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

July 1999

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.

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; concept. paper on transparency and traceability added; acceptance criteria for demonstration of multiple barriers added.
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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.
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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	Updated to reflect changes to NRC total system performance assessment models.
Rev. 2	Appendix D	July 1999	Moved to Section 4.4.

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

1.0 INTRODUCTION

NRC's strategic planning assumptions call for the early identification and resolution, at the staff level, of issues before the receipt of a potential license application 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, Nevada; and (iii) a 1995 report issued by the National Academy of Sciences to advise the U.S. Environmental Protection Agency 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 License Application (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 fiscal year. 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 Yucca Mountain 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 are 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 are 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 review, NRC has identified a set of technical comments regarding the 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 high-level waste 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 U.S. Environmental Protection Agency (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. 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, defensible, and

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[1] The NRC recognizes that pending legislation, if enacted, could affect the regulation and overall performance objective for high-level waste disposal at Yucca Mountain. (*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.

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 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 features, events, and processes 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 National Academy of Sciences (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 high-level waste (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 NRC HLW PROGRAM

It is expected that the implementing regulations for the YM site will require DOE to provide a comprehensive PA in its license application (U.S. Nuclear Regulatory Commission, 1999c). NRC is obligated to ensure in its review of a license application 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–see U.S. Department of Energy, 1988), as required under the Nuclear Waste Policy Act of 1982 (NWPA), 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 engineered barrier system 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 features, events, and processes 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 will be specified for each of the subissues identified in section 2.0. Past independent research efforts by the staff, 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 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 — must satisfy the acceptance criterion on quality assurance. Similarly, the use of expert elicitation must 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 (QA) 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: As part of its site characterization programs, DOE should have in place an acceptable, baselined QA program that meets NRC's requirements. Moreover, DOE has previously committed to qualify data, models, and/or computer codes supporting any potential license application to construct and operate a geologic repository. As part of its TSPA, DOE should provide information to certify that the data, models, and/or computer codes used by the Department have been subject to an NRC-approved QA program. Guidance on an acceptable NRC 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, DOE will need to demonstrate 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, DOE will need to demonstrate 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, it will be acceptable to the staff so long as DOE demonstrates 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

For NRC staff to evaluate compliance of the YM repository with applicable regulatory criteria, the DOE is expected to provide such information in the licence applications as may be necessary for the NRC to fully understand DOE's approach and results of the PA analyses. Transparency and traceability in DOE's PA are necessary for NRC to build confidence that compliance with regulatory criteria will be achieved.

Transparency is defined 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). Traceability is defined as an attribute of an analysis or selected portions of an analysis that would allow an independent PA group to ". . .understand 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).

Transparency and traceability are 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 (NEA, 1998). It is recognized that it may not be possible for all stakeholders (e.g., public, environmental groups, state government, NRC) to understand all technical issues in detail or for experts to understand each other's disciplines in detail (Swedish Nuclear Power Inspectorate, 1998). However, the DOE must provide sufficient transparency and traceability as may be necessary to convince the stakeholders that compliance with regulatory criteria will be achieved.

The NRC staff will ascertain that the PA methodology is sufficiently transparent and traceable in that the PA methodology must be complete, clear, and consistent. Specific aspects of transparency and traceability that will be evaluated include the following items:

- Sufficient data should be available to support decisions and assumptions, such as who, using what basis, made the various decisions and assumptions, and when were they made.
- Facts, expert judgment, value judgment, weaknesses, levels of significance, potential bias, and open questions should be identified.
- Major performance contributors are clearly identified.
- An explicit discussion of uncertainty (e.g., high-risk scenarios) is presented to identify which issues and factors are of most concern or are key sources of disagreement.

- Results from calculations can, in principle, be traced back to modeling decisions and assumptions.

Because of the overall complexity of the YM system and the need to understand the total system behavior, an integral part of the PA analysis is the computer models used in conducting the study. However, the more complex a system or model, the more difficult it is to make it transparent. Without transparency and traceability, the PA model may appear as a cloud or black box [Figure 1(a)] - and visibility into the PA processes is limited. Data flow into the processes and information results. As the degree of transparency and traceability increases, the PA process becomes visible at transition points and may be viewed as a series of black boxes [see Figure 1(b)]. Intermediate results may be checked and verified. For the PA process to be sufficiently transparent and traceable, the internal structure of the boxes (e.g., algorithms, assumptions, and data) must be visible. The roles and responsibilities of each model/module and the interaction of their activities at the appropriate level of detail should be known [see Figure 1(c)].

In describing the limitations of models used in the PA, the TSPA peer review panel stated in their second interim report that:

> Significant errors in PA may occur due to the selection of the wrong deterministic model for a specific phenomena, to an incorrect analytical solution for the model, to an incomplete description of the system to be modeled, or to the fact that an 'abstraction' may not capture the behavior of the system. . . . These . . .limitations are compounded by the fact that the analytical process involves the use and coupling of complex models to assess conditions over extended periods of time. (U.S. Department of Energy, 1997)

NRC staff will ascertain whether the PA computer models are sufficiently transparent and traceable such that the completeness, clarity, and consistency in the PA methodology are verifiable. The following specific attributes may make the model transparent and traceable:

- Conceptual features and processes that are represented in the models, and the algorithms used to implement them should be accurately described.
- A complete description of the conceptual features and processes excluded from the models and algorithms should be described completely and the justification for excluding the features and processes should be provided.
- Structure of the code should be mechanically correct (e.g., modular), and the level of comments in the code should be complete and thorough.
- Input parameters used should be clearly identified, and their validity established.
- Presentation of intermediate results for high doses should be provided. In additional intermediate results that provide insight into the total system analysis, (e.g., results of intermediate calculations of the behavior of individual barrier) should be provided.

4.1.2 Demonstration of Multiple Barriers

The concept of defense-in-depth has been and will continue to be a fundamental tenet of regulatory practice in the nuclear field, particularly regarding nuclear facilities. Risk insights can make the elements of defense-in-depth more clear by quantifying them to the extent practicable. Although the uncertainties associated with the importance of some components of the safety system may be substantial, the fact that these components and uncertainties have been quantified can aid in determining how much defense makes regulatory sense. Decisions on the adequacy of or the necessity for elements of defense should reflect risk insights gained through identification of the individual performance of each defense system in relation to overall performance. Defense-in-depth is an element of the NRC's Safety Philosophy that employs successive compensatory measures to prevent accidents or mitigate damage if a malfunction, accident, or naturally caused event occurs at a nuclear facility. The defense-in-depth philosophy ensures that safety will not be wholly dependent on any single element of the design, construction, maintenance, or operation of a nuclear facility. The net effect of incorporating defense-in-depth into design, construction, maintenance, and operation is that the facility or system in question tends to be more tolerant of failures and external challenges (NRC, 1999b). However, it is recognized that the repository will consist of closely related engineered and natural subsystems. As such, the performance of any single subsystem cannot and should not be considered either truly independent or totally redundant (NRC, 1999c).

To maintain the Commission's defense-in-depth philosophy, the staff recommended and the Commission accepted a proposed regulatory approach that includes assessment of repository barrier performance, without specifying numerical goals for subsystem performance. This approach avoids the incorporation of numerical subsystem requirements that are unrelated to U.S. Environmental Protection Agency standards, thereby allowing maximum flexibility to the licensee to design a repository system with optimal performance. This approach is consistent with recommendations of the National Academy of Sciences. In addition, the Nuclear Waste Policy Act mandated that technical criteria developed by the Commission ". . . shall provide for the use of a system of multiple barriers in the design of the repository (Nuclear Waste Policy Act, 1982).

It is noted that this approach may require DOE to provide greater transparency in its analyses of overall performance, the review of which is discussed in Section 4.1.1 of this IRSR.

Acceptance Criteria with Review Methods

DOE's approach for demonstrating compliance with the multiple barriers requirement will be acceptable if the following acceptance criteria are met:

Criterion T1: The subsystems relied upon by DOE as barriers consist of at least one from the engineered system and one from the natural system.

Review Method: Staff will confirm that the subsystems identified as barriers consist of major repository subsystems and/or components of distinct features, characteristics, or attributes.

Criterion T2: DOE has demonstrated the capability of the identified barriers that are consistent with the approaches used in the TSPA.

Review Method: Staff will verify that the descriptions of the barrier capability are explained in terms of preventing or substantially delaying the movement of water or radioactive material. Staff will verify that the described impacts are consistent with the results from the following studies: DOE's TSPA, sensitivity and uncertainty analyses, importance analysis, "one-off" analysis, analysis beyond the compliance period, and/or any other analysis that would appropriately quantify the barrier capability. Staff will use insights gained from NRC TPA code audit calculations and/or other appropriate quantitative analyses to confirm barrier capabilities. Furthermore, staff will verify that no single credible event or process identified by DOE is able to eliminate all identified barriers.

Criterion T3: DOE has provided technical bases for the barrier capability that are commensurate with the degree of reliance in DOE's safety case.

Review Method: The staff will review DOE's technical basis, such as laboratory and field measurements, natural analog studies, and expert elicitation, supporting the descriptions of the barrier capability and the associated quantitative analyses. Staff will review the key sampled parameters and modeling assumptions to confirm that the numerical results are not sensitive to the sampling scheme, the assigned parameter ranges are appropriate, and alternative modeling assumptions have been investigated.

Technical Basis

A barrier is defined in Draft 10 CFR 63 (Nuclear Regulatory Commission, 1999c) as a "repository subsystem that prevents or substantially delays movement of water or radioactive materials". Preventing or significantly delaying the movement of water or radioactive material from reaching the receptor group location will improve the performance of the repository system because the proposed rule is based on the peak expected annual dose received by the critical group over a time period of compliance of 10,000 years. Repository subsystems that prevent the movement of water or radioactive materials will lower the quantity of radioactive material that reaches the receptor group and therefore reduce the expected annual dose. Repository subsystems that significantly delay key radionuclides from reaching the critical group can extend the time of peak expected annual dose to well beyond the 10,000 year compliance period. Due to radioactive decay of the waste, the relative hazard of the waste decreases over time and at 10,000 years is within a factor of ten of the hazard of uranium ore (U.S. Department of Energy, 1980; Nuclear Regulatory Commission, 1997).

Subsystems identified by DOE to demonstrate compliance with the multiple barriers requirement in draft 10 CFR 63 (Nuclear Regulatory Commission, 1999c) have no quantitative requirements for the performance. Clearly, a subsystem that simply delays radionuclides from reaching the critical group for 50 yr would not be considered to have a significant impact on performance over a 10,000-yr compliance period and would not be considered a barrier. Similarly, a subsystem that prevented the release of only a very small fraction of the total radionuclides released would not be considered a barrier either. It is equally clear that a subsystem that delayed transport of radionuclides to the receptor location by 5,000 yr or prevented the release of 99.9 percent of available radionuclides would have a significant impact on a 10,000 year compliance period and would be considered a barrier. Actual subsystem performance may lie between these extremes, and the impact of the subsystem may include both a delay of the radionuclides reaching the receptor location and a decrease in the quantity of radionuclide released. The judgment of the reviewer will be required to determine whether the impact of a subsystem is significant enough to performance for it to be considered a barrier. Examples of barriers and their capabilities based on the most current analyses and DOE design (Mohanty and McCartin, 1998; Department of Energy, 1998b) include the unsaturated zone, which shields the drifts from infiltrating water; the WP, which prevents water from contacting the waste; or the long transport time of radionuclides through the saturated zone.

Geologic disposal of HLW is based on the assumption that the natural system will act as a barrier to water contacting the waste and to radionuclides being released from the repository. Although the geologic record of the YM region is extensive, ranging from thousands to millions of years, geologic data are subject to interpretation. Additionally, although the properties and configuration of engineered structures can be defined very precisely, there is limited experience with the performance of engineered structures over time periods longer than a few hundred years. Therefore, because of the uncertainties associated with the long-term performance of both the natural and engineered systems, it would not be prudent to rely on either system to provide protection by itself. NRC expects that DOE will demonstrate that the natural system and the engineered barrier system will work in combination to enhance the overall performance of the geologic repository.

The demonstration of the capability of barriers requires that the performance of subsystems claimed as barriers is consistent with the site data, material data, and modeling results used in the TSPA to demonstrate compliance with the regulatory dose limit. Any discrepancies between the TSPA modeling and the modeling or analyses conducted to demonstrate multiple barriers should be clearly identified and justified. Additional information on the adequacy of data and models for the TSPA can be found in Section 4.3 of this IRSR.

The assessment of the system will be conducted with a probabilistic analysis. Therefore, the performance of barriers will be influenced by the sampling of uncertain parameters and by uncertainties in the modeling of the subsystems. This uncertainty could influence whether a subsystem can be considered a barrier or not. For example, if parameters that control the corrosion rate of the WP cause the time of WP failure to range from 100 to 100,000 yr, the uncertainty in parameters describing the corrosion process has a significant influence on the capability of the subsystem to act as a barrier. However, if further review showed that the WPs last for longer than 10,000 yr under 99.9 percent of combinations of sampled parameters, this would constitute sufficient evidence that the WP is acting as a barrier to radionuclide release. Performance of the barriers has no quantitative requirements, so the judgment of the reviewer will be required to determine whether parameter-and modeling-parameter uncertainty impacts on the performance of a subsystem are significant enough to disqualify a subsystem from being considered a barrier.

NRC does not prescribe a method for DOE's demonstration of multiple barriers, but instead believes that DOE should be allowed to choose the methodology used to demonstrate that the repository system consists of multiple barriers to radionuclide release. A discussion on the review of two methods, intermediate outputs and sensitivity analysis, for which information was included in TSPA-VA (Department of Energy, 1998b) and that potentially could be utilized by DOE individually or in combination to demonstrate multiple barriers follows. Discussion on the use of a third method, importance analysis, is also included below. However, DOE is neither required to utilize any one of these methods nor is DOE restricted in its choice of methods to demonstrate multiple barriers as long as all of the above acceptance criteria are met.

Intermediate outputs from the TSPA can be useful for demonstrating how subsystems are contributing to the performance of the system. For example, the WP lifetime and the travel times of radionuclides in the saturated zone can be used to demonstrate the effectivness of these subsystems in delaying the dissolution and transport of radionuclide. However, the presentation of a subsystem's performance during a single deterministic run is generally not sufficient to demonstrate that the subsystem may be considered a barrier. As discussed above, the demonstration that a subsystem is a barrier must consider the impact of parameter and modeling uncertainty. Therefore, intermediate outputs must include probabilistic results of the TSPA calculations unless a subsystem is shown to be an effective barrier using a "worst-case" set of parameter values and modeling assumptions. Additionally, more information than just intermediate outputs from a 10,000-yr compliance calculation may be useful for the demonstration of multiple barriers. Subsystems that may not appear to be effective barriers over 10,000 yr may be shown to be important over a longer calculation of repository performance. For example, barriers that are able to stop actinides from being transported may not appear to be effective barriers based on intermediate outputs in 10,000 yr if (i) no WPs fail in 10,000 yr; (ii) WPs fail, but radionuclides that have the potential to contribute significantly to dose (such as Pu-242) do not reach the barrier in the 10,000-yr compliance calculation because they are retarded in the subsystems [(e.g., radionuclides do not reach the saturated zone (SZ) because they are retarded in the invert or unsaturated zone (UZ), or (iii) the analysis only focuses on those radionuclides that actually contribute dose in 10,000 yr (e.g., technetium and iodine)]. Demonstration of the effectiveness of these barriers may require additional calculations such as extending the TSPA analysis to longer periods of time.

Sensitivity techniques such as regression, differential, or "one-off" analyses can be useful tools for determining those uncertain parameters that have a significant impact on the uncertainty of the estimated PA results and the impact that variation in these important parameters can have on the performance of the repository system. However, these techniques are typically limited to the assessment of a single parameter's impact on performance, and cannot be used to assess the impact on performance of the interaction of multiple uncertain parameters. The reviewer should also keep in mind that any sensitivity analysis will not be able to identify the impact of parameters that are important over long performance calculations using data from a 10,000-yr calculation.

A combination of sensitivity analysis and intermediate output techniques may also be useful for the demonstration of multiple barriers in order to address the shortcomings in either of the methods by itself. For example, intermediate outputs could be used to determine the probabilistic performance of a subsystem. The probabilistic performance of the subsystem could then be used in a modified "one-off" analysis to determine the performance of the repository system when the subsystem is performing at either optimum or worst-case condition or at its 5th and 95th quantile of performance.

Importance analysis can provide additional insights on the level of protection provided by a subsystem. Importance analysis consists of neutralizing all beneficial aspects of a subsystem and determining the change in the resulting expected dose from the system. These results do not produce realistic expectations of system performance, but can be used to determine which subsystems have the greatest impact on repository performance. Staff review of an importance analysis should include a careful review of the impact that the removal of a subsystem has on the validity of the prediced performance of other subsystems. For example, removal of all WPs at time t=0 could cause the fuel dissolution model to return inaccurate results if the fuel dissolution model is not valid at the temperature and humidity conditions present at early times. Staff review of an importance analysis should include confirmation that all aspects of a subsystem have been neutralized and that the radionuclides being considered in the dose assessment are appropriate for the altered system. Removal of a subsystem may cause additional radionuclides to become important in the assessment of dose from the repository.

Again, it is emphasized that the methods presented in this section do not constitute explicit or implicit requirements for the demonstration of multiple barriers nor does the use of these methods ensure compliance with the multiple barriers requirement for the repository. DOE's demonstration of multiple barriers must meet all of the acceptance criteria in this section using any methodology they choose.

NRC review of DOE's demonstration of multiple barriers will focus on the impact that the identified barriers have on key radionuclides. Key radionuclides include those that, due to their inventory, half-life, solubility, lack of retardation in the geosphere, and biosphere dose conversion factor (DCF), are expected to contribute significantly to the expected annual dose to a member of the critical group over the compliance period (such as I-129 and Tc-99). Key radionuclides also include those that are retarded in the geosphere such that they are not likely to reach the receptor group location in significant quantities over the regulatory compliance period, but (due to their inventory, half-life, solubility, and larger biosphere DCFs), have the potential to deliver relatively large doses to the critical group over longer time periods (such as Pu-242 and Np-237). The latter group of radionuclides is important because the radionuclides can deliver a relatively large dose to a receptor compared to I-129 and Tc-99 if they reach the biosphere. Therefore, the release of these radionuclides is more likely to lead to a dose that could exceed the regulatory limit. Subsystems in the repository able to significantly delay these radionuclides from reaching the receptor location provide assurance that the dose limit will not be exceeded because there are additional barriers to the release of these relatively high-risk radionuclides. Therefore, even if a barrier does not have a significant impact on radionuclides that eventually are expected to deliver dose to the critical group during the compliance period, the delay in those radionuclides with high potential risks can significantly impact the performance of the system. To show that a barrier has an appropriate impact on all key radionuclides the following methods could be used:

- The impact of the barrier could be demonstrated by the reduction in the quantity of water that is available to contact the waste. Because water is necessary to cause significant transport of radionuclides from the fuel, barriers that shield the waste from water clearly prevent or significantly delay the release of all radionuclides in the fuel.

- The impact of the barrier could be demonstrated for each key radionuclides. Thus, the reviewer could explicitly determine a barrier's impact on each radionuclide to ensure that the subsystem is an effective barrier for all key radionuclides.

- The impact of a barrier could be demonstrated by summing all radionuclide quantities weighted appropriately by their impact on dose. This would allow a single metric to represent multiple radionuclides and allow for a quick assessment of the barriers that significantly impact the results of the calculation.

Common-mode or common-cause failure is an important concern when evaluating the reliability of complex systems. If a single credible initiating event or mode of failure has the potential to fail all barriers or safety mechanisms that avert a threat from a system, the overall safety of the system is compromised. The review of the repository should include an assessment of how robust the repository is to credible events and processes. Therefore, the reviewer should examine the credible events and processes at YM and determine whether any one has the potential to fail all barriers identified for the repository system.

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 features, events, or processes (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

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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.

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, 1997). If effectively implemented, DOE's current approach to scenario analysis, as discussed at an NRC/DOE Appendix 7 meeting held in 10/98 and a technical exchange held in 5/99 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 (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.

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[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.

Acceptance Criteria with 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 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 IAEA/NEA (1997b) to evaluate DOE's comprehensive list of processes and events. Staff will compare DOE's list to other generic and site-specific efforts [e.g., OECD/NEA database of features, events, and processes (OECD/Nuclear Energy Agency, 1997a)] 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 (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]

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.

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

[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).

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 with 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 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.

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[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 performance assessment based on the probability of their occurrence.

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 with 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.

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 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

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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.

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 Key Technical Issues – KTIs (e.g., Igneous Activity 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., igneous activity 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 igneous activity).

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 igneous activity 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 igneous activity 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 with 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 igneous activity (**I** and $\mathbf{I}^{-}$). These event classes can be combined into scenario classes such as **FSI**, $\mathbf{FSI}^{-}$, $\mathbf{FS}^{-}\mathbf{I}$, $\mathbf{FS}^{-}\mathbf{I}^{-}$, $\mathbf{F}^{-}\mathbf{SI}$, $\mathbf{F}^{-}\mathbf{SI}^{-}$, $\mathbf{F}^{-}\mathbf{S}^{-}\mathbf{I}$, and $\mathbf{F}^{-}\mathbf{S}^{-}\mathbf{I}^{-}$. The Latin Square approach provides a complete set of scenario classes and ensures that the scenario classes are mutually exclusive. Scenario classes are broadly defined and distinct, which is useful for screening scenario classes. This formulation of scenario classes does not make a distinction between 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.

<u>Acceptance Criteria and Review Methods</u>

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

<u>Criterion T1:</u> 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.

<u>Review Method:</u> 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.

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

<u>Review Method:</u> 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 Key

Technical Issues (e.g., Igneous Activity KTI; Structural Deformation and Seismicity 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 igneous activity). 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, igneous activity, 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., **F** and $\mathbf{F}^-$) must equal one. The NRC approach is demonstrated using a simple example, where event classes associated with the independent processes Θ and Ψ are used to form scenario classes. The assumption of independence simplifies the example, but may not be appropriate for all combinations of event classes.

The following probabilities for the two event classes will be assumed in this illustration of the Latin Square method: Θ (P=0.9) and Ψ (P=0.05); where the probabilities are for the processes or events within the event class either being present or occurring within 10,000 years. Each of these event classes has a probability greater than 10^{-4}, so they may not be screened on the basis of probability. The probability of Θ or Ψ not being present or not occurring within 10,000 years can be found using the principles of probability; that is Θ^- (P=0.1) and Ψ^- (P=0.95). These event classes can be combined to form scenario classes (e.g., $\Theta\Psi$, $\Theta\Psi^-$, $\Theta^-\Psi$,$\Theta^-\Psi^-$). 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 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 2. The focal point is the overall repository system where the performance measure is expected 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, staff will examine the contribution to performance from each of three repository subsystems: engineered system, geosphere, and biosphere, as shown in the middle tier of figure 2. 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, direct release to the biosphere; and the dose calculation for the biosphere. This characterization of components is not strictly based on the physical aspects of the system, but from the perspective of a dose or risk calculation for total system performance evaluation. 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 and takes advantage of the results of past NRC Iterative Performance Assessments (IPAs) and reviews of DOE's TSPAs. At the base of the hierarchy are the key elements of the repository system that need to be appropriately abstracted into a TSPA.[9] These key elements, in general, are the integrated processes, features, and events that could impact system performance. The judgment about which elements need to be abstracted is based on staff TSPAs performed in the past, review of DOE's TSPAs, and knowledge of the design options for the YM site and YM site characteristics.

Because TSPAs are considered iterative, some adjustment of the key elements may occur as future TSPAs and other relevant analyses are completed and site data are collected. In its review, the staff will consider elements of DOE's total system performance demonstration and the relative contributions of repository subsystems or their components to identify those areas that require greater emphasis during its review. The staff will also review DOE's TSPA for completeness and adequacy. Completeness refers to the inclusion of important features, events, and processes 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.

As part of a systematic approach to preparing to review DOE's TSPAs, the staff intends to develop acceptance criteria for each of the key elements that it believes should be abstracted into the TSPA. The acceptance criteria for the key elements will eventually form the basis for development of a RP to be used in the review of HLW repository LA. It is expected that DOE's

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[9] As stated in DOE TSPA-VA plan (TRW Environmental Safety System, 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 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.

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.

Staff review of DOE's TSPAs will be performed on individual integrated subissues (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 of level of complexity. This review of model abstractions, however, will incorporate reviews by other KTIs on specific elements of a ISI, both of which will be based on the following five technical acceptance criteria (AC). The programmatic AC 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, and/or natural analog data) are available to adequately support the conceptual models, assumptions, boundary conditions and 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. Alternatively, the parameters or models lacking sufficient data have been replaced by bounding parameter values or models.
Criterion T2	Data Uncertainty and Justification - Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the TSPA are technically defensible and reasonably account for uncertainties and variabilities.
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 Justification - Models implemented in the TSPA provide results consistent with output of detailed process models or empirical observations (laboratory testings or 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.

These five technical criteria highlight the essential steps in a defensible scientific investigation and modeling process: (i) adequate amount of credible information for the system modeling exercise should exist (T1), (ii) the input values used in predicting the system behavior should be verified against applicable sources and reflect the uncertainty (T2), (iii) the subsystem models used to simulate the system behavior should consider all credible interpretations of the available observations (T3), (iv) the subsystem model output should be tested against available observations (T4), and (v) important interactions among the subsystem models should be included in the total system analysis and consistent assumptions and data are used throughout the simulation (T5).

