric transport of contaminants	
	3.3.01.00.00	Drinking water, foodstuffs and drugs, contaminant concentrations in	
	3.3.02.01.00	Plant uptake	
	3.3.02.02.00	Animal uptake	
	3.3.02.03.00	Bioaccumulation	
	3.3.03.01.00	Contaminated non-food products and exposure	
	3.3.04.01.00	Ingestion	
	3.3.04.02.00	Inhalation	
	3.3.04.03.00	External exposure	
	3.3.05.01.00	Radiation doses	
	3.3.06.00.00	Radiological toxicity /effects	
	3.3.08.00.00	Radon and radon daughter exposure	

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APPENDIX D:

SUMMARY OF THE CONCEPTUAL APPROACHES IN TPA VERSION 3.2 CODE FOR THE INTEGRATED SUBISSUES

The Total Performance Assessment (TPA) code is the primary tool that NRC staff is using to independently examine aspects of 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 3.2 code can be found in Mohanty and McCartin (1998).

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 (i.e., 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 (ISIs) are addressed with different levels of complexity. The extent that interdependencies are modeled within the TPA 3.2 code is also variable. Hereafter, the TPA Version 3.2 code is identified as TPA 3.2.

The following discussion of the TPA 3.2 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 PA calculation are identified, and the conceptual model for that part of TPA 3.2 is presented. The reader should not infer that when a ISI is identified, that all relevant phenomena within that ISI are implemented in TPA 3.2. After an overview, the description progresses as follows: 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. 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.

Overview

The TPA code models the repository, the surrounding geology and the local biosphere. 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 airborne pathway and are distributed throughout an ash blanket within the biosphere. RNs within the biosphere are available for uptake by a receptor group. The receptor group may also be susceptible to direct exposure from contamination within the biosphere.

Infiltration and Deep Percolation

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). The **spatial and temporal distribution of flow** arises from the variability in the precipitation, heterogeneity in the biosphere (e.g., near-surface) and heterogeneity in the geosphere. This variability affects calculations related to the **distribution of mass flux between fracture and matrix, WP corrosion, 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 **spatial and temporal distribution of flow** in the UZ is affected by characteristics in both the biosphere and the geosphere, it occurs in the geosphere and is evaluated accordingly.

The mean annual infiltration 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 in equilibrium with the infiltration. The mean annual infiltration 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 mean annual infiltration 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.

Near-Field Environment

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 **WP corrosion, RN release rates [and solubility limits],** and the transport of these RNs through the near-field. **WP corrosion** 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 **spatial and temporal distribution of flow** through the UZ. The **spatial and temporal distribution of flow** will also influence the **quantity and chemistry of the water contacting WPs and waste forms.** In addition, the **spatial and temporal distribution of flow** in the UZ provides an input (i.e., source term of contaminants entering the SZ) into the flow and transport of contamination in the SZ.

Infiltration of the water from the ground surface to the repository will experience changes in its chemical composition. As the water contacts introduced materials comprising the engineered barriers of the repository, its 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 contaminant 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. 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 and Seth, 1996) 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 and temperature profiles are calculated based on 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 WP. Only one thermohydrologic model is used during a given simulation.

Undisturbed Failure of the Waste Package

The failure of emplaced WPs can be considered as occurring from **WP corrosion** 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, **WP corrosion** 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 **spatial and temporal distribution of flow** through the UZ. Fracturing or buckling of parts of the WP can also result in the **mechanical disruption of WPs.** The failure will allow water to contact the waste form [**quantity and chemistry of water contacting WPs 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 failure), 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: an inner overpack consisting of a corrosion resistant material (Alloy C-22) and an outer overpack consisting of a corrosion allowance material. This approach is consistent with DOE conceptual designs for the repository in TSPA-VA.

Corrosion of the WP is strongly determined by the following environmental conditions. The temperature (average repository and WP surface) and RH are used to determine 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.

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 WPs** 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. 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 3.2. 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 calculated based on the diameter of the volcanic conduit for the extrusive event, and the dimensions of subsurface igneous intrusions for the intrusive event. All WPs affected by a volcanic event are assumed to fail for both extrusive and intrusive events. The entire contents of the WP are assumed to be incorporated into ash and transported to the surface for direct release for the extrusive event.

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 both cases, the contamination must pass through the UZ. In the case of volcanic activity, waste is entrained in ash that erupts from the mountain, it is **transported through the air,** and eventually is deposited on the ground surface, where they are **diluted in the 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 unsaturated and SZs is affected by the number of failed WPs (**WP corrosion** and **mechanical disruption of WPs**)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 **spatial and temporal distribution of flow, the distribution of mass flux between fractures and the matrix**, and the **retardation in fractures in the UZ**; whereas, transport in the SZ is characterized by the **flow rates in water-production zones** and the **retardation in the water-production zones and the alluvium.** 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 **location and lifestyle of the receptor 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 release from the WP is possible. Releases are modeled to occur by only advective release through the remnants of the WP because diffusive transport was found to contribute negligibly to the source term. 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 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. Two different conceptual models are used for evaluating releases from failed WPs; 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 considered negligible at this time. Any switching between fracture and matrix flow is assumed to occur only at hydrostratigraphic interfaces.

The contamination within the SZ is considered to be transported along streamtubes that are 1D representations of the SZ flow. The dimensions of the streamtubes are based on two-dimensional simulations by Baca et al. (1996) and terminate at the location of the receptor group. Four 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 four 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 3.2.

The RNs released through an extrusive volcanic event are dispersed and deposited with the ash resulting from the event. Attributes of the volcanic event are estimated from 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.

Exposure of the Receptor Group

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 rates in water-production zones** and the **retardation in water-production zones and alluvium**. 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 **dilution of RNs in soil**. The processes within the biosphere will then result in the redistribution, dilution, and uptake of RNs. These processes are influenced by the **location and lifestyle of the receptor group**. Exposure is also impacted by the **spatial and temporal distribution of flow** through climatic conditions that determine whether the biosphere is classified as the current biosphere or a pluvial biosphere and the **dilution of RNs in soil**. The approach taken to evaluate the exposure of receptor groups in TPA 3.2 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 individuals located within 20 kilometers 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 individuals located at least 20 kilometers from the repository that use the contaminated water for drinking and residential, agricultural use; they are also exposed to surface contamination through ingestion, inhalation, and direct exposure. A set of DCFs were developed using unit concentration-based total effective dose equivalents through external GENII-S calculations for exposure from drinking water and surface contamination assuming current biosphere and pluvial biosphere conditions. 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 of RNs from surface processes.