The remainder of section 4.3 provides more detail on these five technical acceptance criteria and the corresponding review methods (RMs) for each of the 14 ISIs (see the bottom tier in figure 2). Note that although the AC and RMs 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. For each ISI, those DOE repository safety strategy hypotheses considered pertinent to that ISI can be found in appendix A. Descriptions for the pertinent KTI subissues that have been identified at the beginning of each ISI section are listed in Appendix B. The relationship of individual KTI subissues to a particular ISI is also described in Section 3 of the KTIs IRSRs (Stablein, 1997a-f, 1998a, 1998b). 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 C as supporting documentation.

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 not currently disagreement 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. Additional discussions on Open Items and discussion points related to specific model abstractions are included in the appropriate ISI sections later in this chapter. See tables 2 and 3 for a summary of Open Items and table 4 for a summary of discussion points.

TSPA-VA (U.S. Department of Energy, 1998b) indicates that DOE has conducted expert elicitations utilized in TSPA-VA in accordance with NUREG-1563 (Kotra et al., 1996). This is considered appropriate by NRC staff. However, NRC staff still has concerns that expert elicitation is utilized inappropriately in 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 judgement that they are correct because this methodology may provide a non-conservative 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 judgement of whether they are correct. 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 TSPA-VA, DOE considers the impacts of direct release, enhanced source term, and indirect effects due to igneous activity. 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 the 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 radionuclides 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 radionuclides based on these or other criteria, but believes that the licensee must be able to show that exclusion of additional radionuclides from the analysis would not impact the estimated performance of the system. There is basic agreement between NRC and DOE staff on the methodology that will be used to screen radionuclides from the analysis, so discussion point TE4 is not an open issue at this time. However, the methodology and results of the screening of radionuclides will continue to be evaluated in future TSPAs as more data on the system become available to NRC and DOE staff.

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 TSPA-VA (U.S. Department of Energy, 1998b). These results are utilized 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 Latin Hypercube Sampling techniques and alternative conceptual models. Alternate conceptual models were evaluated for changes in the water chemistry due to spent fuel 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 to be 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 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 in 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, 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, AC and RMs are focused on defining those aspects of the analysis necessary to make this evaluation.

4.3.1.1 Engineered Barriers

In this section, technical AC and RMs for the four key elements in the engineered barriers abstraction, as identified in figure 2 (i.e., WP Corrosion, Mechanical Disruption of the Waste Packages, 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 key elements represent the essential factors to be considered in demonstrating the engineered barriers' contribution to 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 Waste Package Degradation (Temperature, Humidity and Chemistry)

Pertinent KTI subissues: CLST1, CLST6, ENFE2, IA2, RDTME1, RDTME3, TEF1, TEF2, TEF3

The WP is the primary engineered component 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 in part 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.

Percolating groundwater can be in contact with the spent fuel by entering WPs that have corroded, thereby releasing to the groundwater RNs contained in the WP. Currently there are three corrosion degradation regimes considered in assessments of WP lifetimes: (i) dry air oxidation, (ii) humid air corrosion, and (iii) aqueous corrosion. Modeling approaches used by DOE to predict WP corrosion have been based on empirical relationships in TRW Environmental Safety Systems, Inc. (1995, 1997), and a complete description of the empirical equations used in the models is given therein. It is recognized that the future DOE TSPA will include a mechanistic modeling of the WP corrosion process.[10] However, the most recent DOE TSPA (DOE,1998b) uses an empirical description of WP corrosion. Dry air oxidation of the container is considered negligible. Humid air corrosion is assumed when the relative humidity (RH) is above a critical value (sampled uniformly between 65 and 75 percent) and below the RH at which aqueous corrosion is assumed to occur (sampled uniformly between 85 and 95 percent). For carbon steel, active general corrosion in humid air is modeled using a parametric equation in which the corrosion rate is dependent on time, RH, and temperature. The general corrosion rate of Alloy C-22 was obtained from an expert elicitation considering moderately oxidizing environments with a pH of 3-10, moderately oxidizing environments with a pH of 2.5, and a highly oxidizing environment with a pH of 2.5. Pitting corrosion of both carbon steel and corrosion resistant alloys was also modeled based on input from an expert elicitation process. The critical temperature for localized corrosion of Alloy C-22 was 80°C. At lower temperatures, localized corrosion of Alloy C-22 is not considered. In addition, the effect of galvanic coupling is not considered. The NRC has previously questioned the adequacy of the approach used by DOE in the modeling of aqueous corrosion and, in particular, the lack of consideration of the chemical composition and redox conditions of the environment in the modeling of localized corrosion of the inner and outer overpack materials (Baca and Jarzemba, 1997). The technical bases for many of the parameters used to model WP degradation are unclear. These parameters include the general corrosion rate of Alloy C-22, and criteria for the initiation, propagation rate, and repassivation of localized corrosion. In addition, the effect of welding on the localized corrosion resistance of Alloy C-22 has not been addressed by DOE. Modeling approaches used by NRC to describe WP corrosion have been more mechanistic in nature (Mohanty et al., 1997) and analyses similar to those in TRW Environmental Safety Systems, Inc. (1995) using these more mechanistic models have yielded different results for median WP lifetime (Baca and Jarzemba, 1997). Among other findings, these analyses indicate that the near-field environment (temperature and RH) and, for certain inner overpack materials under consideration by DOE, the beneficial effect of galvanic coupling[11] can affect WP lifetime.

Acceptance Criteria with 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 engineered system's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for

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[10] DOE/NRC Technical Exchange on Performance Assessment, March 17-19, 1998 Center for Nuclear Waste Regulatory Analyses, San Antonio, TX.

[11] Galvanic coupling may extend the WP lifetime for WP designs that include certain corrosion resistant inner overpack materials such as alloys 825 and 625. For other inner overpack materials currently under consideration by DOE, such as alloy C-22, galvanic coupling may not play an important role in estimating the WP lifetime.

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. 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 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 definition of parameter values and conceptual models is 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: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the WP corrosion abstraction, such as the critical 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 YM region (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, 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: 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: WP corrosion abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or 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: 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.[12] For example, the staff should determine whether the conditions and assumptions used to generate look-up tables or regression equations[13] 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, etc. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's or 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[14] 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).

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[12] For TSPA-VA, the types of abstraction are defined in section 3.3 of the TSPA-VA Plan (TRW, 1996).

[13] This is called response-surface abstractions in the TSPA-VA Plan (TRW, 1996).

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

- Near-field chemistry (e.g., pH, chloride concentration, dissolved oxygen concentration, carbonate/bicarbonate concentration) affects WP corrosion rate. 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 3. Staff should verify that DOE's domain-based[15] and temporal abstractions appropriately handled the physical couplings (T-H-M-C) 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 non-defensible predictions.

Technical Basis

Approaches to abstracting this key element to system performance have taken two forms: DOE's empirical description of the WP corrosion process and NRC's mechanistic modeling. Modeling approaches used by DOE to predict WP corrosion have been based on empirical relationships in TRW Environmental Safety Systems, Inc. (1995, 1997); and a complete description of the empirical equations used in the models is given therein. The process is modeled as humid air corrosion when the relative humidity (RH) is above a critical value (sampled uniformly between 65 and 75 percent) and below the RH at which aqueous corrosion is assumed to occur (sampled uniformly between 85 and 95 percent). Dry air oxidation of the container is considered negligible (Stahl, 1993; McCright 1998). Input from expert elicitation has been used to calculate the aqueous general corrosion rate of both carbon steel and Alloy C-22. Localized corrosion of alloy C-22 is not considered below 80°C, and no localized corrosion penetration rate is provided. Effects of welding on the localized corrosion resistance are ignored. The NRC has previously questioned the adequacy of this approach. Specifically, modeling approaches used by NRC to describe WP corrosion have been more mechanistic in nature (Baca, 1997), and analyses similar to those in TRW Environmental Safety Systems, Inc. (1995) using these more mechanistic models have yielded different results for median WP lifetime (Baca and Jarzemba, 1997). Among other findings, these analyses have found that the near-field environment temperature and RH and particularly the beneficial effect of galvanic coupling may affect WP lifetime for inner overpack materials such as alloys 625 and 825.

There are currently three corrosion degradation regimes considered in assessments of WP lifetimes: (i) dry air oxidation, (ii) humid air corrosion, and (iii) aqueous corrosion. These three degradation regimes, along with galvanic coupling of WP constituents, are explained in the following paragraphs.

In DOE's TSPA-VA design (U.S. Department of Energy, 1998b), the container system consists of a 10-cm-thick outer overpack made of a corrosion-allowance steel, such as A516 Grade 55 (a wrought C-Mn steel), and a 2-cm-thick inner overpack made of a corrosion-resistant Ni-base

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

alloy, such as alloys 825, 625, or C-22. The material currently selected for the inner overpack is Alloy C-22, which was selected as a result of concerns regarding the resistance to localized corrosion of Alloys 825 and 625 under more aggressive environmental conditions. Additional barriers, such as a multipurpose canister (made of type 316L stainless steel), may be present, but they are not currently considered in DOE's or NRC's PAs. The purpose of the corrosion allowance outer overpack is to provide, in addition to radiation shielding, a predictable containment time determined by uniform corrosion. The purpose of the inner overpack is to provide a long containment time determined by a low-corrosion rate dictated by the formation of a protective oxide film. Alternate container designs have been considered. Ceramic coatings on the carbon steel overpack have been proposed as a means to delay the penetration of the outer barrier (McCright, 1998).The expected DOE TSPA-SR design is the enhanced design alternative (EDA) II that uses a 2-cm-thick outer overpack made of a corrosion-resistant Ni-base alloy, such as Alloy C-22 over a 5-cm-thick 316LNG inner barrier (Howard, 1999). Because the corrosion resistant Ni-base alloy overpack material is protected by an oxide film, the localized corrosion rate can be extremely high where the film is breached and environmental and electrochemical conditions can promote the initiation and propagation of pitting or crevice corrosion. A crucial assumption in DOE's WP design is the resistance to localized corrosion or stress corrosion cracking of the inner overpack material. If the outer barrier is breached by localized corrosion, DOE may seek to take credit for galvanic protection of the inner barrier by the carbon steel overpack to extend WP life. However, the use of alloy C-22 diminishes the importance of this factor because of its inherent resistance to localized corrosion even under aggressive environmental conditions. No credit was taken in TSPA-VA for galvanic coupling. The absence of a corrosion allowance barrier in the EDA II design obviates the use of galvanic protection to extend WP lifetimes. Therefore, discussion point TE17 is not considered an Open Item.

Implicit in the choice of an arid geographical area and unsaturated hydrological conditions for the proposed repository is the assumption that the containers experience negligible degradation under dry conditions. Dry air oxidation has been shown to lead to only a shallow penetration of the container (Ahn, 1996; Larose and Rapp, 1996; Henshall, 1996) with a minor decrease in wall thickness as a result of oxide formation. This limited penetration should not have an effect on the subsequent performance in an aqueous environment. A decrease in the performance of the container may occur due to a thickening of the protective oxide film, which, in turn can result in an increase in corrosion potential (Sagar, 1997); formation of various iron(III) oxides, which can undergo reduction, thus increasing the corrosion potential (Tsuru et al., 1995); or formation of nonconductive scale, which may affect the metallic contact between the outer and inner overpacks, impeding adequate galvanic protection.

The occurrence of wet (humid air and aqueous) corrosion is determined by the 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. In reality, the corrosion behavior is a complex function of RH. At low RH values, the condensed water film is quite thin, enabling easy access of oxygen to the metallic surface. However, corrosion is stifled through the rapid accumulation of corrosion products. The alternating wet and dry conditions of periodic changes in RH can add to the complexity of the corrosion process in humid air environments.

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 8 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) and promote the active localized dissolution at discrete sites while the remaining surface corrodes at a slow rate determined by the passive current density. Volcanic events, such as the formation of a nearby dike, may change the near-field temperature and chemistry (e.g., pH, sulfide concentration) to which the WP is exposed. At this time, however, studies for determining the effects of nearby dike intrusions on near-field temperature are not mature (Connor et al., 1997) and studies for determining the effects on near-field chemistry are even less developed. Consequently, although identified in figure 2, the effect of igneous activities on the near-field environment has not been considered in the TSPA by either NRC or DOE.

In the VA reference design, the corrosion resistant Ni-base alloy will be exposed to the near-field environment after the carbon steel outer overpack is penetrated. For the EDA II WP configuration, the corrosion resistant Ni-base alloy will be exposed to the near-field environment upon emplacement of the WP in the repository. Aqueous corrosion of the corrosion resistant Ni-base alloy is determined by the chemistry of the environment contacting the alloy, the critical potential for localized corrosion of the alloy, and its corrosion potential. Generally, the critical potential is independent of pH, but decreases with an increase in both chloride concentration and temperature. Presence of sulfides and thiosulfates also can contribute to a decrease in the critical potential. The critical potential increases with an increase in the chromium, molybdenum, and tungsten content of the alloy $\left(E_{crit}^{825} < E_{crit}^{625} < E_{crit}^{C-22}\right)$. Considerable attention has been focused on the nature of the critical potential, and it has been shown that the repassivation potential measured by short-term laboratory tests forms a conservative lower-bound estimate of the long-term critical potential of an alloy in a given environment (Sridhar et al., 1995). Localized corrosion may be initiated when the corrosion potential of the alloy exceeds the critical potential. Corrosion potential is dependent on dissolved oxygen concentrations, pH, and temperature. After localized corrosion is initiated, the rate of penetration can be quite rapid (Mohanty et al., 1997).

The present DOE modeling approach does not consider the effect of near-field conditions, especially temperature and chloride concentration, on the initiation and propagation of localized corrosion. The assumption that localized corrosion of Alloy C-22 cannot be initiated at temperatures less than 80°C is inconsistent with experimental observations (American Society for Testing and Materials, 1998). No propagation rate for localized corrosion is explicitly provided in DOE's calculations (McCright, 1998; DOE, 1998); however a pit-stifling criterion is used to determine the maximum localized corrosion penetration of the Alloy C-22 barrier. The technical basis for this criterion, which is inversely proportional to the passive current density, is not clear. A maximum penetration depth of 0.2 mm was calculated using a high passive current density of 4×10^{-6} A/cm^2 that is inconsistent with passive current densities reported in the literature as well as the results of long-term corrosion rate measurements conducted by DOE (McCright, 1998). Using passive current densities consistent with those reported for corrosion resistant alloys (1×10^{-8} to 3×10^{-7} A/cm^2), the maximum pit penetration depths could exceed the thickness of the WP barrier without stifling.

Uniform corrosion of Alloy C-22 is expected under aqueous conditions when the corrosion potential of the material is less than the critical potential for localized corrosion. Longer WP lifetimes are expected when no localized corrosion can be sustained, since the passive dissolution rates of corrosion resistant materials are low. The present DOE approach uses uniform corrosion rates for Alloy C-22 based on expert elicitation that vary from 10^{-8} to 10^{-2} mm/yr (10^{-11} to 10^{-6} A/cm^2). Since the large range of passive dissolution rates is not consistent with previous observations, DOE should provide a technical basis for this assumption.

Galvanic coupling between the outer steel and inner alloy overpack can serve to reduce the corrosion potential of the inner overpack below its critical potential. However, the efficiency and duration of galvanic coupling can be affected by the presence of oxide scale or corrosion products (Dunn and Cragnolino, 1997). Galvanic protection of the Alloy C-22 barrier is not possible with the EDA II configuration, since no carbon steel barrier is used in this design.

Aside from material selection and the environment interacting with the material, WP performance could depend on its design and construction. Therefore, the specific consideration of corrosion modes associated with the weldments is essential because it is well-known that in many engineered structures and components, welded joints are more prone to corrosion failure than the base metal. The possible susceptibility of weldments of the inner overpack (especially alloy C-22) may need to be considered in WP performance calculations. Segregation of alloying elements during weld solidification and formation of secondary phases that are detrimental to both the mechanical properties and the corrosion resistance of the material have been observed in Alloy C-22 welds. Topologically close packed (TCP) phases such as μ- and P-phase typically form within the grain boundary region and contain high concentrations of Mo and W. Since Mo and W are known to provide resistance to localized corrosion, consumption of these alloying elements within the TCP phases can be expected to render the alloy more susceptible to localized corrosion at the grain boundaries. Reduction of the critical pitting temperature and increased passive dissolution rates after welding are known to occur with Ni-Cr-Mo-Fe alloys (Farmer, 1999).

The data used by DOE to support its modeling of C-22 behavior and the basis for the corrosion potentials to determine the corrosion rate of the WP are being evaluated in the CLST KTI. Therefore, discussion points TE18 and TE19 do not need to be tracked in this IRSR, and they will not be considered Open Items.

TSPA-VA did not take credit for the contribution of degraded WPs shielding the waste from contact with dripping water. Therefore, the issue raised in discussion point TE16 is no longer an issue and is considered closed at this time.

4.3.1.1.2 Mechanical Disruption of Waste Packages (Seismicity, Faulting, Rockfall, and Dike Intrusion)

Pertinent KTI subissues: CLST2, IA2, RDTME1, RDTME2, RDTME3, SDS1, SDS2, SDS3, SDS4

The ability of the WP to contain and, in the long term, limit release of RNs is in part determined by the long-term mechanical strength of WP materials relative to the imposed loads that are anticipated. This section focuses on those disruptive events that lead to release via the groundwater pathway. Seismicity, faulting, and dike intrusion are all disruptive events that may affect performance of the proposed repository at YM. Each disruptive event has the ability to prematurely fail a number of WPs, leading to earlier releases of RNs. Although TSPA-95 (TRW Environmental Safety Systems, Inc., 1995) did not address disruptive scenarios, DOE TSPA-VA included these disruptive events. NRC TSPAs (e.g., Wescott et al., 1995) have included seismicity, faulting, and volcanism. The relative importance of these disruptive events in a TSPA where peak individual dose or risk is the performance measure remains to be determined. It is noted that the effects on performance of combined disruptive events (e.g., faulting and volcanism) may be more than the sum of the effects for the individual events acting alone and methods for combining the effects of different disruptive events are still under debate. For example, faults may act as structural controls for volcanic dike formation, hence the two events do not act independently.[16]

Acceptance Criteria with Review Methods

DOE's approach to abstracting mechanical 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 used in the performance calculations to demonstrate engineered system's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing mechanical disruption of WPs 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 used and to define relevant parameters in DOE's mechanical disruption of WPs 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

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[16] Section 4.4 will address the scenario analysis subissue in more detail.

values and conceptual models is 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.[17]

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the mechanical disruption of WPs 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 WPs input/data in the performance calculations. Staff should ascertain that the input values used in the mechanical disruption of WPs calculations in TSPA are reasonable based on data from the YM region (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 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 the input values and correlations used by DOE.

Criterion T3: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the mechanical disruption of WPs 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 WPs 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 bounds the range of uncertainties resulting from alternative modeling approaches.

Criterion T4: Mechanical disruption of WPs abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

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

Review Method: Staff should ascertain whether DOE demonstrated that the output of mechanical disruption of WPs 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 WPs 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: Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the mechanical disruption of WPs 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 mechanical disruption of WPs. Important design features that will set the initial and boundary conditions for abstracting mechanical disruption of WPs include WP design and material selection, use of backfill, drift size and spacing, WP spacing, etc. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's or 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 4. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (e.g., hydrological and mechanical couplings) 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 WPs for potential inconsistency in the analysis and non-defensible predictions.

Technical Basis

This section describes the technical basis for the abstraction of geologic processes that have the ability to prematurely fail WPs (compared to their lifetimes if only corrosion was considered as a failure mechanism) by exerting mechanical forces on the WP. The processes described herein are seismically induced rockfall onto the WP, stress induced failure of the WPs from fault slip, and failure of WPs from dike intrusion in the proposed repository. Formation of a volcanic conduit coincident with WP location (i.e., volcanism) is not included here as WP contents disrupted by this mechanism are assumed to be ejected to the surface in current modeling (Jarzemba, 1997), subsequently removing them from the repository system. Volcanism is considered in Section 4.3.2.3. If future modeling efforts by DOE show that credit may be taken for only partial ejection of WPs, it may be necessary to include mechanical disruption of the nonejected fraction of the WP from volcanism here.

Geomechanical conditions at YM are characterized by a highly fractured rock mass with prominent vertical and subvertical faults and joints (U.S. Department of Energy, 1988; Brechtel et al., 1995). The impacts of seismicity on the repository include both the effects of low-frequency seismic events of large magnitude, and the cumulative effect of repeated episodes of integrated subissues seismic loading due to high-frequency, low-magnitude events on the stability of emplacement drifts (Ahola et al.,1995). The potential effects of drift instability (i.e., rock falls) on WP performance include: (i) breach of corrosion-weakened WPs, (ii) contribution to local acceleration of WP corrosion through the creation of localized depressions where liquid water may pool on the WP surface, and (iii) alterations to the near-field environment. The first two of these effects are expected to be more pronounced if emplacement drifts are not backfilled, and the last may arise if seismic activity results in the filling of drifts in the vicinity of WPs. In current NRC modeling, damage to the WP from a seismic event is estimated by calculating the maximum strain that the WP experiences due to rock falls; if the strain reaches a threshold value, the WP is considered to be failed.

The possibility of new (or currently unknown) or underappreciated faults at YM undergoing displacement within the repository footprint at some future time is also of interest for WP performance. Fully appreciated faults are assumed to have adequate standoff distances to avoid WP failure from fault displacement. Fault displacement that traverses the repository may intersect a number of WPs, thereby exposing them to stress, and possible failure. Current NRC models for this class of scenarios (Hsiung et al., 1992) use probabilistic techniques to determine the timing, location, displacement, orientation, length, and width of faults within a region that includes the repository footprint. Faults are considered as zones or bands of deformation with finite width. A number of critical assumptions and simplifications are inherent in the abstraction of the faulting geologic process. Conservative assumptions in NRC's abstracted model include: up to 50 percent of faulting will occur in new or underappreciated faults, the entire WP fails once the minimum threshold displacement is exceeded, fault zone widths are based on surface fault observations though widths are observed to decrease with depth, and emplacement drifts are randomly oriented. Nonconservative abstraction simplifications are: no link between corrosion, faulting, seismic, and volcanic activity; one faulting event per realization, irrespective of the recurrence interval; unaccounted for co-seismic slip on a new or an underappreciated fault generated by rupture on other existing faults; and additional faulting from underground excavation is not considered (U.S. Nuclear Regulatory Commission, 1998a). The effective recurrence (i.e., the frequency of faulting events within the boundary of the repository) is estimated using (i) the critical faulting region, (ii) the recurrence rate of faulting, and (iii) the percent of faults in the critical region that also intersect the repository. Mohanty and McCartin (1998) provides an estimate of 5.0×10^{-6} as the annual probability of a discrete fault displacement event occurring within the repository footprint on a new or underappreciated fault. Current efforts in this area include determining a proper threshold displacement for WP failure. Also, this threshold displacement may depend on whether or not the repository is backfilled. If it is determined that mechanical disruption of WPs is an important contributor to performance, then a more robust approach to mechanical failure will be developed that considers thresholds for ductile metallic materials deformation. In the case of a thermally embrittled material, a criterion based on fracture stress or a critical stress intensity may be developed (Cragnolino et al., 1996). In the current modeling approach, faults are generated randomly, independent of a link between intrabasin secondary faults, principal block-bounding faults, and basin-boundary faults. This approach is used because it is straightforward; however, anticipated revisions include modeling principal and secondary faulting.

TSPA-VA (U.S. Department of Energy, 1998b) evaluates the impacts of seismicity based on falling rocks causing failure of the WPs. The TSPA-VA model evaluates the size of the rock that is likely to fall based on the magnitude of the earthquake and the fracture spacing of the rock in the Exploratory Studies Facility. Rock fall can cause either the initiation of a crack, which can lead to enhanced corrosion rate due to localized corrosion, or a through crack, which corresponds to failure of the WP. The extent of damage that a falling rock causes to a WP is based on the size of the falling rock and the thickness of the outer overpack remaining. The size of the rock required to cause damage to the WP was determined as a function of outer wall thickness based on dynamic modeling of the rockfall and WPs assuming a spherical rock shape (CRWMS M&O, 1996a,b). TSPA-VA did not evaluate the impact of WP failure from fault displacement.

Formation of volcanic dikes in the repository footprint at future times may also need to be incorporated into the PA. Magma forming the dike, typically at temperatures of about 1,100°C, may result in the premature failure of WPs. Previous iterations of TSPAs used probabilistic methods to determine the number of WPs coincident with the sampled dike location (Wescott et al., 1995; Lin et al., 1993). The annual probability of an intrusive igneous event penetrating the proposed repository has been less extensively studied than the annual probability of penetration of the repository by an extrusive event. However, the probability of intrusive events has been estimated as 2-5 times that of extrusive events occurring within the repository footprint (Stablein, 1998b). An intrusive event is defined here as the penetration of the repository by an igneous dike or dike swarm. Intrusive events may occur with igneous activity that results in cone formation (either inside or outside the repository footprint). No waste is directly extruded into the accessible environment from the intrusive dike(s), but WPs may be disrupted/failed in place by the dike(s), the near-field environment in which the WPs exist may be adversely affected by the intrusive event or the hydrological regime in the vicinity may be affected.

TSPA-VA modeled the enhanced source term from volcanic events, which are igneous events in which magma penetrates the repository drifts, but the intrusion does not continue to the ground surface causing a direct release. Once the magma enters the drift, TSPA-VA models determine whether the enhanced corrosion, high temperature, or abrasion associated with the magma will cause failure of the WP and potential release of radionuclides. TSPA-VA models also determine the quantity of waste that will be dissolved by the magma that enters the WP and the dissolution rate of the waste that has interacted with the magma. After the waste is removed from the WP, the transport of the enhanced source to the critical group is performed concurrently with the base case release.

WP material instability may occur as a result of prolonged exposure to relatively high temperature. Thermal embrittlement of carbon and low alloy steels occur when impurities such as P originally present in the steel segregate to grain boundaries during thermal exposure, promoting reduction in fracture toughness as a consequence of long-term thermal aging at repository temperatures (above 200°C for several thousand years) anticipated at high areal mass loadings.

The necessary stresses for mechanical failure to occur may arise as a consequence of processes that cause material instability in combination with applied loads resulting from disruptive events or residual stress generated as a result of welding operations. The applied load may cause degradation of the mechanical properties of the material (i.e., fracture toughness) in combination with the effect of the residual and applied stress on the mechanical integrity of the WP. Recent DOE testing has revealed the possibility of stress corrosion cracking (SCC) of Alloy C-22 in oxidizing and concentrated chloride solutions. The possible susceptibility of Alloy C-22 to SCC may need to be considered in WP performance calculations.

Spent nuclear fuel (SNF) cladding can act as a barrier to the release of radionuclides from the WP. Several mechanisms have been identified for the failure of Zircaloy cladding, such as creep, SCC, localized corrosion, cladding oxidation, hydrogen embrittlement, delayed hydride cracking, damage due to rock fall, and unzipping due to volume expansion from fuel oxidation. However, the TSPA-VA abstraction is limited to failure during reactor operation, creep failure, mechanical disruption, and general and localized corrosion failure. Localized corrosion of fuel cladding may occur, depending on oxidizing conditions, chloride concentration and temperature; otherwise, the rate of uniform corrosion is extremely low as a result of the protective characteristic of the ZrO_2 passive film. Sufficiently high hoop stress generated as a result of fuel pellet expansion during irradiation may be present in the cladding to cause SCC under the same electrochemical conditions that promote localized corrosion. Hydrogen embrittlement could be an important failure mechanism as a result of dissolution of circumferential hydrides and reorientation in the radial direction if high temperatures (above 290-300°C) are reached and relatively high hoop stresses are present. Two key factors in calculating mechanical failure of cladding are the evaluation of the impact from rock fall and the criterion for mechanical failure. The mechanical failure calculation should include the consideration of existing defects in the cladding and propagation of cracks as a function of time. The importance of the evaluation of cladding failure is related to the release of radionuclides as a result of SNF dissolution and the surface area involved as a result of the contact with groundwater. NRC's current model does not account for mechanistic initiation and growth of a crack but allows specification of the fraction of the SNF surface area that would be exposed.

The impacts of seismic events on WPs will continue to be evaluated in the SDS IRSR. Therefore, Discussion Point TE22 will not be tracked as an Open Item in the TSPAI IRSR.

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

Pertinent KTI subissues:	CLST1, CLST2, CLST3, CLST4, CLST6, ENFE1, ENFE2, ENFE3, RDTME1, RDTME3, TEF1, TEF2, TEF3, USFIC2, USFIC3, USFIC4

RN release rates depend on the quantity and chemistry of water contacting the WPs and subsequently the waste forms. The quantity and chemistry of water contacting waste forms is a major factor in determining RN migration to the accessible environment. The quantity and chemistry of water contacting the WP is 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, etc.), then the only corrosion failure modes that would be important in PAs (PAs) would be dry air oxidation and humid air corrosion. Also for this case, groundwater release would be largely eliminated, even if 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 accessible environment. Finally, the availability of water after the repository environment has cooled also affects microbially induced corrosion.

The chemistry of water contacting the waste plays an important role in determining the source term for exposure from the groundwater pathway. For example, release rates and solubilities of RNs in water depend on pH, carbonate, and oxygen contents (e.g., 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 waste alteration rates and aqueous speciation.

Acceptance Criteria with Review Methods

DOE's approach to 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 system's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory, and/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 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 definition of parameter values and conceptual models is 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: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the quantity and chemistry of water contacting WPs and waste forms abstraction, such as the pH, chloride concentration, and amount of water flowing in and out of the breached WP, are technically defensible and reasonably account for uncertainties and variabilities.

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 YM region (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 correlations used by DOE.

Criterion T3: 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: Output of quantity and chemistry of water contacting WPs and waste forms abstraction are justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of quantity and chemistry of water contacting WPs and waste forms abstraction reasonably reproduces or bounds 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 or against field and laboratory data and natural analogs.

Criterion T5: 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, 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 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, etc. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's or 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 in the 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 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 (WP corrosion).

- 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 (radionuclide release and solubility limits).

These relationships are illustrated in figure 5. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C) 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.

Technical Basis

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. Current models for predicting WP lifetimes have regimes for failure based on the RH of the near-field environment as described in Section 4.3.1.1.1. For several monolayers of water to sorb to the surface of the WP, the RH of the near-field environment contacting 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 as discussed in Section 4.3.1.1.1. 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 release of the RNs is dissolution-rate 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 rate 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. 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, which may be diverted around the repository drifts; 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. As discussed previously in this section and in Section 4.3.1.1.1, the pH and chloride concentration of water contacting waste are important for determining the rate and type of corrosion (e.g., uniform or pitting corrosion). Also, parameters such as pH and oxygen potential 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 chemistry are characterized as providing one of the major sources of uncertainty for predicting RN solubilities. Distribution coefficients for RNs speciation between the aqueous phase and for host rock minerals of the repository block and other parts of the repository system also depend on pH and other water chemical characteristics (Turner, 1993, 1995).

The impacts on performance of changes of the water chemistry due to the repository liner and interactions between the engineered barrier system and the natural system will be evaluated in the ENFE IRSR. Therefore, discussion points TE20 and TE21 will not be tracked as Open Items in the TSPAI IRSR.

4.3.1.1.4 Radionuclide Release Rates and Solubility Limits

Pertinent KTI subissues: CLST3, CLST4, CLST6, ENFE3, RDTME1, RDTME3

The release of RNs from the WP and engineered barriers depends on the concentration of RNs contained in the water of breached WPs. RN release from the SNF into water contacting waste forms is, in turn, dependent on either the solubility of the individual RN or release rates from the waste matrix. RN solubilities represent the upper limit for individual RN concentrations in WP water and depend on chemical conditions in the near-field environment.

A typical approach to analyze the radionuclide release rates and solubility limits is as follows. The dissolution rate 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. If releases of RNs to WP water would dictate concentrations greater than the solubility limits, then RN concentrations are limited by RN solubilities. In this manner, both RN solubilities and the waste matrix release rate contribute to estimates of repository performance.

Acceptance Criteria with Review Methods

DOE's approach in abstracting radionuclide release rates and solubility limits 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 system's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory, or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing radionuclide 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. 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions and/or bounding assumptions used in the radionuclide release rates and solubility limits abstraction, such as the pH, temperature, 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 radionuclide release rates and solubility limits input/data in the performance calculations. Staff should ascertain that the input values used in estimating the radionuclide release rates and solubility limits in TSPA are reasonable based on data from the YM region (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 correlations between the input values are 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: 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 radionuclide 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 radionuclide release rates and solubility limits abstraction. Staff should run the 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: Radionuclide release rates and solubility limits abstraction output are justified through comparison to outputs of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of radionuclide 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 radionuclide release rates and solubility limits 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: Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the radionuclide 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, 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 radionuclide release rates and solubility limits. Important design features that will set the initial and boundary conditions for abstracting the radionuclide 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), etc. If DOE decides not to take credit for certain design features that have been demonstrated in NRC's or 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 as follows:

- 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 unsaturated zone).

These relationships and other computational input/output are illustrated in figure 6. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C) 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 radionuclide release rates and solubility limits for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

Radionuclide release from the EBS will depend on several processes related to the dissolution of the waste forms, the contact of the waste forms with liquid water, transport in liquid water, and the solubility limits of radionuclides and other components of the decomposed fuel. The waste form will begin to decompose once it comes into contact with air, water vapor, or liquid water, but transport away from the waste form generally requires a liquid water pathway.

Radionuclides would be released from the waste form to the water within the WP at a rate controlled by the (i) rate of waste form decomposition (i.e., congruent dissolution), (ii) rate of dissolution of secondary mineral into which the RNs have become incorporated (e.g., schoepite), or (3) solubilities of the RNs themselves. The product of flow rate through the WP and concentration of radionuclides in the WP waters ultimately controls the release rate to the geosphere (although molecular diffusion might be relatively important in a situation where flow rates are small). Solubilities of radionuclide elements might limit concentrations in WP water if release of RNs from the waste form would result in concentrations higher than the solubility limits (although colloid formation is also a possibility).

Current NRC PA models (Mohanty et al., 1997) use the "bath tub" model where a volume of water is stored within a failed WP.[18] Advective releases from the WP are estimated, which requires estimation of time-dependent RN concentrations in the water contained within the WP. Diffusive releases are not included in the model because previous modeling efforts demonstrated that diffusive releases were several orders of magnitude smaller than advective releases. 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. To estimate time dependent RN concentrations inside a breached WP, alternative expressions for the dissolution rate of SNF by the contacting WP waters (e.g., Gray and Wilson, 1995) are used and a mass balance is performed for the radionuclide concentration in the WP water. The total release rate of RNs to WP waters is based on the dissolution rate of the fuel, with RNs assumed to be released in the same relative quantities as they are found in the fuel matrix. Rate equations are used to estimate RN concentrations as a function of time in WP waters, with the upper limit being the solubilities of the RNs.

The effect of the invert will be taken into consideration by assuming that the radionuclides exiting the WP will go through the invert before leaving the EBS. The physical properties of the invert may have been altered by the cemetitious materials. The invert could sorb the radionuclides and decrease the release rate from the EBS depending on whether it is matrix or fracture flow through the invert.

Models of radionuclide release rates and solubility in DOE's TSPA-VA (U.S. Department of Energy, 1998b) are similar to NRC assessments. However, the DOE model does not account for reduced RN release rates in portions of the waste not submerged in liquid water and, in this respect, DOE's model is more conservative. Justification for this conservatism in DOE's model is that a thin water film may be present over the entire WP contents thus enabling RN releases from the non-submerged components of the waste. On the other hand, DOE's models do take credit for the protection of the fuel due to the long-term integrity of the fuel cladding, which NRC models do not. Cladding shields the waste form from being contacted by water, and therefore lowers releases of RNs. DOE will have to provide a strong technical basis to take credit for the extremely long cladding lifetimes found in TSPA-VA.

RN solubilities and waste matrix reaction rates depend strongly on the near-field environment (e.g., temperature and chemistry of water contacting waste). The chemistry of water contacting the waste affects the oxidation state in which RNs exist, aqueous speciation, and the solubility and release rates of the RNs. In an oxidizing environment such as the YM repository setting, UO_2 in SNF will ultimately convert to U_3O_8 or UO_3, which have significantly greater solubilities than UO_2 in a reducing environment. Similarly, Tc, Np, U, and Pu are generally considered to be very soluble under oxidizing conditions but relatively insoluble under reducing conditions (Kerrisk, 1984). Solubility limits are also sensitive to the chemistry of the near-field environment. For example, the models for dissolution rate of SNF (and hence RNs contained in the fuel) in Mohanty, et al. (1997) contain equations with terms dependent upon pH, carbonate concentration, temperature, etc.

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[18] A "flow through" model, in which water will not accumulate as in the "bath tub" model, has been incorporated in the NRC's TPA code and mimics DOE's model for mass transfer from the SNF to the contacting water.

Secondary minerals could precipitate on or near the SNF as a result of heterogeneous reactions between uranyl species and the near-field environment. The secondary minerals may mitigate radionuclide release by partially blocking the SNF surface from directly coming in contact with the water and they may incorporate RNs into their structures. Periodic spallation of the alteration products could occur, exposing fresh surfaces of SNF for further dissolution. 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 secondary mineral deposits (Buck et al.,1998; Bates,1998b).

In spite of small volumetric inventory of HLW glass, its contribution to performance could be significant if the radionuclide release rate is higher than the SNF (e.g., radionuclide release in colloidal form or pulse release of radionuclides from the hydrated surface layer). Formation of secondary minerals could affect the long-term release rate from glass. The glass alteration model should reflect data from natural analogs for long-term behavior. Secondary phases on the surface of the glass waste could be released as colloids. DOE's long-term dissolution model for glass waste forms should consider the dominant colloid formation processes under anticipated repository conditions. Microbes can also change the solubilities of radionuclides by the increased production of organic acids.

In summary, radionuclide release from the WP might be controlled by solubility limits of radionuclide elements, or of the products of waste form alteration. Unless colloids form, RN solubilities represent the upper limit for RN concentrations in the WP water, and depend on parameters describing the near-field environment.

The basis for the solubility limits for radionuclides will continue to be evaluated in the CLST and ENFE IRSRs. Therefore discussion point TE15 will not be tracked as an Open Item in the TSPAI IRSR.

TSPA-VA analyzed the impact of colloids on performance and concluded that it was minor. Colloid transport of radionuclides will continue to be evaluated in the CLST and RT IRSRs, and discussion point TE11 will not be tracked as an Open Item in the TSPAI IRSR.

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, AC and RMs 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 AC and RMs for the three key elements under the UZ flow and transport abstraction, as identified in figure 2 (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 UZ's contribution to 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

Pertinent KTI subissues: ENFE1, IA2, RDTME1, RDTME3, SDS1, SDS2, SDS3, SDS4, TEF1, TEF2, TEF3, USFIC1, USFIC2, USFIC3, USFIC4

Most PAs assume that percolation to the repository horizon is primarily vertical and that flow is considered to be uniform over large spatial dimensions (typically averaged over 0.1 to 1 square kilometer). Various hypotheses have been advanced as to how shallow infiltration and deep percolation are related. The contrast in matrix properties between the nonwelded Paintbrush Tuff (PTn) layer and the underlying welded units has been hypothesized to cause systematic lateral diversion (Kessler and McGuire, 1996), thereby reducing deep percolation fluxes relative to shallow infiltration. Given that there is no indication of perching or lateral flow within or above the PTn at the scale of the shallow infiltration and site-scale flow model (TRW Environmental Systems, Inc., 1998), it appears reasonable to assume that, on a mean annual basis, percolation is equal to shallow infiltration at the repository horizon. The possibility of nonvertical flow under the PTn layer from the west flank of YM in Solitario Canyon has not been considered in YM PAs to date. Flow from the repository to the water table, which is important for transport modeling of RNs, should not be assumed to be primarily vertical. The presence of perched water and stratified geochemical signatures suggest that 2D or 3D models should be used.

Matrix properties of the nonwelded layers underlying the repository at YM have the potential to retard movement of many RNs owing to their highly adsorptive properties. The nonwelded layers are comprised of vitric, devitrified, and zeolitically altered rocks. The low-permeability zeolitic units are known to have strong sorption capabilities for many of the radionuclides (Triay et al., 1996). The benefit derived from the geochemical properties of the matrix of zeolitic units is uncertain owing to flow conditions that may limit the contact of RNs with the zeolites. For example, the low matrix permeability of the zeolitic units may lead to lateral diversion around a low-permeability unit (Robinson et al., 1997) or increase the potential for fracture flow within the low-permeability unit, or both, resulting in limited contact of RNs with the zeolites. The devitrified and vitric rock layers, however, may be more important for retarding movement of RNs, since their sorption capabilities are strong, though not as strong as for the zeolites; and the movement of water is likely through the matrix of these units. The matrix permeabilities of the nonwelded vitric and devitrified layers are larger than the current estimates of percolation flux; hence flow in the matrix would dominate over flow in the fractures. The effect of lateral diversion on the spatial distribution of flow and the potential for fracture flow have not been considered in NRC PAs to date.

The assumption of steady-state unsaturated flow, though widely used and possibly justified, is not consistent with geochemical data such as the bomb pulse ^{36}Cl data. Temporal patterns (episodic flow) as compared with steady-state flows may lead to larger seepage rates into drifts and faster movement of RNs to the water table. Active fracture models that would support the geochemical evidence for fast pathways have been incorporated into YM PAs as alternative cases.

Acceptance Criteria with 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 geosphere's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory and/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. 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or 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 YM region (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 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: 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 geosphere produced by DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Spatial and temporal distribution of flow abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or 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: 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, etc. 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 :

- 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 7. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C-M) 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.

Technical Basis

This section discusses: (i) changes in net infiltration and deep percolation due to climatic change, (ii) spatial distribution of infiltration, (iii) lateral movement of percolation fluxes, and (iv) focused deep-percolation pathways. Deep percolation fluxes, resulting from infiltration of meteoric waters, have been shown to be of importance to performance of the proposed repository (Wescott et al., 1995; TRW Environmental Safety Systems, Inc., 1995; Kessler and McGuire, 1996; Department of Energy, 1998b). Infiltration and deep percolation are important because they: (i) determine the quantity of water flowing past the WP, and (ii) affect the flux of dissolved RNs moving through the unsaturated zone.

The percolation rate at the repository horizon is generally assumed to be 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 may also be focused by heterogeneities such as fracture and fault zones (Nuclear Regulatory Commission, 1998b). Although shallow infiltration is not spatially or temporally uniform, the wetting pulses attenuate and spread to become more spatially and temporally uniform such that 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 Electric Power Research Institute (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, imply that focused shallow infiltration, fracture pathways through the 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.

A 3D or vertically-oriented 2D model may be necessary below the repository (Nuclear Regulatory Commission, 1998b) to account for lateral flow diversion in the perched water zone below the repository. The geochemical data in and around the perched water zone suggest that at least a portion of the water is young. The perching itself suggests that lateral movement, and possible bypassing of highly RN sorbing zeolitic layers, occurs; although the extent of the perched water bodies are unknown and the condition of the bodies in terms of transient or steady state is not clear. Likely pathways for RNs include vertically through nonwelded vitric and devitrified tuffs or laterally above zeolitically altered tuffs and then through fractures bypassing the zeolitic tuff matrix. The current NRC model assumes that 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-yr 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 1-D simulations, incorporating the influences of soil depth, elevation, and solar load.

Releases of RNs are distributed to the subareas in the NRC PA with transport calculations done using NEFTRAN II. Lateral diversion and matrix diffusion are not incorporated, but retardation in the matrix is included. Flow in any particular layer is either through the matrix or the fractures depending on a comparison of the percolation rate and the material's matrix saturated hydraulic conductivity.

DOE's TSPA-VA (Department of Energy, 1998b) uses a spatially heterogeneous shallow infiltration map (Flint et al., 1996) as a boundary condition to a site-scale UZ flow model (Bodvarsson et al., 1997) to determine percolation at the repository horizon. Subarea averaging of the percolation is used as input to the drift-scale seepage model. For the shallow infiltration, DOE links the periodicity of MAI to glacial cycles through postulated mean annual precipitation changes. The recent DOE model for shallow infiltration incorporates the effects due to runoff/runon and variations in vegetation and temperature due to climate change.

Flow fields from the 3D site-scale, dual-permeability UZ model are directly incorporated into DOE's PA for transport modeling of RNs using a cell-based particle-tracking algorithm. Releases from canisters are spread over the appropriate repository subarea. The linkage to the SZ transport is through average mass flux rates to the SZ subareas; these do not directly project from the repository subareas. The cell-based particle tracker (Robinson et al., 1997) accounts for dispersion, matrix diffusion, and retardation of RNs in the matrix.

NRC staff does not currently have an issue with the estimates of deep percolation or the assumption of steady-state conditions for unsaturated zone flow in the analyses in TSPA-VA. Therefore, discussion points TE12 and TE13 are not considered open issues at this time. The USFIC KTI will continue to evaluate these issues as new data and modeling results become available in the future.

Discussion point TE6 addresses NRC staff concerns that DOE modeling inappropriately spreads radionuclide releases from small numbers of WP failures over entire subareas in the transition between release from the EBS and UZ transport calculations and the transition between UZ transport calculations and SZ transport calculations. This issue will be tracked by the USFIC KTI; therefore, this discussion point will not be tracked as an Open Item in the TSPAI IRSR.

4.3.2.1.2 Distribution of Mass Flux between Fracture and Matrix

Pertinent KTI subissues:	ENFE1, ENFE4, RDTME1, RDTME3, SDS1, SDS3, TEF1, TEF2, TEF3, USFIC3, USFIC4

The proportion of water flowing within the rock matrix is dependent on total percolation flux. If the capacity of the rock matrix to conduct water is larger than the total infiltration flux, 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 unsaturated zone 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. Heterogeneity in matrix properties at the drift scale may enable flow to locally exceed matrix capacity even when flow is predominantly through the matrix, thereby making more likely the possibility of liquid water entering the drifts.

Transport of RNs is strongly affected by the proportion of flow within the rock matrix. Subsurface flow that is predominantly through matrix ensures relatively slow movement of water. In addition, the mineral surface area available for cation sorption is much greater within the rock matrix than within fractures; thus cationic RNs are likely to be highly retarded when transported through rock matrix. In contrast, subsurface flow within well-interconnected fractures is more likely to result in (i) liquid flux into drifts, (ii) rapid pathways through the UZ, and (iii) minimal sorption onto rock constituents.

Acceptance Criteria with Review Methods

DOE's approach in abstracting distribution of mass flux between fracture and matrix 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 geosphere's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the distribution of mass flux between fracture and matrix in the 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 definition of parameter values and conceptual models is 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/or uncertainty analyses to test for 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: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the distribution of mass flux between fracture and matrix in the abstraction, such as hydrologic properties, stratigraphy, and infiltration rate, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated distribution of mass flux between fracture and matrix input/data in the performance calculations. Staff should ascertain that the input values used in the distribution of mass flux between fracture and matrix calculations in TSPA are reasonable based on data from the YM region (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, the 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 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: 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 distribution of mass flux between fracture and matrix 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: Distribution of mass flux between fracture and matrix abstraction output is justified through comparison to output of detailed flow process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain that DOE demonstrated that the output of distribution of mass flux between fracture and matrix 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 distribution of mass flux between fracture and matrix 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: Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the distribution of mass flux between fracture and matrix 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 distribution of mass flux between fracture and matrix. Important design features that will set the initial and boundary conditions for calculating the distribution of mass flux between fracture and matrix include thermal loading strategy, drift spacing, drift design, etc. 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 8. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C) 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 distribution of mass flux between fracture and matrix for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

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 (i) water flowing in rock matrix is far less likely to drip onto a WP and (ii) radionuclide transport through rock matrix is very slow and subject to significant sorption on mineral surfaces.

The current NRC conceptualization for unsaturated zone flow and RN transport assumes that gravity drainage occurs in the rock below the PTn stratigraphic layer, with flow preferentially partitioned into the matrix up to a limiting saturation. Above the limiting saturation, an increasing proportion of flow is conducted by fractures. Baca and Jarzemba (1997) note that, in the repository horizon, significant fracture flow is expected when matrix saturation exceeds 95 percent; they further note that an infiltration rate of 2 mm/yr may cause 26 to 73 percent of the total flow to occur in fractures. When calculating RN release, the current NRC model assumes that matrix heterogeneity and pre-emplacement percolation fluxes determine the fraction of drifts with liquid entering the drift. When calculating temporal variation of RN transport in the UZ, the current NRC model assumes that transport within each stratigraphic unit is either entirely within the matrix (if the subarea-averaged deep percolation flux is less than the saturated hydraulic conductivity of the rock matrix) or entirely within the fractures (if the subarea-averaged deep percolation flux exceeds the saturated hydraulic conductivity of the rock matrix). Thus, it is conservatively assumed that RNs completely bypass the rock matrix in any formation within which fracture flow occurs.

In the TSPA-VA, DOE used a dual-permeability conceptualization in which downward flow of infiltrating water in both fractures and matrix is considered. TSPA predictions of repository performance have been shown to be sensitive to fracture-matrix (F-M) flux distributions (also referred to as "flow fields"). It is, therefore, 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 DOE's TSPA-VA base case and sensitivity analyses (U.S. Department of Energy, 1998b, Volume 3) do not adequately bound this uncertainty — the result being that the expected benefits of water flowing through rock matrix may be overly optimistic. This assertion is discussed further in the following paragraphs.

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 that have been collected in the Exploratory Studies Facility (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 terms of the predicted fraction of water flowing in rock matrix.

Although considerably 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 may be greater than those estimated from rock-core samples. Despite the uncertainty in the parameter values assigned to rock matrix, the base case UZ flow fields that are used in TSPA-VA analyses to account for uncertainty appear to all use the same set of rock matrix hydraulic properties (CRWMS M&O, 1998, Tables 2-21 through 2-23).

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 a 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 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 to in the UZ can be significantly delayed en route to the water table due to flow in 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 License Application Plan and Costs (U.S. Department of Energy, 1998b, Volume 4) may result in resolution of this concern. For example, DOE is conducting analyses to determine the effects of heterogeneity on the distribution of mass flux between fracture and matrix 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 (December 14–16, 1998, Albuquerque, NM), DOE researchers addressed the limitations of the F-M interaction factor and proposed the following:

- 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, to improve the conceptual models for fracture/matrix interaction and perched water;
- validation of models through continued analysis of site data and data from analog sites;
- evaluation of the appropriate range of parameters given the nonunique flow fields obtained from inverse model calibration methods.

The unsaturated zone flow model used in TSPA-VA is based on a three-dimensional flow model in Bodvarrson et al. (1996). Review of this model in association with the review of TSPA-VA confirmed that the issues raised in Open Item #OSC0000001347C102 are not relevant to this model. Therefore, this open item is considered resolved.

4.3.2.1.3 Retardation in the Unsaturated Zone

Pertinent KTI subissues:	ENFE4, RDTME1, RDTME3, RT1, RT2, RT3, USFIC3, USFIC4, USFIC6

Groundwater transporting RNs in the UZ may be subject to geochemical processes that can alter its RN concentration. One of the key geochemical processes that may lower RN concentrations—and thus enhance repository performance—is retardation. Retardation occurs by both chemical and physical processes (Fetter, 1993). Mathematically, the retardation factor (R_d) is the factor by which the transport velocity of a given component is reduced relative to the groundwater velocity. Retardation is constituted by the following processes: adsorption, ion exchange, and filtration of particulates. Sorption (a term encompassing the first two processes in the preceding list) onto mineral surfaces is the most widely recognized process for retardation. The most important factors common to all RNs in establishing R_ds for PA are the physical and chemical characteristics of the groundwater (e.g., pH, temperature, availability of complex-forming compounds) and of the substrate (e.g., mineralogy, surface area, surface charge). RN concentration changes resulting from these physical and chemical processes will be reflected in the rate of migration of the RNs through the UZ. This will ultimately affect estimated exposures to the receptor group that is assumed to consume the water. Therefore, retardation in the UZ has a potentially favorable influence on repository performance in that it results in reduction of RN concentrations in groundwater and potentially limits the distance RNs can migrate from the repository.

Currently, due to lack of data, neither DOE's nor NRC's PAs (Department of Energy, 1998b; Nuclear Regulatory Commission, 1998) take credit for retardation in fractures. One important difference between NRC's and DOE's UZ RN-transport models is that DOE assumes that chemical and thermal equilibrium exists between water flowing in fractures and the nearby rock matrix. This assumption leads to a retardation process known as matrix diffusion, where RNs, can diffuse from fractures into water contained in the rock matrix and sorbed onto rock constituents. Matrix diffusion and the accompanying sorption of RNs onto the rock matrix can lead to significant reduction in RN concentration at the receptor location.

Acceptance Criteria with Review Methods

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

Criterion T1: Sufficient data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the retardation 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the retardation in the UZ abstraction, such as the sorption on fracture surfaces, and K_d for matrix, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated retardation in fractures in the UZ input/data in the performance calculations. Staff should ascertain that the input values used in the retardation in fracture in the UZ calculations in TSPA are reasonable based on data from the YM region, 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 radionuclides traveling in fractures in the unsaturated zone 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: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the retardation 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 retardation 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 DOE's approach reflects or bounds the range of uncertainties owing to alternative modeling approaches.

Criterion T4: Retardation in the UZ abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE has demonstrated that the output of retardation 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 retardation 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: Important physical phenomena and couplings and consistent and appropriate assumptions are incorporated into the consideration of retardation 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 retardation 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 of fractures (radionuclide 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 9. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C) 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 retardation in the UZ for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

There remains uncertainty regarding the distribution of unsaturated zone 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 unsaturated zone flow is concentrated in fractures, then highly sorptive zeolite minerals may not be effective in retarding RN transport if they are sparse in fracture assemblages. Groundwater moving through fractures may be primarily interacting with relatively nonsorptive, comparatively low-surface-area minerals such as quartz and calcite.
- Typical application of the retardation factor in transport models assumes the sorption reactions that underlie K_d are linear, reversible, and fast in comparison

to the transport rate of the radionuclide within the fracture. 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 RN transport by removing solutes from fracture water and sequestering them in more sorptive matrix minerals. However, there are indications from YM region 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.

4.3.2.2 Saturated Zone Flow and Transport

In this section, the technical AC and RMs for the two key elements under the SZ flow and transport abstraction, as identified in figure 2 (i.e., flow rates in water-production zones and retardation in water-production zones and alluvium) are discussed. 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 SZ's contribution to 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 Rates in Water Production Zones

Pertinent KTI subissues: SDS3, USFIC4, USFIC5

To estimate the dose to a receptor group, the mean RN concentration in the pumping well must be known. RN concentrations in the well are affected by longitudinal and transverse dispersive processes during transport, the geometry of the plume near the well, and the capture zone of the pumping well. One approach for estimating the average RN concentration in the well is to use a borehole dilution factor, which converts resident RN concentrations in the aquifer into RN concentrations at the well head. Such dilution factors can be computed by using groundwater flow models (Fedors and Wittmeyer, 1998).

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. It is currently assumed that longitudinal and transverse macro-dispersion will be relatively small within tuff aquifer production zones. However, because basin-scale groundwater flow patterns in the tuff aquifer are likely to be complexly controlled by high-permeability features such as faults and zones with interconnected fractures, 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 and mostly horizontal production zones (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, hydraulic conductivity, and the magnitude of the natural and imposed hydraulic gradients. Near a pumping well, flow in the production zones also will be affected by the amount and distribution of pumping, the well diameter, the length of the screened interval(s), degree of aquifer penetration, and the radius of influence of the well. Because of the predominantly horizontal groundwater flow, the volumetric flow in the production zones will govern the availability of groundwater for RN transport. Properties of the production zones, such as thickness and effective porosity, will also affect the sorption and dispersion of RNs during transport.

Acceptance Criteria with Review Methods

DOE's approach in abstracting flow rates in water-production zones 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 geosphere's contribution to total system performance.

Criterion T1: Sufficient hydrogeologic data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the flow rates in water-production zones 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the flow rates in the water-production zones 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 variabilities.

Review Method: This acceptance criteria will focus on the integrated flow rates in water-production zones input/data in the performance calculations. Staff should ascertain that the input values used in the flow rates in water-production zones calculations in TSPA are reasonable based on data from the YM region (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's input values by comparison to the corresponding input values in staff's 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: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the flow rates in water-production zones.

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

Criterion T4: Flow rates in water-production zones abstraction output are justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of flow rates in the water-production zones 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 rates in the water-production zones 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: Important site (geologic and hydraulic) features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the flow rates in the water-production zones 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 flow rates in water-production zones. If DOE decides not to take credit for certain site features that have been demonstrated in NRC's or 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 rates in water-production zones. 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).
- Amount of water flowing in production zones affects the importance of retardation in SZ. Retardation in SZ will slow down RN transport to receptor groups (retardation in water production zones and alluvium).

These relationships and other computational input are illustrated in figure 10. 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 DOE's approach in flow rates in water-production zones for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

Total-system Performance Assessments 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 radionuclide releases from the repository will occur along the saturated flow path. RN concentrations decrease due to dispersion transverse to the flow path. Previously published DOE TSPA (TRW Environmental Safety Systems, Inc., 1995) evaluated dilution in the saturated zone that relied on largely unsupported values for vertical mixing (i.e., mixing depths up to 2.9 km). Other analyses (Baca et al., 1996; Kessler and McGuire, 1996) that made other—less optimistic—assumptions affecting vertical mixing resulted in correspondingly less dilution. Estimates of RN concentrations need to be consistent with their use in estimating 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). RN concentrations would 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 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 pumping well.

Analyses performed in the TSPA-VA (U.S. Department of Energy, 1998b) use a dilution factor along the SZ flow path that is orders of magnitude smaller than the one previously used. The dilution factor distribution, developed by the SZEE panel members, was used in TSPA-VA with a range from 1 to 100 and a median value of 10. 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 with a dilution factor, which is applied to resident aquifer RN concentrations at the receptor location. This reduction in the dilution factor addresses the concern raised in discussion point TE9, which is not considered an open issue at this time. The modeling of flow and transport of radionuclides in the saturated zone and the impacts of dilution of radionuclides in the saturated zone will continue to be evaluated in the USFIC and RT IRSR; and, therefore, discussion point TE10 will not be tracked as an Open Item in the TSPAI IRSR.

Information gleaned from the recent technical exchanges with DOE indicate that a new SZFT model will be used for performing TSPA-LA analyses. The fully three-dimensional groundwater flow model will be coupled with a transport model based on the random walk particle tracking method. This approach provides an improvement over streamtube flow and transport model.

4.3.2.2.2 Retardation in Water Production Zones and Alluvium

Pertinent KTI subissues: IA2, RT1, RT2, RT3, USFIC6

RN concentration changes resulting from physical and chemical processes are reflected in the rate of delivery of the RNs to and within aquifer production zones. This ultimately affects the exposure to the receptor group that consumes the water. Therefore, retardation in aquifer production zones and alluvium has a potentially significant influence on repository performance because it may result in reduction of RN concentrations in groundwater at the receptor group location. Due to lack of data, the most conservative approach to this ISI would be to assume that no retardation accompanies SZ flow. This assumption would avoid the necessity of additional data collection to resolve the uncertainties posed in this section and Section 4.3.2.1.3. For most RNs, such an assumption may be overly conservative and would yield unrealistic results.

In DOE's TSPA-VA report (Department of Energy, 1998b), the authors differentiated between sorption properties (e.g., K_ds) assigned to streamtubes in volcanic tuff and portions of the streamtube in the alluvium. In general, the alluvium is modeled as providing more retardation than the volcanic tuff because transport through the alluvium is primarily through the rock matrix. The current version of the TPA code allows different properties for distinct portions of the streamtube, but the numerical values of these properties for alluvium are yet to be finalized.

Acceptance Criteria with Review Methods

DOE's approach in abstracting retardation in water-production zones 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 geosphere's contribution to total system performance.

Criterion T1: Sufficient data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the retardation in the water-production zones and alluvium 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the retardation in water-production zones and alluvium abstraction, such as distribution coefficients for different radionuclides on mineral assemblages in the fractured tuff and alluvial aquifers and the range of effective porosities in both the fractured tuff and alluvial aquifers, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated retardation in water-production zones and alluvium input/data in the performance calculations. Staff should ascertain that the input values used in the retardation in water-production zones and alluvium calculations in TSPA are reasonable based on data from the YM region (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 (geologic features and hydrologic properties) and the assumptions of the conceptual models for the YM site (e.g., transport velocities should vary in accordance with hydrologic unit properties and gradient). 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: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the retardation in water-production zones and alluvium abstraction.

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

Criterion T4: Retardation in water-production zones and alluvium abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE has demonstrated that the output of the retardation in water-production zones and alluvium 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 retardation in water-production zones and alluvium 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: Important site (geologic and hydrologic) features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the retardation in water-production zones and alluvium 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 retardation in production zones and alluvium. If DOE decides not to take credit for certain site features or processes that have been demonstrated in NRC's or 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:

- Amount of water flowing in water-production zones affects the importance of retardation in SZ. Retardation in SZ will slow down transport of RNs to receptor groups (flow rates in water-production zones).

The above relationships are illustrated in figure 11. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the UZ to SZ RN transport coupling. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in retardation in water-production zones and alluvium for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

This section describes the technical basis for the abstraction of retardation in production zones and alluvium to repository PAs. Specifically, the ability of different minerals to limit migration velocities of RNs through sorption is discussed.

After groundwater reaches the water table below the repository, migration of RNs to aquifer production zones will be subject to geochemical processes that can alter RN concentrations and rate of movement. As discussed in Section 4.3.2.1.3, one of the key geochemical processes that may lower RN concentrations—and thus enhance repository performance—is retardation at the leading edge of the plume. Section 4.3.2.1.3 also outlines the specific types of retardation mechanisms and explains how retardation is sensitive to the chemical and physical characteristics of the groundwater and host rock. Many of the same subjects that were abstracted in modeling retardation in the UZ are considered in modeling retardation in the SZ. These subjects are fracture retardation, retardation in the rock matrix, kinetics, particulates/colloids, and variability in the retardation factor. Discussed here are the first two items; Section 4.3.2.1.3 discusses the others. Also included here are subjects specific to possible saturated flow in the alluvium.

As in the case of the UZ, it is possible that fracture flow is an important component of groundwater migration in the Tertiary volcanic aquifer production zones beneath and down-gradient from YM. This flow may affect the capacity of the groundwater system to retard RN transport if fracture-lining minerals have lower sorptive capacities than matrix minerals which would be the case, for example, if quartz and calcite are dominant fracture phases. This ISI is therefore linked to those concerned with the distribution of advective flow in production zones among fracture and matrix pathways.

If fractures do account for a major portion of production zone groundwater flow, then one potential retardation mechanism (in addition to sorption and particulate/colloid filtration) would be matrix diffusion, wherein solutes are diffused into matrix pore waters as a result of concentration gradients with respect to fracture waters. Such gradients could be present if the matrix minerals were more sorptive than the fracture minerals. This mechanism requires chemical interaction between the two waters, but there is some evidence that such interaction is reduced in much of the SZ beneath YM. For example, Murphy (1995) calculates that waters from Tertiary volcanic aquifer production zones are undersaturated with respect to calcite, yet this mineral is widespread in the host matrix tuffs. Calcite-water reaction kinetics are rapid enough that water from production zones should be saturated in calcite if there is significant chemical interaction between matrix and fracture waters. The retardation effectiveness of matrix diffusion therefore requires full evaluation if it is to be included in transport models. However, there is currently insufficient geochemical data for rock matrix pore water to determine the efficacy of matrix diffusion in the saturated zone (Winterle, 1998).

It has become apparent that flow in the alluvium may have a significant effect on groundwater evolution in the YM region. Furthermore, it is possible that flow in the alluvium may have a favorable influence on the potential for RN retardation. For example, the alluvium more closely represents a porous medium than fractured tuffs do, and probably has a much higher effective porosity. In addition, alluvium may tend to contain sorptive minerals such as iron oxides, oxyhydroxides, and clays. However, previous efforts to characterize groundwater host rocks at YM have tended to overlook alluvium; so few data are available on the hydraulic and mineralogic properties central to the evaluation of alluvium transport characteristics. This lack of data is compounded by the likelihood that these characteristics vary considerably geographically as a result of variations in the source rocks for the alluvium. Recently, Nye County initiated a drilling program in the alluvium for eventual use for groundwater monitoring. This drilling program has resulted in an increase in the level of knowledge of the alluvium characteristics. However, significant gaps remain in the saturated zone where no characterization has been performed. Therefore, geographical variation in alluvium properties may not be fully captured based on this drilling program alone.

DOE's approach to transport and retardation in the alluvium and the data supporting this approach will continue to be evaluated in the USFIC and RT IRSRs. Discussion Point TE7, therefore, will not be tracked as an Open Item in the TSPAI IRSR. Additionally, The impacts of matrix diffusion on performance in both the unsaturated and saturated zones will continue to be evaluated in the USFIC and RT IRSRs. Discussion Point TE8, therefore, will not be tracked as an Open Item in the TSPAI IRSR.

4.3.2.2.3 Direct Release and Transport

In this section, the technical AC and RMs for the two key elements under direct release and transport, as identified in figure 2 (i.e., volcanic disruption of WPs and airborne transport of radionuclides), are discussed. 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.

4.3.2.2.4 Volcanic Disruption of Waste Packages

Pertinent KTI subissues: IA1, IA2, SDS1, SDS4

A future volcanic eruption at the proposed YM repository site probably would involve dense, basaltic magma at high temperatures impacting WPs at high velocities for days to weeks. These adverse thermal, chemical, and mechanical effects of volcanic activity likely would result in the mechanical disruption of WPs. NRC has included the direct release of radionuclides due to volcanism as a disruptive scenario in its TPA code to estimate the repository performance. The latest iteration of DOE's TSPA (U.S. Department of Energy, 1998b) also models the impacts of volcanic disruption of WPs through the direct release of radionuclides, in addition to modeling an enhanced source term due to additional failure of WPs, and indirect effects of volcanic activity on transport of radionuclides in the saturated zone.

Acceptance Criteria with 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: 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. Alternatively, the parameters or models lacking sufficient data have been replaced by bounding parameter values or models.

Review Method: Acceptable models will be consistent with the geologic record of basaltic igneous activity in the YMR. Staff should determine the adequacy and sufficiency of DOE characterization and documentation of past YMR igneous activity, 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 is based on appropriate other sources such as expert elicitation conducted in accordance with NUREG-1563.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the volcanic disruption of WPs abstraction are technically defensible and reasonably account for uncertainties and variabilities. 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 igneous activity 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 correlations between parameters have been appropriately established by DOE.

Criterion T3: 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 quality assurance programs. Staff should determine if credible alternative modeling approaches reflect, bound, or exceed the range of uncertainty in expected annual dose proposed by DOE.

Criterion T4: Outputs of the volcanic disruption of WPs abstraction are justified through comparison to outputs of detailed process models or empirical observations (laboratory testings or 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 is 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 the 1975 Tolbachik, Russia; 1943–52 Parícutin, Mexico; and 1850–1995 Cerro Negro, Nicaragua, violent strombolian eruptions.

Criterion T5: 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, of reasonable analogy 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 12 illustrates computational input/output for this ISI.

Technical Basis

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 U.S. Nuclear Regulatory Commission (1998). Additionally, the technical basis for the probability of volcanic events is discussed below. Staff anticipate that the acceptance criteria for the probability of volcanic events, which are currently located in the IA IRSR (U.S. Nuclear Regulatory Commission, 1998) will be included in the scenario analysis section of the Yucca Mountain Review Plan.

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, 1998), which represents an ability to fragment and transport volcanic particles for at least tens of kilometers down wind. Because recent (≤1 million years) eruptions in the YMR have preserved characteristics of violent strombolian activity, models of volcanic eruption through the proposed repository need to encompass this style of volcanism. Current TPA calculations assume the subsurface volcanic conduit has a diameter of 1–50 m, which is based on data from analog volcanoes. The number of WP 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, as these effects may affect the number of WP entrained during a repository-penetrating volcanic eruption (U.S. Nuclear Regulatory Commission, 1998).

Other parameters necessary for volcanism risk calculations, primarily related to interactions between basaltic magma and engineered barrier systems, 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, 1998b), staff conclude that

WP failure during direct entrainment into a volcanic conduit is a reasonably conservative assumption (U.S. Nuclear Regulatory Commission, 1998c). Available data and models also have not evaluated HLW behavior under appropriate volcanic conditions (e.g., U.S. Department of Energy, 1998b). The physical, thermal, and chemical loads imparted on HLW particles entrained in a volcanic conduit likely will induce fragmentation, reducing HLW average particle sizes significantly (U.S. Nuclear Regulatory Commission, 1998).

DOE's TSPA-VA (U.S. Department of Energy, 1998b) for YM attempted to perform more detailed modeling than previous TSPA regarding the interaction of magma with the WP and transport of spent fuel out of the repository. Staff have several concerns with the analyses presented in the TSPA-VA (e.g., U.S. Nuclear Regulatory Commission, 1999a). First, 62.7 percent of the realizations in TSPA-VA analyzing direct release due to volcanism had volcanic conduits that formed outside the repository boundary and thus were unable to effect release. In contrast to NRC modeling, TSPA-VA did not assume that all the HLW incorporated into volcanic conduit was available for entrainment and transport. In the TSPA-VA modeling, if a WP was intersected by a volcanic conduit, calculations were performed to determine if the WP failed due to corrosion or mechanical abrasion. For the 10^6 yr performance period analyzed, 20 percent of the realizations that had a conduit intersect a WP did not have WP failure within the conduit. More importantly, the process models used in TSPA-VA would not permit a WP to fail until the WP was at least 160,000 years old. If the WP did fail, HLW was not removed from the breeched WP in 50 percent of the TSPA-VA realizations. NRC staff have expressed concern in their evaluation of TSPA-VA that there is a lack of data and analysis to support the models of WP failure and spent-fuel release contained in TSPA-VA (U.S. Nuclear Regulatory Commission, 1999). In addition, consistency was lacking for models used in volcanic disruption of the WP calculations and those supporting airborne transport of radionuclides, mechanical disruption of the WP, and dilution of radionuclides in soil due to disruptive processes calculations. Informal communications with DOE staff since the TSPA-VA have addressed many of these technical concerns with the volcanism risk calculations. DOE staff recognize the need to develop additional models and data to support future DOE TSPA for igneous activity.

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 basecase dose) radiological dose to individuals located 20 km 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 less than 1 mrem/yr and occurs around 1,000 years after repository closure. Although this value is demonstrably below the proposed performance standard of 25 mrem/yr, these analyses demonstrate that DOE's license application will need a clear and credible treatment of igneous activity disruptive processes.

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, 1998). A volcanic event is defined herein as the formation of a new volcano, which has a subsurface conduit that penetrates the proposed repository emplacement drifts after closure. NRC-preferred probability models account for observed patterns in YM region volcanic activity, including: the tendency for basaltic volcanoes to cluster, northeast-trending vent alignments, and structural control of the locations of individual volcanoes (Connor and Hill, 1995; Hill et al., 1996; U.S. Nuclear Regulatory Commission, 1998). These studies have used geologic information relevant to past patterns of volcanic activity in the YM area to estimate the recurrence rate of new volcano formation in the repository footprint for the next 10,000 years, and have estimated that the annual probability of a volcano penetrating the repository generally ranges between 10^{-8} and 10^{-7}. DOE's Probabilistic Volcanic Hazards Assessment (Geomatrix, 1996), however, combined intrusive and extrusive igneous processes into a single event definition, with a resulting mean annual probability of disruption of 1.5×10^{-8}. There is insufficient information to separate this probability estimate into extrusive and intrusive components. DOE's TSPA-VA (U.S. Department of Energy, 1998b) derived the annual probability of volcanic events from the combined probability by creating a new class of volcanic source-zone models to conclude the mean annual probability of volcanic disruption was about 6×10^{-9}. Staff conclude that DOE TSPA-VA models used to lower the annual probability $<10^{-8}$ would not meet current acceptance criteria, in that they are not consistent with geologic features and models used elsewhere within the program. These evaluations are presented in detail in the ongoing revision of Nuclear Regulatory Commission (1998) revision.

4.3.2.2.5 Airborne Transport of Radionuclides

Pertinent KTI subissues: IA2

Volcanism is the only direct release mechanism currently under consideration by NRC at this time. Therefore, this discussion focuses on the airborne transport of radionuclides which have been incorporated into the volcanic ash. Modeling the entrainment of HLW and airborne transport of tephra is a necessary step in analyzing the consequences of volcanic events because basaltic volcanism has the potential to eject material that could result in the airborne transport of tephra (and more importantly RNs contained within the tephra) from the proposed repository location to receptor locations (Sagar, 1997). The latest DOE TSPA (U.S. Department of Energy, 1998b) models the direct release of radionuclides from a volcanic event as a disruptive event at the repository. SF is modeled as being 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 RNs incorporated within tephra.

Acceptance Criteria with Review Methods

DOE's approach in abstracting the airborne transport of radionuclides 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 effect of direct release and transport on the total system performance.

Criterion T1: Sufficient data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the airborne transport of radionuclides 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the airborne transport of radionuclides abstraction, such as the magnitude of eruption and deposition velocity, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated airborne transport of radionuclides input/data in the performance calculations. Staff should ascertain that the input values used in the airborne transport of radionuclides in TSPA are reasonable based on data from the YM region and other applicable atmospheric tracer experiments 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 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 ash, 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: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the airborne transport of radionuclides 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 radionuclides 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: Airborne transport of radionuclides abstraction output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of the airborne transport of radionuclides 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 radionuclides against the results produced by the process-level models developed by the staff.

Criterion T5: Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the airborne transport of radionuclides 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 radionuclides. 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 or 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, ash blankets may be thick, effectively shielding some RNs (dilution of RNs in soil due to surface processes).

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

These relationships and other computational input are illustrated in figure 13. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in airborne transport of radionuclides for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

Basaltic volcanoes are capable of ejecting material that is transported tens of kilometers away by air dispersion, depending on characteristics associated with the tephra mass being extruded (e.g., size distribution, density, etc.) and characteristics of the volcanic event (e.g., column height, wind speed, etc.) (Jarzemba, 1997; Suzuki, 1983; Hill et al., 1996; Sparks, 1986; Woods, 1988, 1995). However, there are typically large uncertainties in modeling the airborne transport of tephra. Previous studies have found that the deposition (i.e., depth) of ash can vary by many orders of magnitude at specified distances and directions from the volcanic event

(Jarzemba, 1997; Hill et al., 1997). To account for uncertainties in model predictions, previous studies have sampled the values of parameters important for predicting the transport and subsequent deposition of ash from representative probability distributions (Jarzemba and LaPlante, 1996; Jarzemba, 1997). A diagram identifying these parameters is presented in figure 14. Current NRC/CNWRA assessments address this ISI by using a model which is 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.

DOE modeling of the airborne transport of RNs utilizes a modified version of the ASHPLUME code (Jarzemba et al., 1997). This is the same code that the NRC utilizes 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 the use of the NRC code does not ensure acceptance by the NRC and that DOE will be required to demonstrate 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 towards the critical group during the volcanic event. For these realizations, the quantity of ash reaching the critical group location from the volcanic event will be very small. However, DOE's model does not consider the redistribution of the contaminated ash, which could lead to ash that was originally transported away from the critical group to later be redeposited at the receptor group location. If credit is taken by DOE for the distribution of wind directions during the volcanic event, this redistribution of ash after the event should be considered.

Numerical models that quantify the physics of basaltic eruptions have been developed (Sparks et al., 1997), but considerable uncertainty exists in how to simulate the entrainment and dispersal of HLW in the eruption column. Physically accurate eruption column models provide an opportunity to extend the understanding of tephra plumes (U.S. Nuclear Regulatory Commission, 1998c).

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 AC and RMs for the three key elements in dose calculation, as identified in figure 2 (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 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, the key elements represent essential factors to be considered in dose calculation that 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 key elements are met.

4.3.3.1.1 Dilution of Radionuclides in Groundwater due to Well Pumping

Pertinent KTI subissue: USFIC5

This ISI relates to the various methods that can be used to calculate the effects of well pumping on RN concentrations at the wellhead. 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 RN transport 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 may be calculated by dividing the mass or activity of the RNs captured by the well by the volumetric discharge rate of the well. If a complex 3D transport model incorporating the effects 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 precisely determined plume geometry.

In DOE's TSPA-VA (U.S. Department of Energy, 1998b) dilution due to well pumping was not considered. Instead, 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 DOE TSPA-VA use of dilution factors, no credit was taken for large-scale mixing induced by interbasin groundwater flow—a process generally deemed insignificant by the SZEE, except in cases where regional flow is strongly affected by transient behavior. As a result, dilution factors reported in TSPA-VA account only for macro-dispersive processes, and are several orders of magnitude smaller than those reported in TSPA-95 (TRW, 1995). 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.

Since dilution of RN concentrations in the aquifer will continue to be evaluated as part of the USFIC IRSR, discussion point TE14 will not be tracked as an Open Item in the TSPAI IRSR.

Acceptance Criteria with Review Methods

DOE's approach in abstracting dilution of radionuclides 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: Sufficient data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the dilution of radionuclides in groundwater 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. 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 definition of parameter values and conceptual models is 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/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: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the dilution of radionuclides 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 uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated dilution of radionuclides in groundwater due to well pumping input/data in the performance calculations. Staff should ascertain that the input values used in the dilution of radionuclides in groundwater due to well pumping calculations in TSPA are reasonable based on data from the YM region, e.g., Amargosa Valley surveys (Cannon Center for Survey Research, 1997), and other applicable laboratory testings 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 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 correlations used by DOE.

Criterion T3: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the dilution of radionuclides 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 radionuclides 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: Dilution of radionuclides in groundwater 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 radionuclides in groundwater 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 radionuclides in groundwater 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: Important hydrogeologic features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the dilution of radionuclides in groundwater 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; 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 dilution of radionuclides in groundwater due to well pumping. Important site features that will set the initial and boundary conditions for abstracting the dilution of radionuclides in groundwater due to well pumping include hydraulic gradient, hydraulic conductivities of the production zones, the effect of climate change on the amount of flow through UZ and SZ, etc. If DOE decides not to take credit for certain site features or processes that have been demonstrated in NRC's or 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 radionuclides in groundwater due to pumping (flow rates in water-production zones).

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

These relationships are illustrated in Figure 15. 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 radionuclides in groundwater due to well pumping for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

This section describes the technical basis for the abstraction of dilution of RNs in groundwater due to 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 and Jackass Flats. Active pumping of groundwater will create cones of depression that will intercept all 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 casing 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.

RN dilution due to 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 and dividing the result 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.

4.3.3.1.2 Dilution of Radionuclides in Soil due to Surface Processes

Pertinent KTI subissue: NONE

This integrated subissue relates to the calculation of the concentration of radionuclides in the soil due to deposition of a volcanic ash blanket or application of contaminated water on the soil. The most recent DOE's TSPA (U.S. Department of Energy, 1998b) calculated 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. 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 radionuclide inventory in the ash blanket due to surface erosion, leaching, and radioactive decay. The NRC/CNWRA assessments also use the models in the GENII-S code (Napier et al., 1988; Leigh et al., 1993) to calculate the dose from radionuclides deposited on the ground surface and the ASHRMOVO module to perform calculations for the surface leaching of RNs out of the biosphere.

Irrigation of 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 (i.e., external, incorporation in foodstuffs, inhalation of resuspended materials). In general, the computational models use either the concentration of RNs per 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 biosphere exposure pathways.

Acceptance Criteria with Review Methods

DOE's approach in abstracting dilution of radionuclides in soil due to surface processes 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: Sufficient data (field, laboratory, and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the dilution of radionuclides in soil due to surface processes 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 definition of parameter values and conceptual models is 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/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.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the dilution of radionuclides in soil due to surface processes abstraction, such as depth of the plowed layers and mass loading factor, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated dilution of radionuclides in soil due to surface processes input/data in the performance calculations. Staff should ascertain that the input values used in the dilution of radionuclides in soil due to surface processes calculations in TSPA are reasonable based on data from the YM region, e.g., Amargosa Valley survey (Cannon Center for Survey Research, 1997), 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., dilution of radionuclides in soil due to surface processes should consider the current farming practices (soil types, crop type, growing seasons, etc.)]. 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 staff's 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: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and their results and limitations appropriately factored into the dilution of radionuclides in soil due to surface processes abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative models and provided supporting information for the approaches used in the dilution of radionuclides in soil due to surface processes 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: Dilution of radionuclides in soil due to surface processes output is justified through comparison to output of detailed process models or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE demonstrated that the output of dilution of radionuclides in soil due to surface processes 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 dilution of radionuclides in soil due to surface processes 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: Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the dilution of radionuclides in soil due to surface processes 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 dilution of radionuclides in soil due to surface processes. If DOE decides not to take credit for certain site features or processes that have been demonstrated in NRC's or 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 integrated subissues:

- 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 radionuclides (airborne transport of radionuclides).

These relationships are illustrated in figure 16. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the couplings between direct release and biosphere (e.g., RN transport, deposition, and decay). To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in dilution of radionuclides in soil due to surface processes for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

This section describes the technical basis for the abstraction of dilution of radionuclides in soil due to surface processes to repository PAs. Specifically, the depth beyond which RNs cannot contribute to direct exposures and processes that can distribute RNs to deeper soil layers are discussed.

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, etc.) 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 upon the process. For example, some plant types, such as carrots, are able to extract soil water from only the top 15 cm or so of soil, however, alfalfa has a tap root that can penetrate several meters into the soil (LaPlante and Poor, 1997). Another example of how the dilution of 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 m above the soil due to contamination in the uppermost 15 cm is 7.25×10^{-17} [Sv/s]/[Bq/m^3], however, the dose rate at 1 m above the soil due to contamination from all the soil deeper than 15 cm is only 1.43×10^{-17} [Sv/s]/[Bq/m^3] (Eckerman and Ryman, 1993) (i.e., contamination in the uppermost 15 cm of soil accounts for 84 percent of the exposure).[19] This fraction would increase for RNs whose gamma ray emissions are less energetic.

There are at least two processes by which RNs originally spread upon the soil surface (e.g., by irrigation with radioactively contaminated groundwater) can become distributed to lower soil layers, effectively removing them from the biosphere. The first process is manual redistributionby 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 upon the soil surface, due to 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 upon 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.

4.3.3.1.3 Lifestyle of Critical Group

Pertinent KTI subissues: USFIC1, USFIC2, USFIC3, USFIC5, RT3, IA2

The integrated subissue for lifestyle of the critical group is directly related to repository performance. Parameters associated with the lifestyle of receptor groups and the biosphere in which they exist enable performance assessors to transform groundwater and ground surface radionuclide concentrations to individual doses. The DCFs used in PA dose calculations (that convert water and soil radionuclide concentrations to dose) are based on assumptions about the lifestyle of the critical group. DCFs proportionally affect PA dose results, and assumptions about the critical group can significantly affect the magnitude of the calculated dose. Past NRC/CNWRA uncertainty analysis of the DCFs (LaPlante and Poor, 1997) indicate that the range of DCFs produced when input parameters are sampled from known or estimated distributions span about an order of magnitude and approximate 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 quantitative importance analyses have been conducted to date by CNWRA to quantify the importance of this integrated subissue relative to others, DOE analyses suggest the DCFs that result from this integrated subissue are of moderate importance to post-closure performance (U.S. Department of Energy, 1998). Moderate importance means uncertainty in the DCF contributes a factor of 5 to 50 increase or decrease in peak dose from the expected value.

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[19] Note: 1 Sv=100 rem and 3.7×10^{10} Bq=1 Ci.

Acceptance Criteria with 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 biosphere's contribution to total system performance.

Criterion 1: Sufficient data (field, laboratory, and 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. Alternatively, the parameters or models lacking sufficient data have been replaced by bounding parameter values and 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. Staff will ensure DOE has provided sufficient information to demonstrate that features, events, and processes 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 YM region. 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 YM region. 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 analogous data from scientific literature that are appropriately QA qualified. Where sufficient data do not exist, staff should ensure that the definition of parameter values and conceptual models is 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/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 features, events, or processes in its conceptual models.

Criterion 2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the lifestyle of critical group abstraction such as consumption rates, plant and animal uptake factors, mass loading factors, and DCFs are technically defensible and reasonably account for uncertainties and variabilities.

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 YM region (e.g., locally derived food/water consumption rates, agricultural practices, cultural practices) and other applicable research and analogous 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 features, events, and processes 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 YM region. 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 YM region 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 correlations between the input values (if used) 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 3: 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 inform DOE's approach and NRC 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 radionuclides from soil, soil resuspension, and the inhalation dose model for igneous events.

Criterion 4: 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. This can be done initially by comparison of DOE biosphere DCFs with the results of dose modeling using the GENII-S code and DOE input parameter data. Staff should also compare results of NRC TPA code modeling using DOE biosphere DCFs 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: Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the lifestyle and location 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 features, events, and processes of the biosphere and critical group such as soil types, K_d's, assumed or known volcanic ash properties, and the physical/chemical properties of radionuclides 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 radionuclide-specific dose estimates so that, conceptually, total dose estimates represent the dose contribution of all radionuclides expected to be 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 or 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 integrated subissues.

- Radionuclide transport through fractured rock (RT/GS-3) requires assumptions about chemical species that are likely to be transported so that retardation coefficients can be determined. The internal dose factors used to convert radionuclide intakes to dose also rely on general chemical classifications of the radioactive materials ingested by the critical group. Both assumptions should be checked for consistency.

- Quantity and chemistry of water contacting waste (EBS-3) involve consideration of present-day infiltration, which is dependent upon precipitation and evapotranspiration conditions. Precipitation and evapotranspiration are also parameters that influence the leach factors for the dose conversion calculation that affect removal of radionuclides from surface soils. These assumptions should be checked for consistency.

- Airborne transport of radionuclides (GS-7) includes assumptions regarding the particle sizes of air transported ash/radionuclides to the location of the critical group. The lifestyle of the critical group subissue (BS-3) incorporates a mass loading factor for the ash/radionuclide material into the dose calculations. The mass loading factor is based on a number of variable parameters including the particle size of the ash/radionuclide material and perhaps the thickness of the ash blanket. These assumptions should be checked for consistency to the extent practicable.

The above relationships are illustrated in figure 17. 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.

Technical Basis

The scope of the integrated subissue of lifestyle of the critical group encompasses key aspects of critical group dose estimates based on estimated radionuclide 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. Staff analysis of DOE's VA as it pertains to this integrated subissue is included to provide a description of current technical issues and status of resolution.

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 International Council on Radiation Protection (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 radionuclides. The critical group exists in an environment defined by pertinent site-specific conditions referred to as the reference biosphere (an abstraction of the actual biosphere for modeling purposes). 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 license application 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 integrated subissue 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 (Nuclear Regulatory Commission, 1999d). 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, 1996). 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 DCFs 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 mean annual temperature (MAT) of 61 °F and a mean annual precipitation (MAP) of 5.9 in. (Wittmeyer et al., 1996). Recent studies indicate that the climate in the YM region 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; Stablein, 1997a) 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 YM region 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.

DOE's approach to calculating DCFs in TSPA-VA is very similar to the NRC approach used in the TPA code and appears consistent with proposed NRC requirements for reference biosphere and critical group in draft 10 CFR Part 63. DOE uses the same biosphere/pathway/dose models (GENII-S)(Leigh et al., 1993) as NRC to calculate an annual dose to the average member of a 20 km farming group in Amargosa Valley. Most of DOE's input parameters are the same as used by NRC/CNWRA. The use of site-specific survey data for local demographics (Cannon Center for Survey Research, 1997) is an improvement over NRC/CNWRA modeling. Additional similarities and differences in approach to modeling the *critical* group abstraction are discussed in the following paragraphs. The assessment of dose in TSPA-VA assumes that at the receptor location, groundwater is utilized for drinking, irrigation of crops, and water for livestock. Additional pathways for exposure of the critical group considered by TSPA-VA include inhalation and inadvertent ingestion of contaminated soil, and direct exposure by radionuclides in the environment. These pathways are considered adequate to calculate the dose from radionuclides in the environment; therefore, Open Item OSC0000001347C116 can be closed.

A comparison of critical group and biosphere parameters showed, in general, good agreement between DOE and NRC values. These input parameter choices were compared with current parameter selections for TPA Version 3.2, and a sample of DCF calculations were confirmed by running the GENII-S (Leigh et al., 1993) code. One notable difference was for the range used for the mass loading factor used in the inhalation model. DOE's range (2.4E-6, 1.54E-4) is less conservative than the range selected by NRC/CNWRA staff for use in TPA 3.2 (1.0E-4, 1.0E-2). These 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 very uncertain parameter for use in calculating inhalation dose from the igneous activity disruptive event. Therefore, a technically defensible basis for the chosen factor's applicability to known or assumed volcanic ash characteristics is important as well. The potential lack of conservatism may be offset by DOE's 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 integrated subissue for dilution of radionuclides in soil for more information on dilution issues in this IRSR.

DOE's implementation of DCFs 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 radionuclide-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 radionuclide leads to large value selections for all radionuclides for a given realization (CRWMS M&O, 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 DCFs for each iteration of the TSPA). Another concern was that double sampling would de-couple the DCFs from their original sampling vectors such that all re-sampled DCFs for a given TSPA iteration would not be based on the same suite of input parameters (e.g., 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 radionuclides in a given iteration of the code. DOE's statement that the DCFs were correlated by the magnitude of the DCF is questionable because the various factors that contribute to the magnitude of DCFs vary among radionuclides; 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 radionuclides 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 or other strong evidence that the abstraction approach is not introducing a significant source of bias in PA calculations.

4.4 DEMONSTRATION OF THE OVERALL PERFORMANCE OBJECTIVE

A proposed strategy for developing regulations for the disposal of high-level radioactive waste 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 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 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 Site Characterization Plan, DOE has produced a series of TSPAs (Wilson et al., 1993; TRW Environmental Safety Systems, 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 base case. 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:

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

where,

$R(t)$ = Scenario class expected annual dose at time t

ΔT = Increment of time associated with event n (in years)

p = Annual probability of event

$D_n(t)$ = Mean annual dose from event n at time t

E = Number of times of event occurrence for which mean dose histories are calculated

For the base case scenario class:

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

where,

p_i = Annual event probability of event i

K = 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 $5*10^{-6}$/yr, and the annual probability of occurrence for scenario class **Ψ** is $1*10^{-7}$/yr. The scenario class **{ΘΨ}** is screened out on the basis its probability of occurrence ($5*10^{-13}$/yr) is less than 10^{-8}/yr, so the consequence analyses of only the base case 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 base case performance of the repository is as shown in figure 18. Figures 19 and 20 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 21 shows the scenario class expected annual dose for the base case scenario. Figures 22 and 23 show the scenario class expected annual dose history for scenario class **Θ** and **Ψ**, respectively.

Figure 24 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.

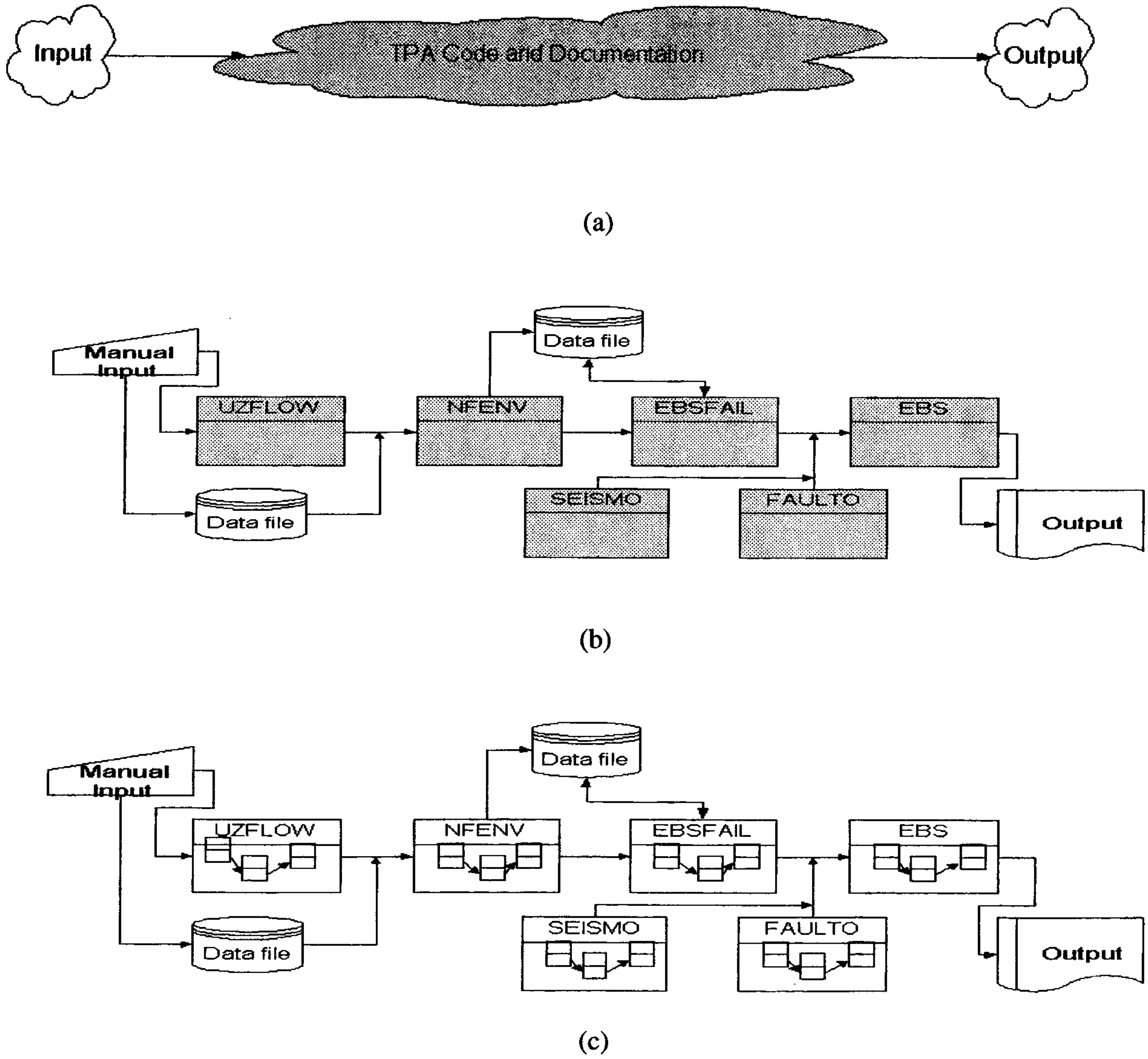


Figure 1. TPA Code - Degrees of Transparency: (a) black box, (b) partially transparent, (c) fully transparent

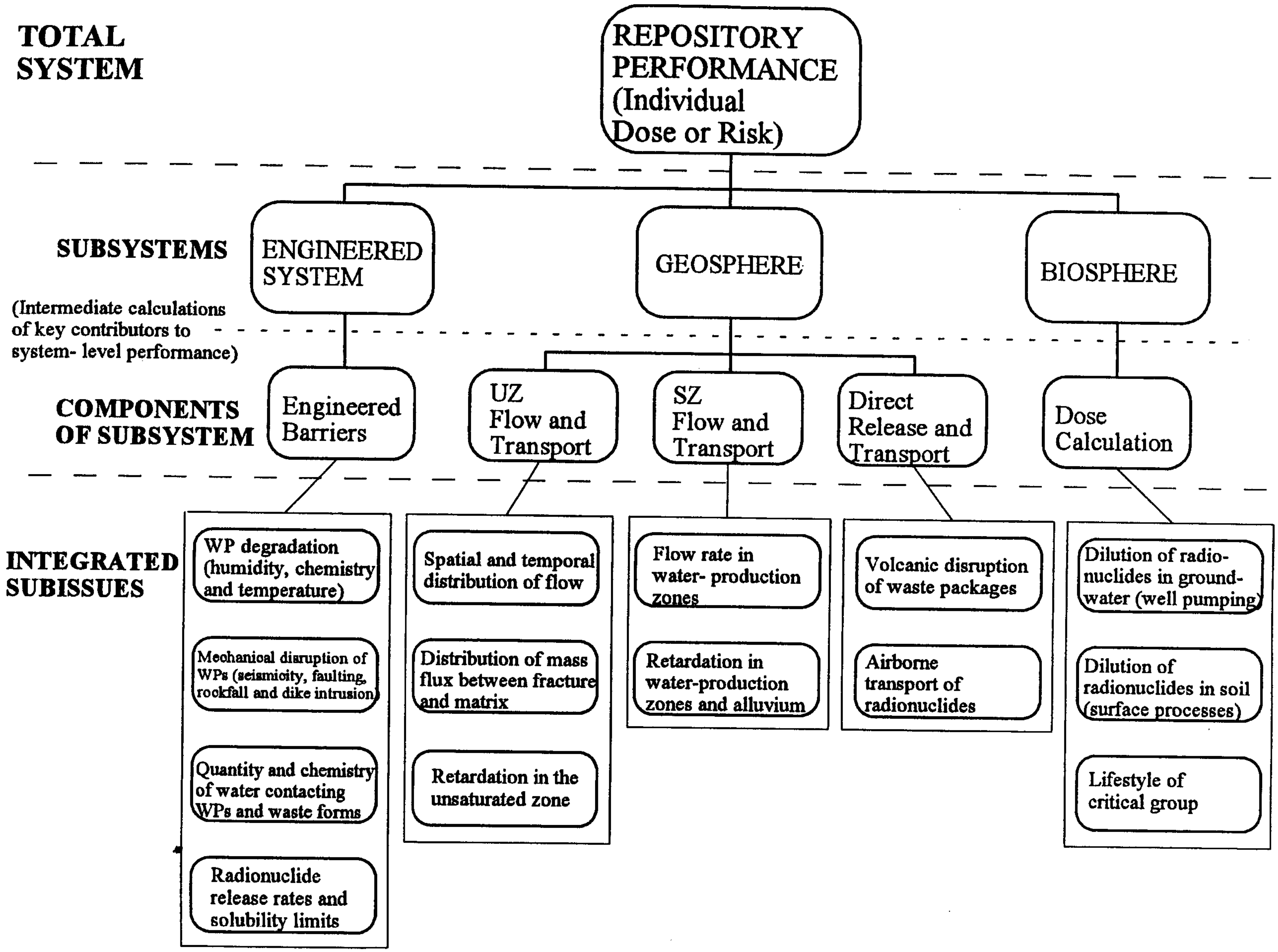
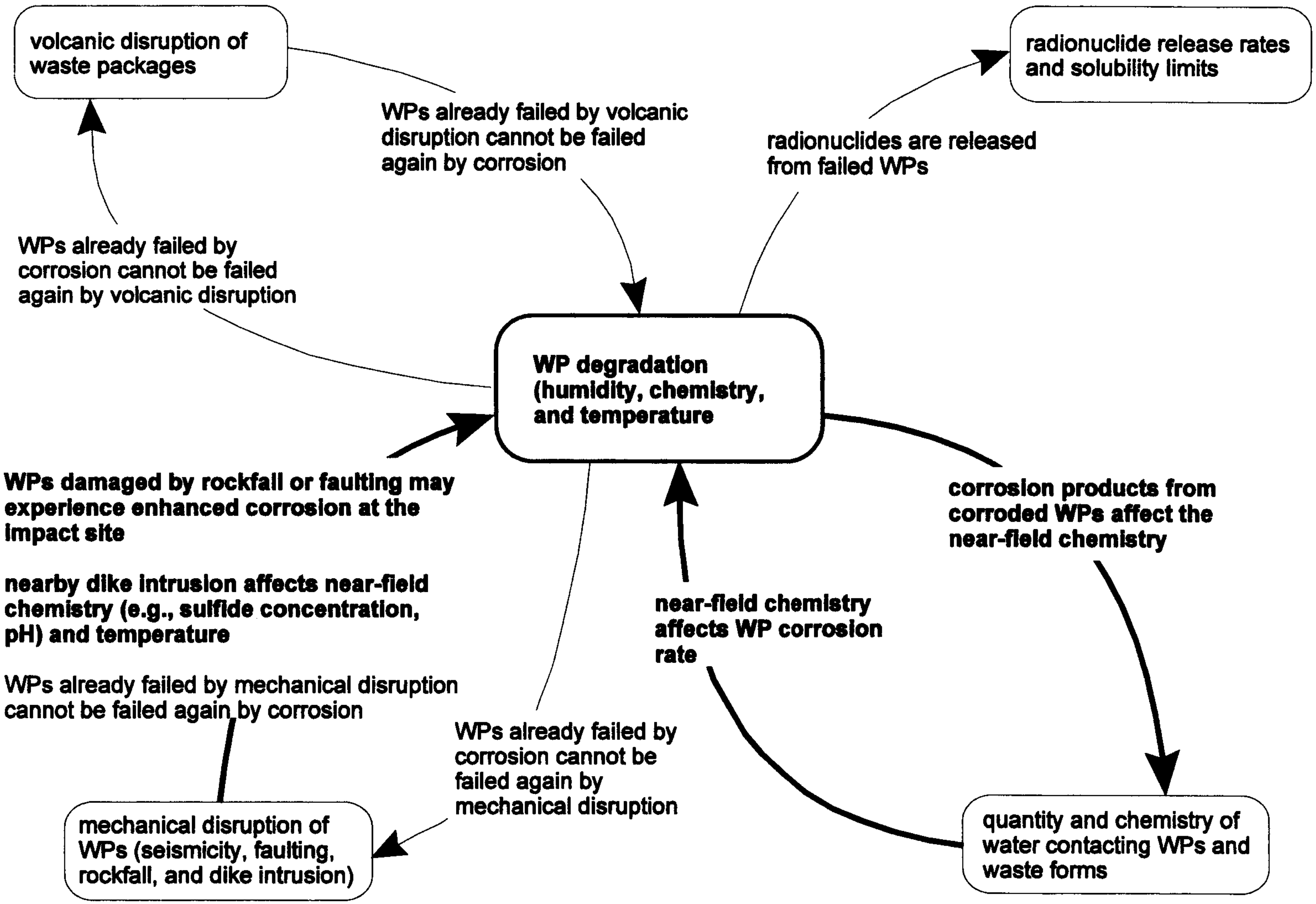
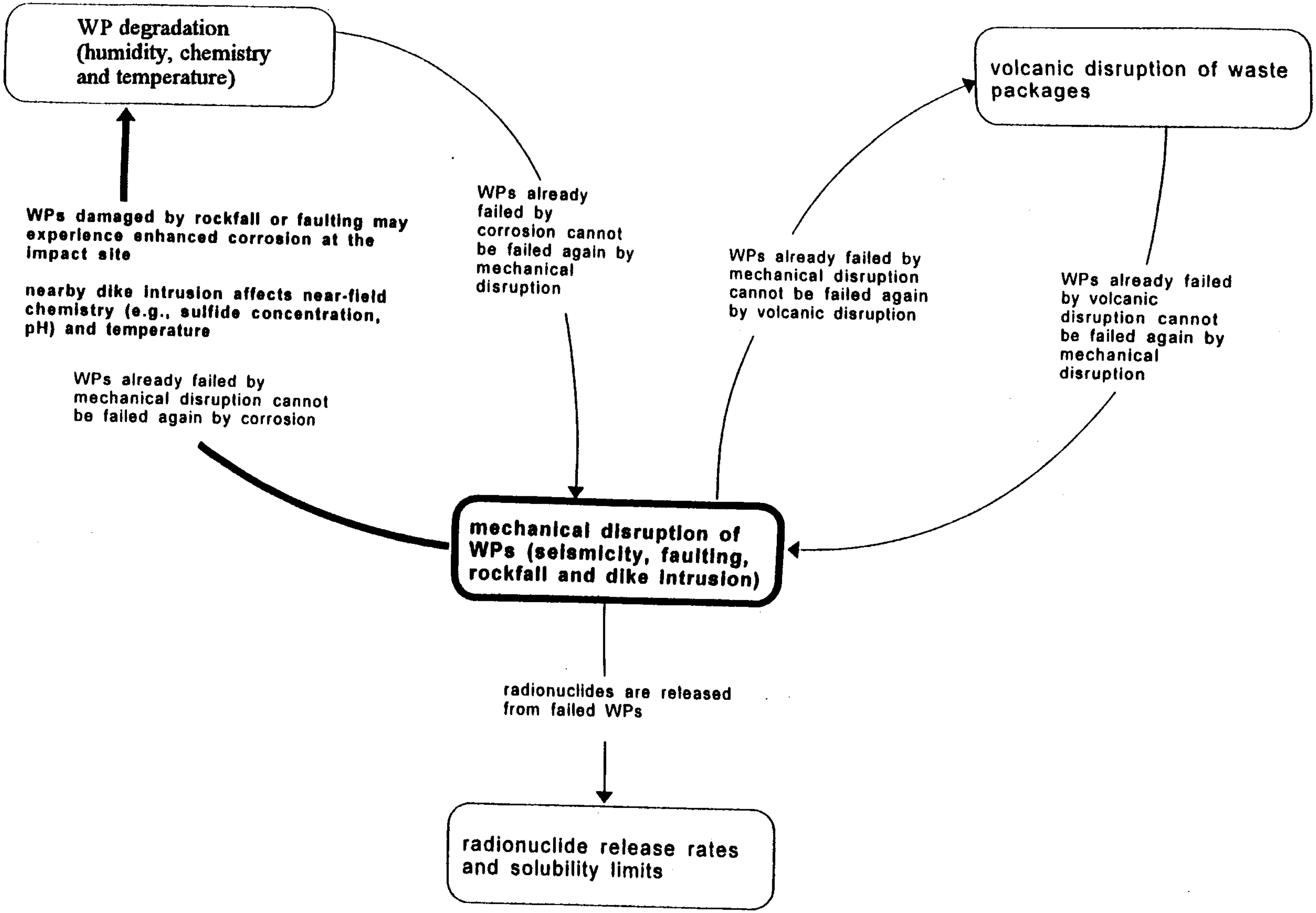


Figure 2. Flowdown diagram for total system performance assessment



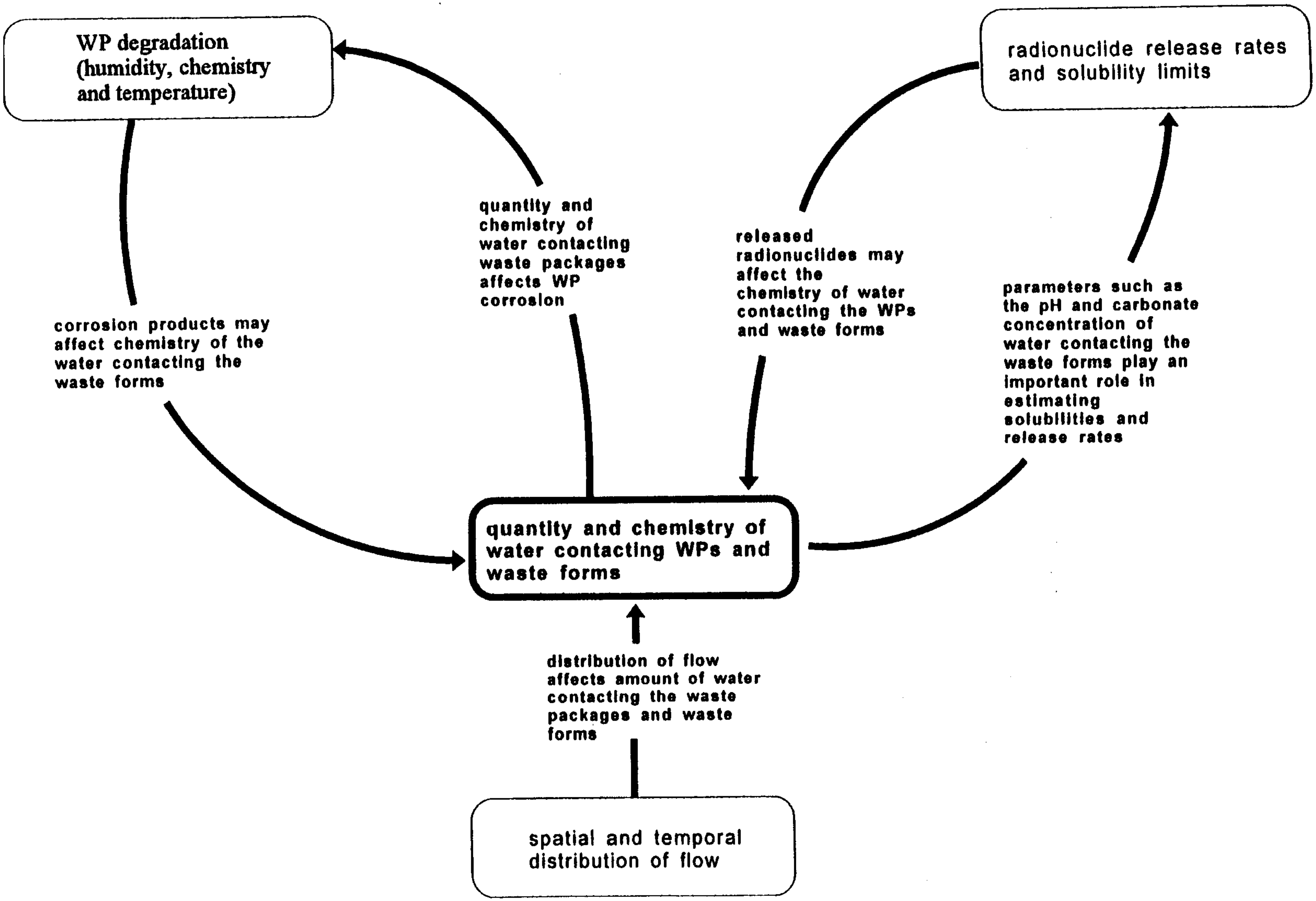
*** Relationships in bold are identified in the text**

Figure 3. A diagram illustrating the relationships between "waste package corrosion" and other integrated subissues



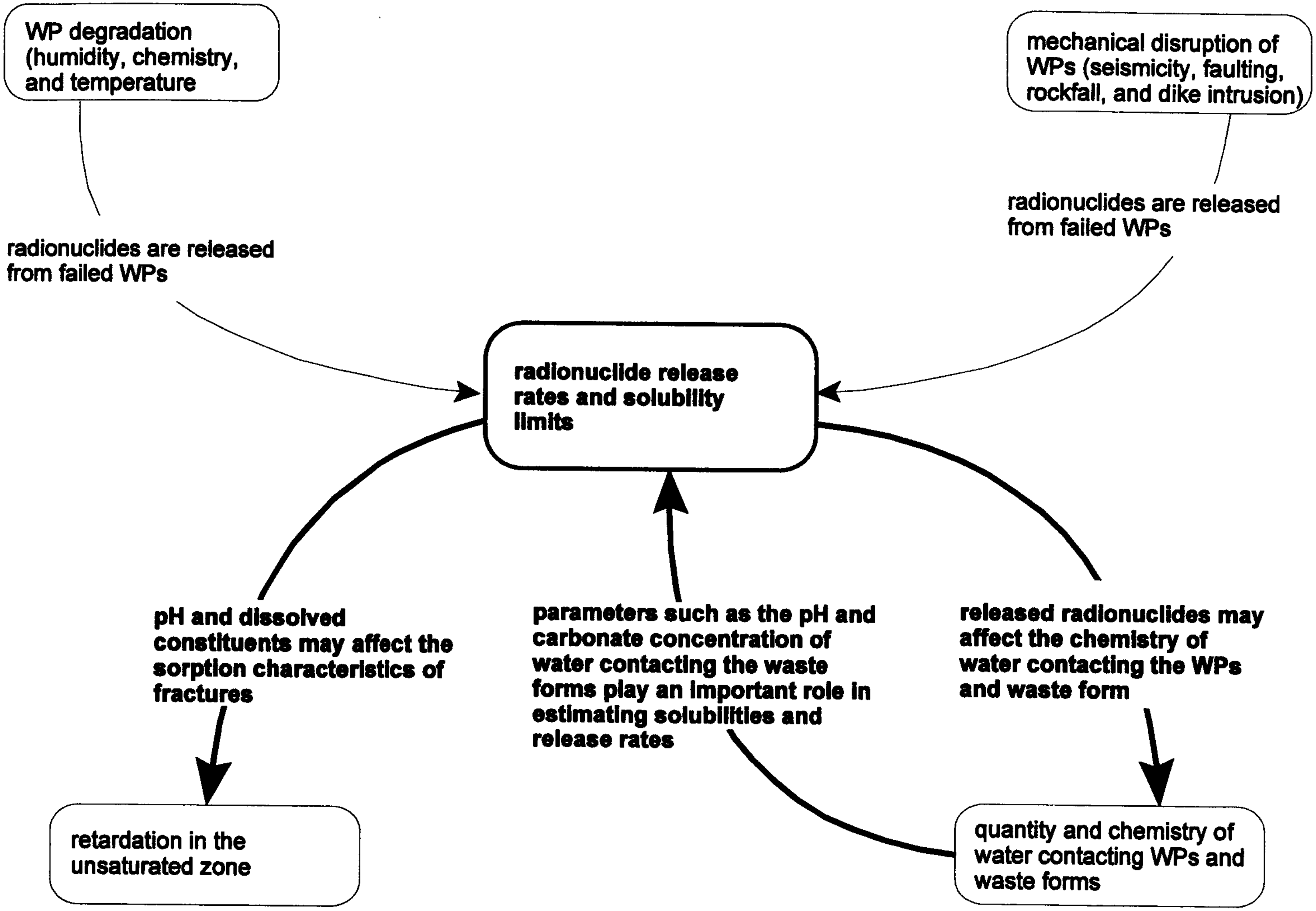
* Relationships in bold are identified in the text

Figure 4. A diagram illustrating the input to and output from mechanical disruption of waste packages



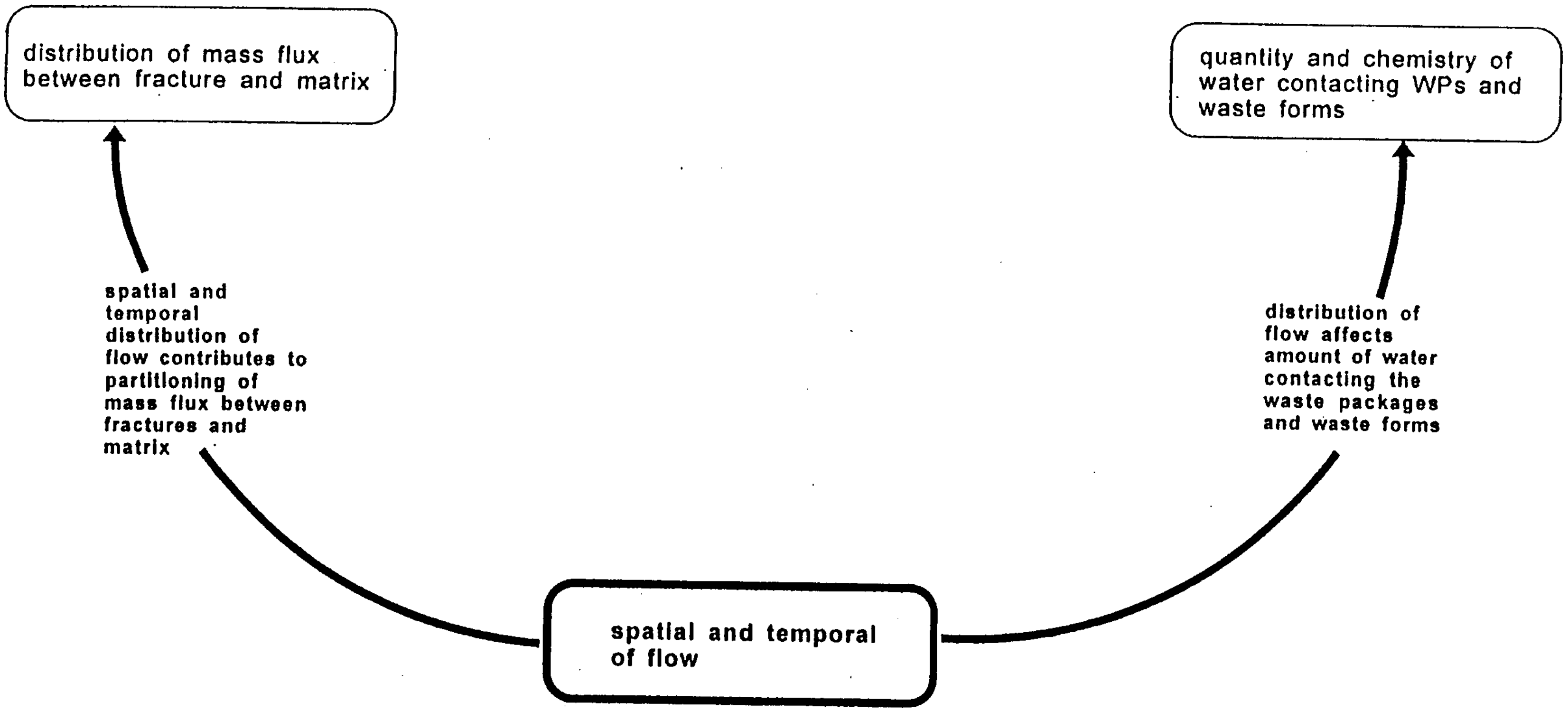
* Relationships in bold are identified in the text

Figure 5. A diagram illustrating the input to and output from quantity and chemistry of water contacting waste packages integrated subissue



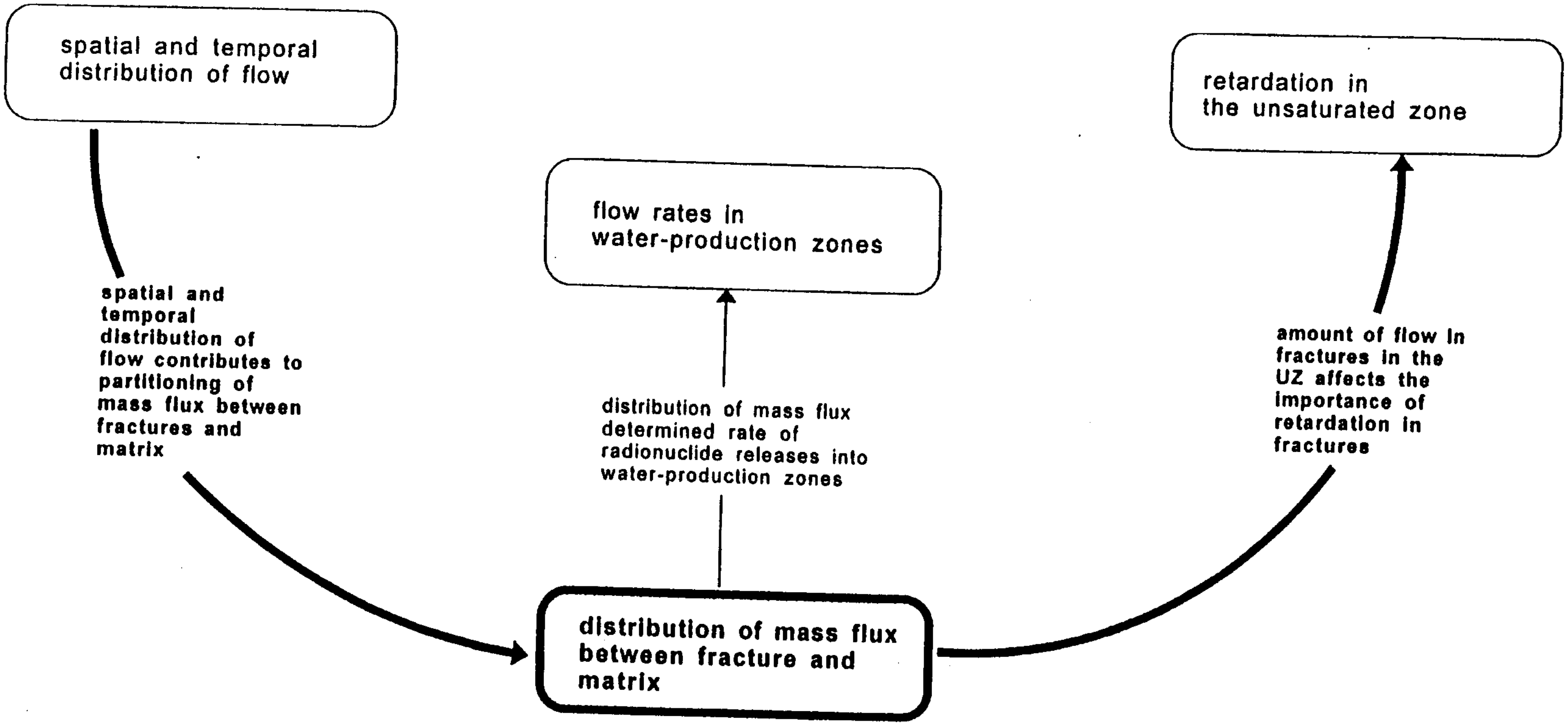
* Relationships in bold are identified in the text

Figure 6. A diagram illustrating the input to and output from radionuclide release rates and solubility limits integrated subissues



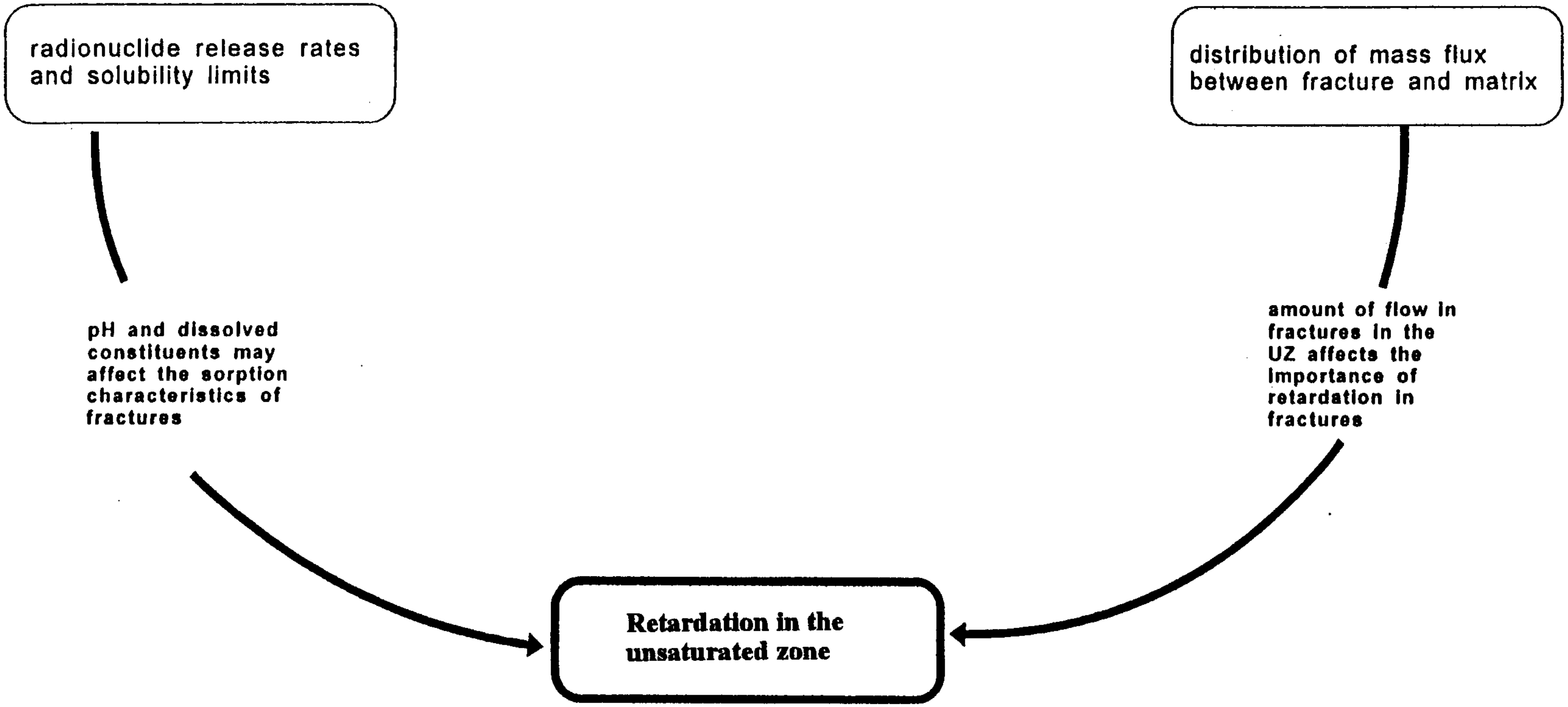
* Relationships in bold are identified in the text

Figure 7. A diagram illustrating the relationships between "spatial and temporal distribution of flow" and other integrated subissues



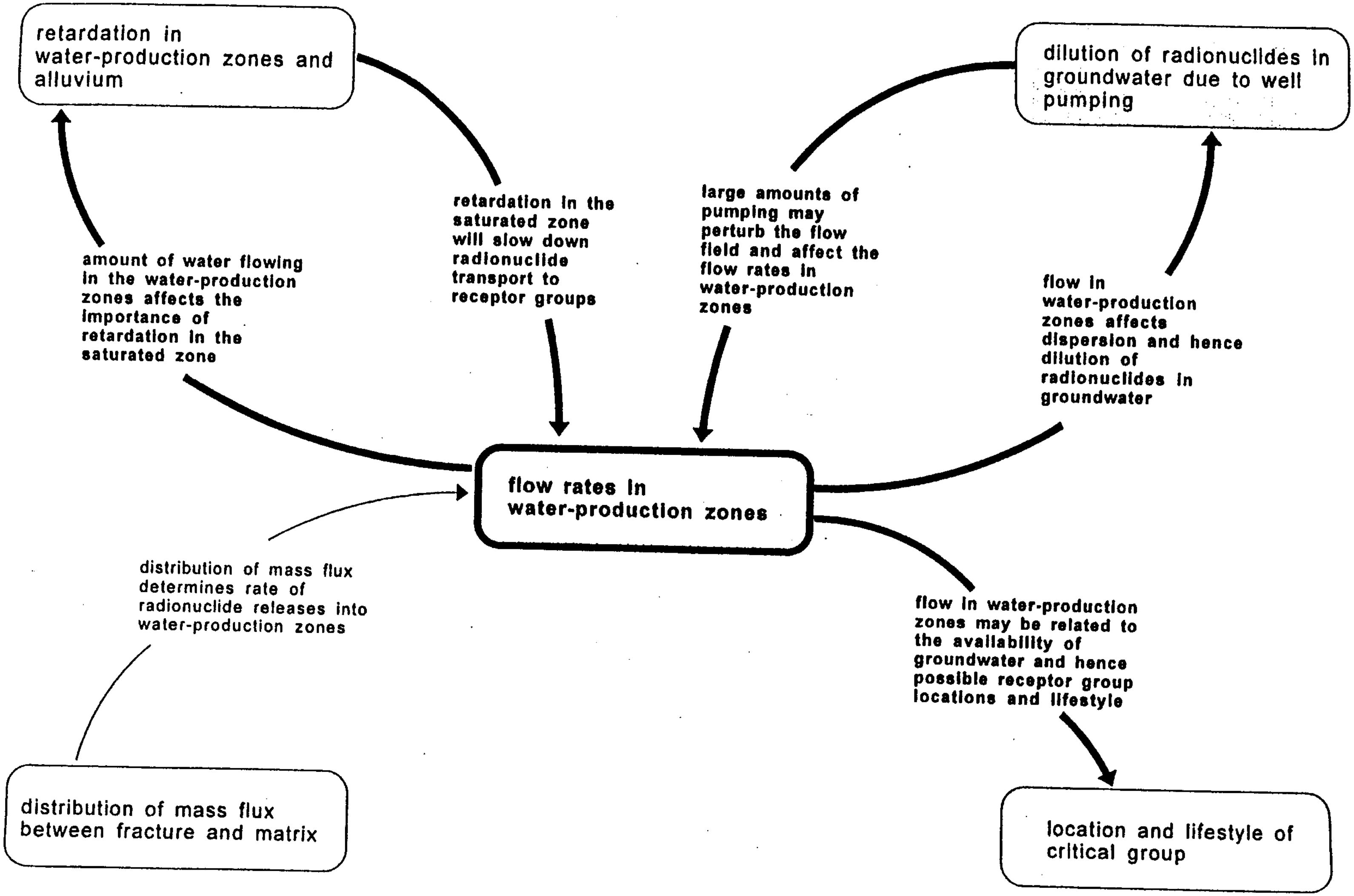
* Relationships in bold are identified in the text

Figure 8. A diagram illustrating the input to and output from distribution of mass flux between fracture and matrix integrated subissues



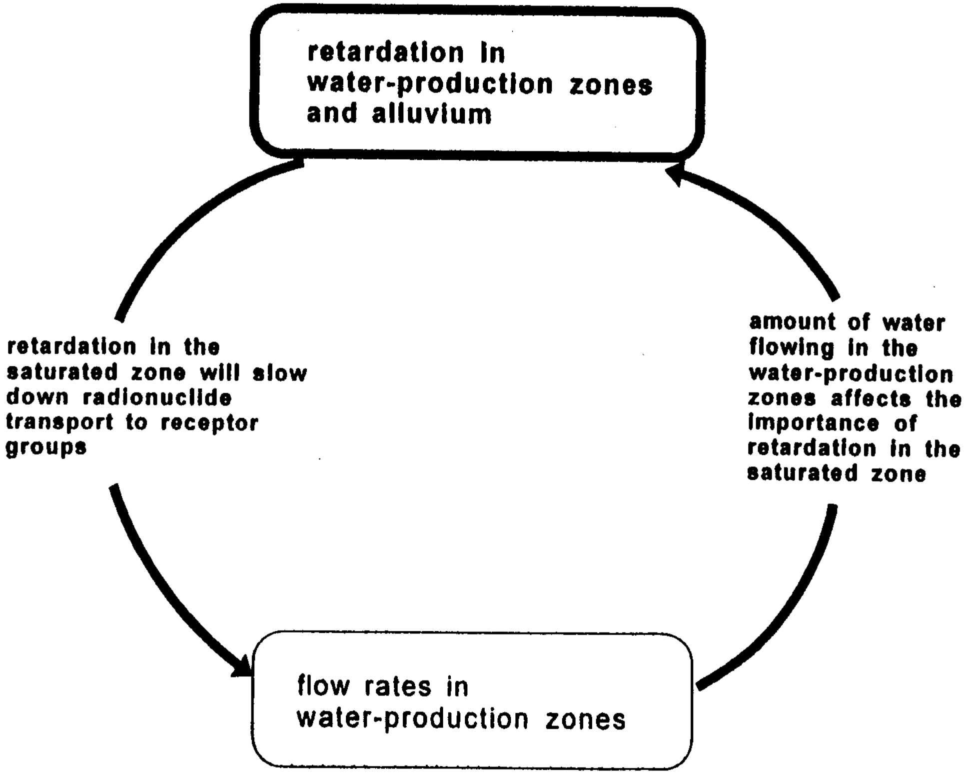
* Relationships in bold are identified in the text

Figure 9. A diagram illustrating the input to and output from retardation in fractures in the unsaturated zone integrated subissues



* Relationships in bold are identified in the text

Figure 10. A diagram illustrating the input to and output from flow rates in water production zones integrated subissues



* Relationships in bold are identified in the text

Figure 11. A diagram illustrating the relationship between “retardation in water production zones and alluvium” and other integrated subissues

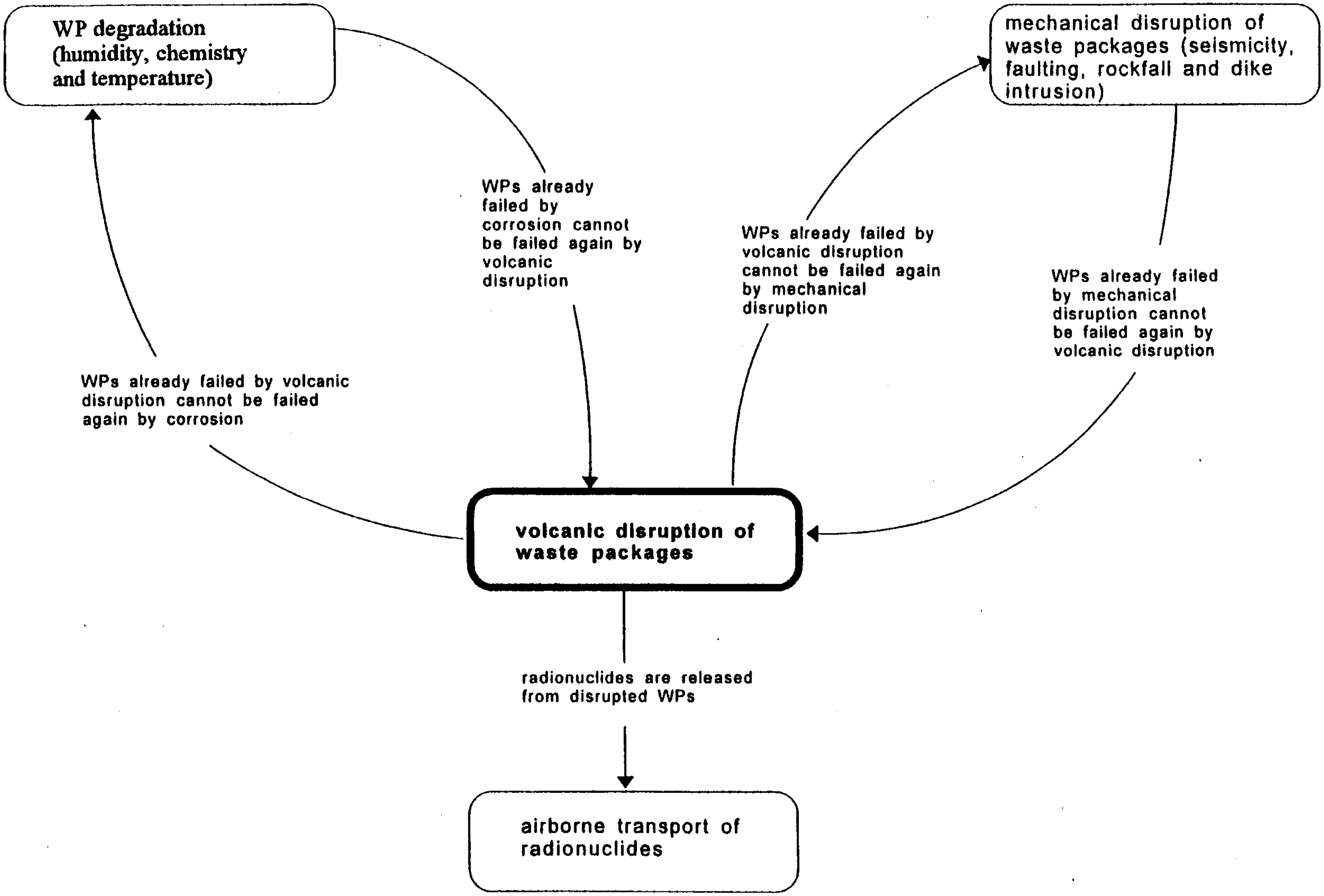
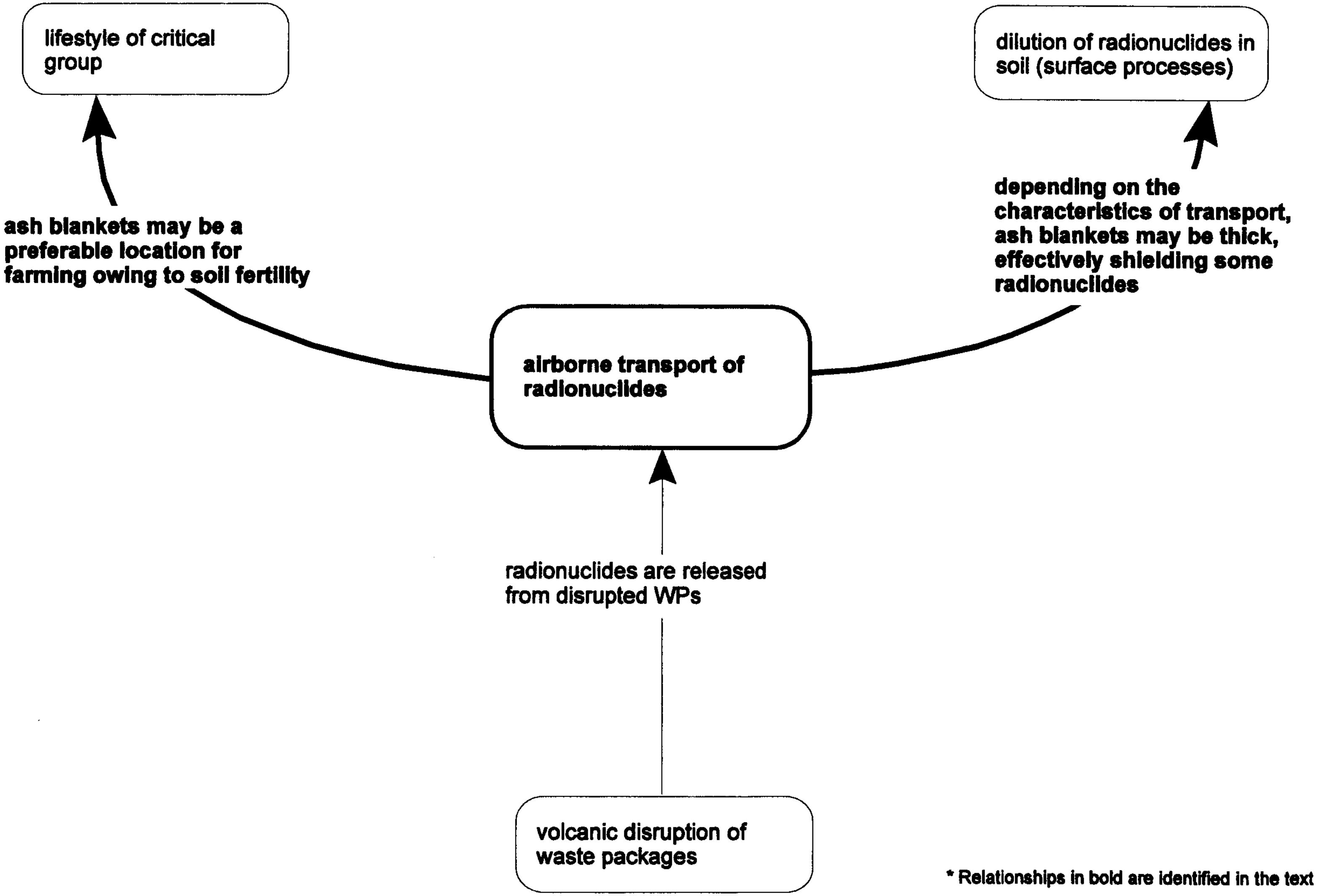


Figure 12. A diagram illustrating the input and output from volcanic disruption of waste packages



* Relationships in bold are identified in the text

Figure 13. A diagram illustrating the relationships between "airborne transport of radionuclides" and other integrated subissues

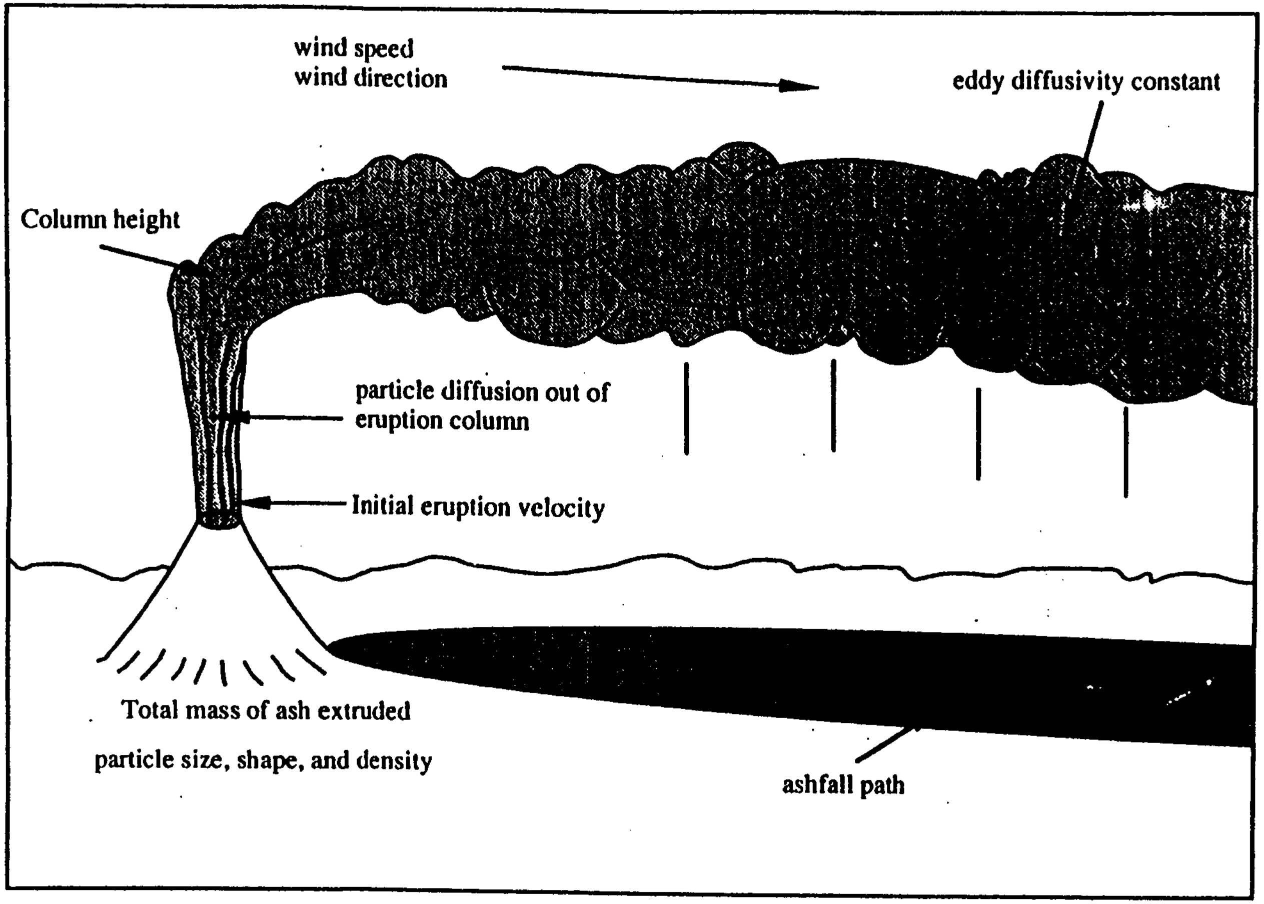


Figure 14. A diagram illustrating the important processes and parameters for estimating airborne transport of tephra

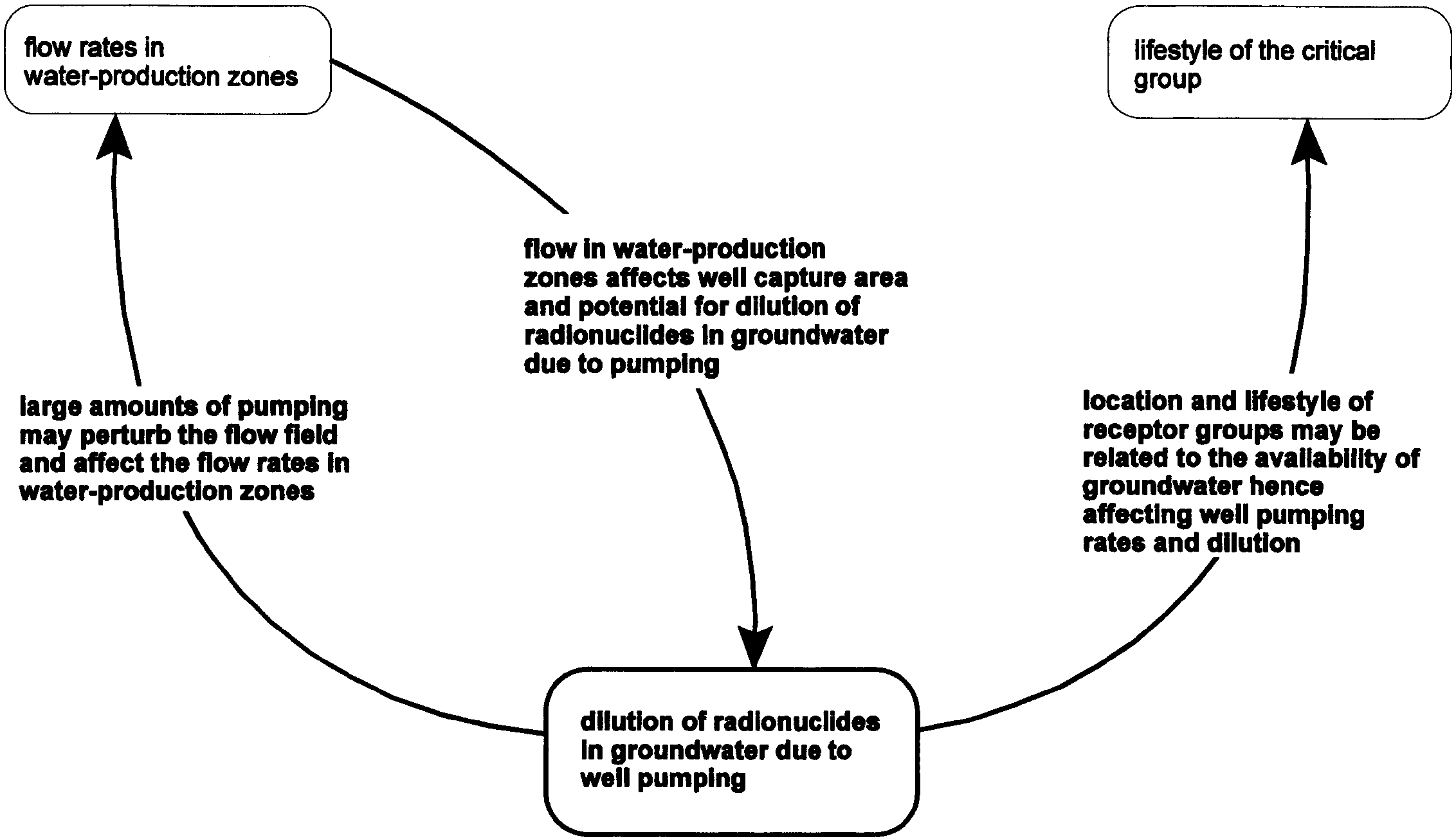


Figure 15. A diagram illustrating the input to and output from dilution of radionuclides in groundwater due to well pumping integrated subissues

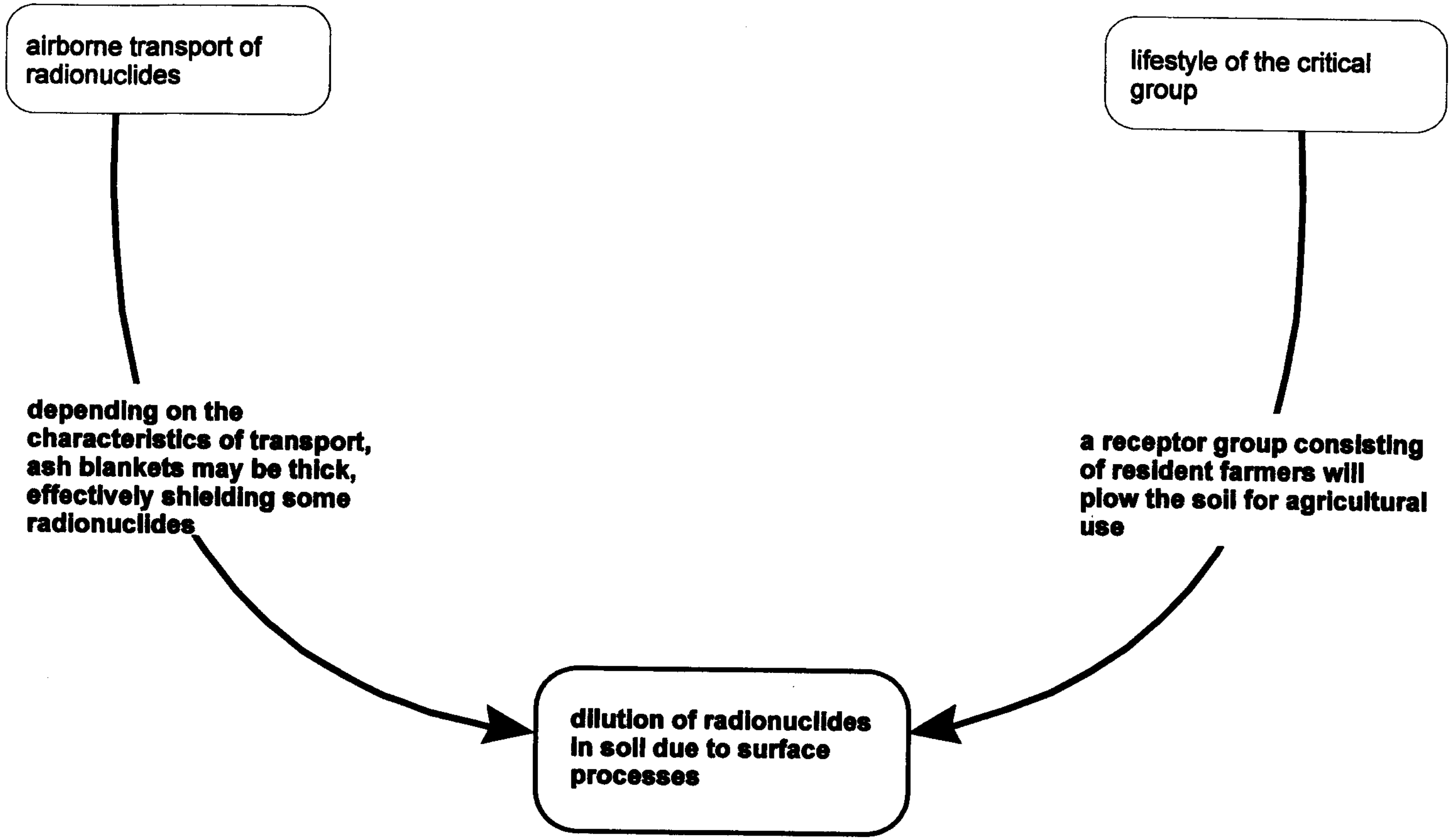
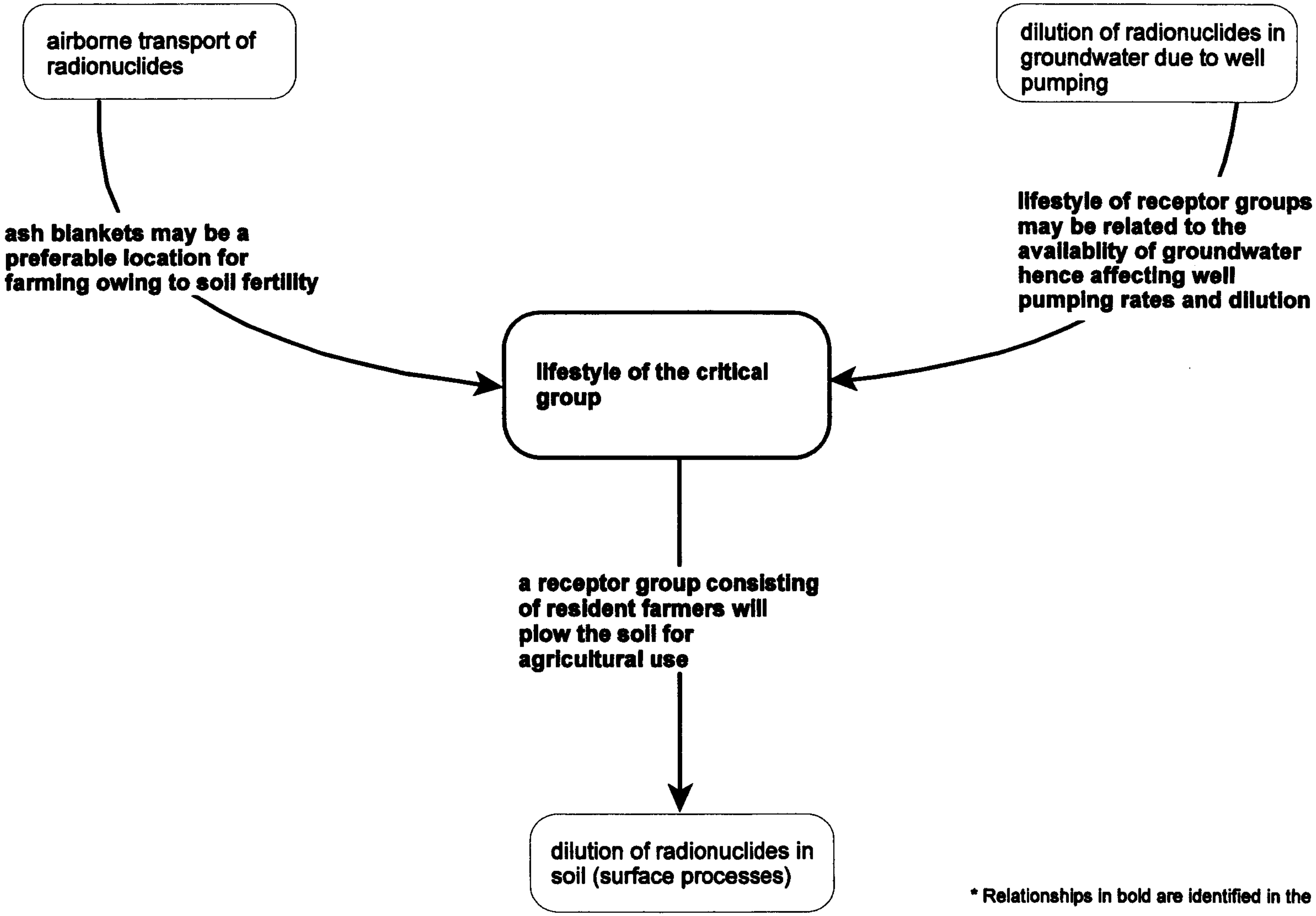


Figure 16. A diagram illustrating the input to and output from dilution of radionuclides in soil due to surface processes integrated subissues



*** Relationships in bold are identified in the text**

Figure 17. A diagram illustrating the relationships between “lifestyle of the critical group” and other integrated subissues

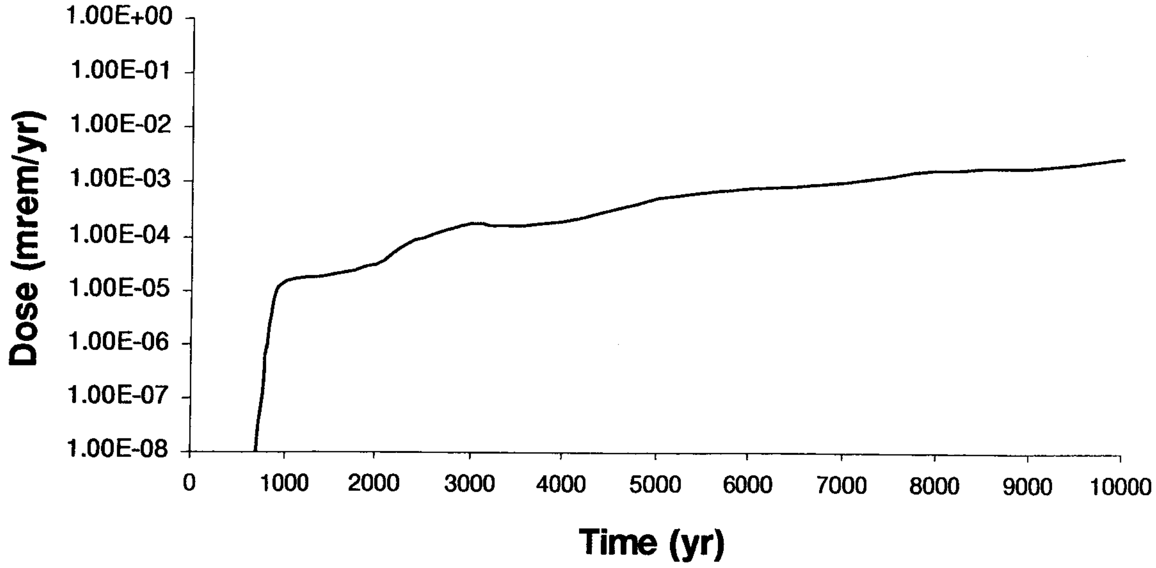


Figure 18. Mean Dose History for the Base Case Performance of the Repository

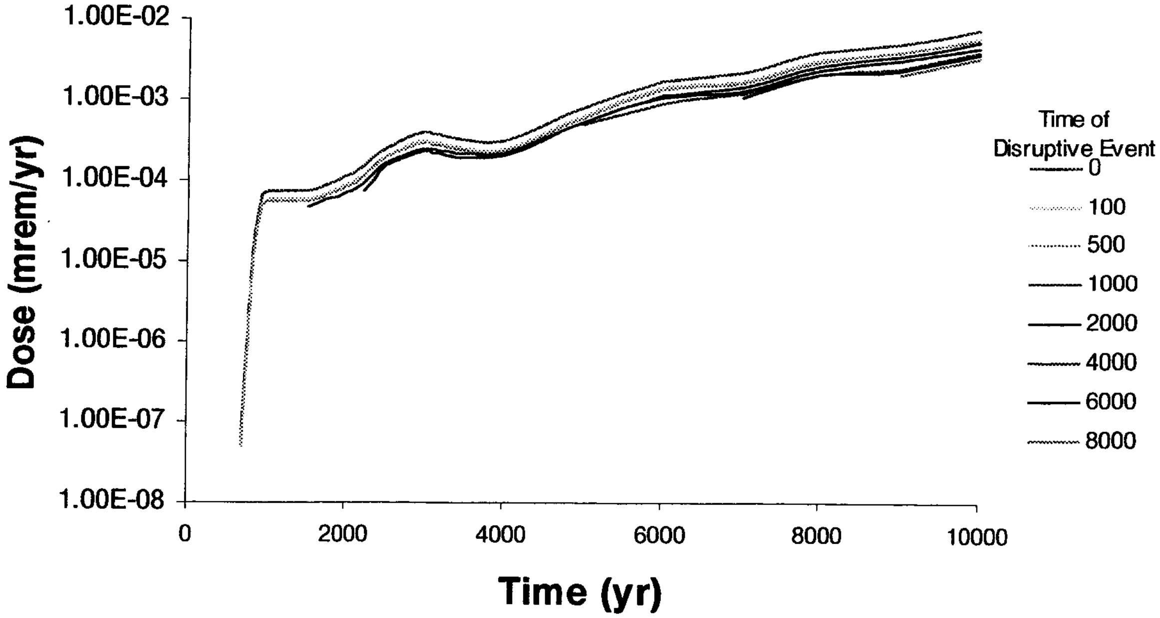


Figure 19. Scenario Class Dose History for Scenario Class Θ Based on Time of Occurrence of the Disruptive Event

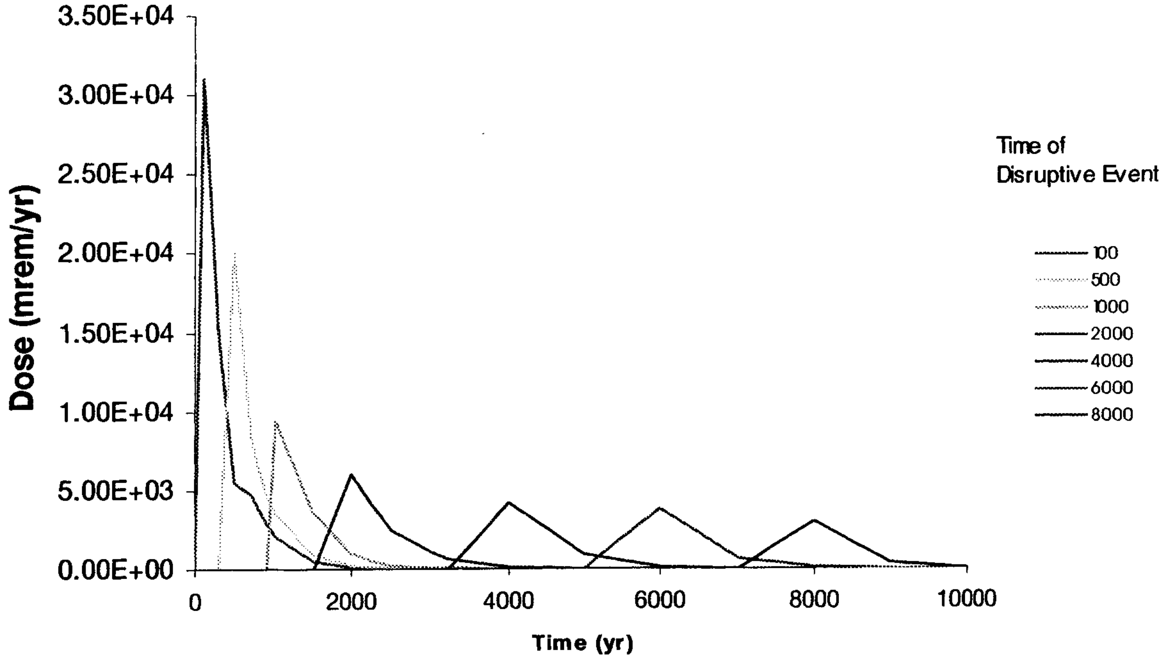


Figure 20. Scenario Class Dose History for Scenario Class Ψ Based on Time of Occurrence of the Disruptive Event

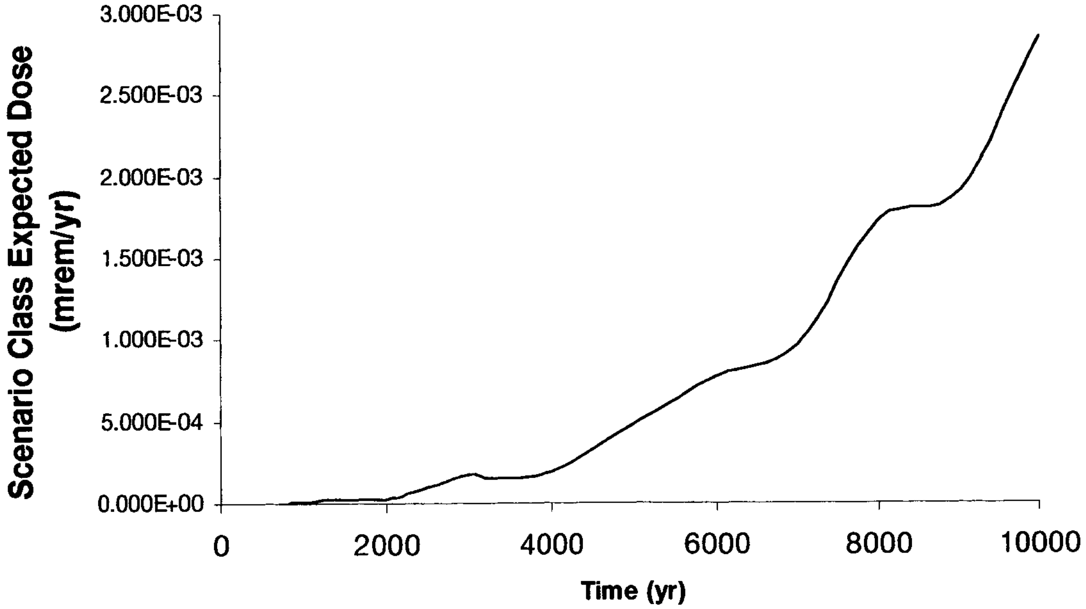


Figure 21. Scenario class expected dose history for basecase

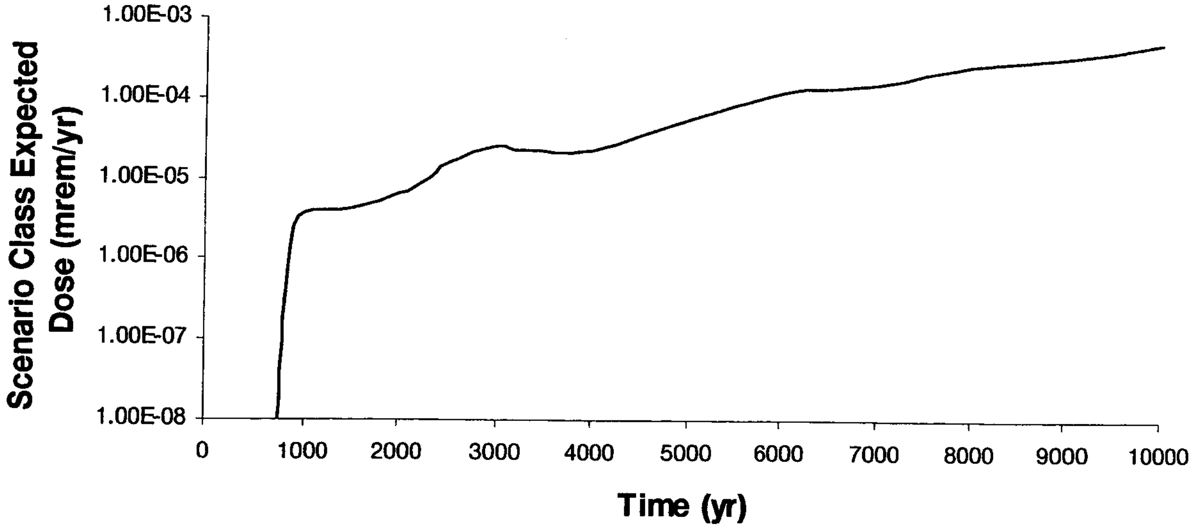


Figure 22. Scenario Class Expected Dose History for Scenario Θ

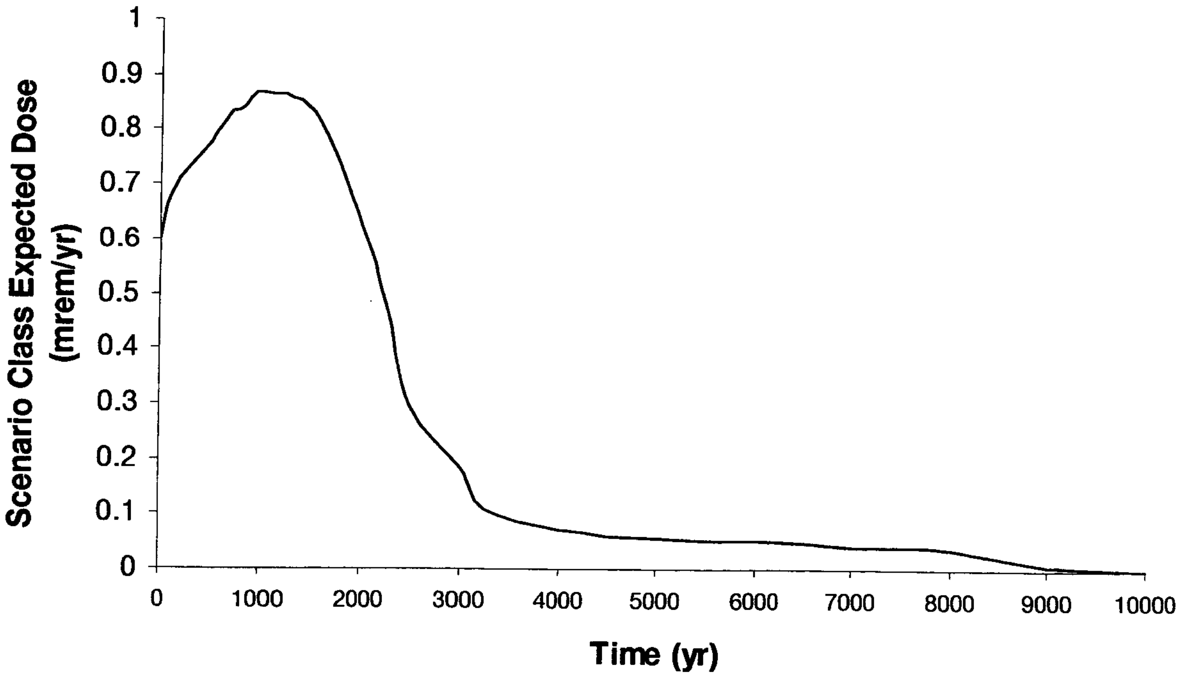


Figure 23. Scenario Class Expected Dose History for Scenario Class Ψ

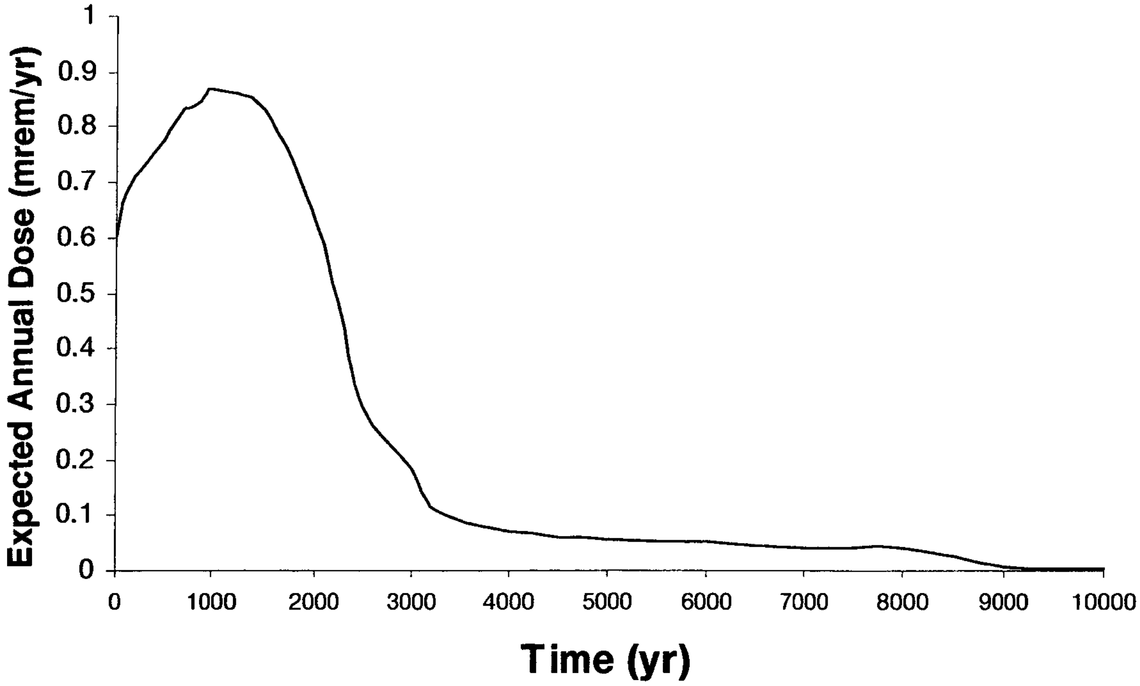


Figure 24. Expected Annual Dose

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 high-level radioactive waste 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 *Site Characterization Plan* (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 NRC, 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, 10 of these scenario-related Open Items were resolved at the staff level.[20] The status of the resolution of TSPAI Open Items is summarized in table 3, including scenario-related Open Items.

Table 4 includes a summary of discussion points that have been raised at recent DOE/NRC Technical Exchanges. These discussion points are discussed in the Sections identified 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.

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[20] 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 license application 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.

Table 2. Resolution summary for TSPAI KTI Open Items

Status of TSPAI KTI Open Items	Number
Resolved	26
Open	6

Table 3. Summary of TSPAI KTI 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	2/12/98; Letter M. Bell to S. Brocoum
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)

Table 3. Summary of TSPAI KTI Open Item status (cont'd)

Item ID	Status	Title	Comment
OSC0000001347C103	Resolved	The Ross sequence numbers 59 through 62 and 64 through 69 do not characterize scenarios	Austin (1996)
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), Roberts (1992), Holonich (1993)
OSC0000001347C110	Resolved	SCP text is unclear as to how human intrusion will be handled	Holonich (1992), Roberts (1992), Holonich (1993)
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), Roberts (1992), Holonich (1993)
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 3. Summary of TSPAI KTI 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.
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.

Table 3. Summary of TSPAI KTI Open Item status (cont'd).

Item ID	Status	Title	Comment
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.
OSC0000001347C099	Open	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.
OSC0000001347C105	Open	Site characterization should provide data, analyses, or justification 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 site characterization is needed	See discussion in Section 4.3.

Table 4. Discussion points identified in recent DOE/NRC 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 4. Discussion points identified in recent DOE/NRC 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
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

Table 4. Discussion points identified in recent DOE/NRC performance assessment technical exchanges (cont'd)

	Questions	Discussion
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

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APPENDIX A:

INTEGRATED SUBISSUES
AND
RELEVANT HYPOTHESES IN
DOE'S REPOSITORY SAFETY STRATEGY

Appendix A. Integrated subissues and relevant hypotheses in DOE's repository safety strategy

Integrated subissues	Hypotheses in DOE's Repository Safety Strategy (U.S. DOE, 1998)																	
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18
WP degradation				X	X	X	X	X	X									
Mechanical disruption of WPs																X	X	X
Quantity and chemistry of water contacting WPs and waste forms				X						X								
Radionuclide release rates and solubility limits											X	X						
Spatial and temporal distribution of flow	X	X	X															
Distribution of mass flux between fracture and matrix													X					
Retardation in fractures in the UZ														X				
Flow rates in water-production zones															X			
Retardation in water-production zones and alluvium														X				
Volcanic disruption of WPs																		X
Airborne transport of radionuclides																		X
Dilution of RNs in groundwater															X			
Dilution of RNs in soil																		X
Lifestyle of critical group	Not Applicable																	

U.S. DEPARTMENT OF ENERGY REPOSITORY SAFETY STRATEGY

LIMITED WATER CONTACTING THE WASTE PACKAGES

Hypothesis #1
Percolation flux at repository depth can be bounded.

Hypothesis #2
Seepage into the emplacement drifts will be a fraction of the percolation flux.

Hypothesis #3
Bounds can be placed on thermally induced changes in seepage rates.

Hypothesis #4
The amount of seepage that contacts WPs can be limited.

LONG WASTE PACKAGE LIFETIME

Hypothesis #5
Heat produced by emplaced waste will reduce relative humidity at the WP surface.

Hypothesis #6
Corrosion rates are very low at low relative humidity.

Hypothesis #7
Double-walled WPs will significantly increase containment times due to protection of the inner barrier by the outer barrier.

Hypothesis #8
Engineered enhancements can extend the long period of containment of the inner barrier.

SLOW RATE OF RELEASE OF RADIONUCLIDES FROM THE WASTE FORM

Hypothesis #9
Containment time will be sufficient to prevent oxidation of spend fuel during the thermal period.

Hypothesis #10
The amount of water that contacts waste can be limited.

Hypothesis #11
Release rate of soluble radionuclides will be controlled by slow dissolution of the waste form.

Hypothesis #12
Release rate of actinides will be controlled by solubility limits rather than by colloidal stability.

CONCENTRATION REDUCTION DURING TRANSPORT THROUGH ENGINEERED AND NATURAL BARRIERS

Hypothesis #13
Physical properties of both engineered and natural barriers will reduce radionuclide concentrations during transport.

Hypothesis #14
Chemical properties of both the engineered and natural barriers will reduce radionuclide concentrations during transport.

Hypothesis #15
Contaminants in the lower volume flow percolating down to the water table will be diluted by the higher volume flow in the aquifer.

DISRUPTIVE PROCESSES AND EVENTS

Hypothesis #16
The amount of movement on faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years.

Hypothesis #17
The severity of ground motion expected in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse.

Hypothesis #18
Volcanic events within the controlled area will be rare and the dose consequences of volcanism will be too small to significantly affect waste isolation.

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 radionuclide release
ENFE4	Effects of thermal-hydrologic-chemical processes on radionuclide transport 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

	radionuclides to the near-field environment
CLST2	Effects of materials stability and mechanical failure on the lifetime of the containers and the release of radionuclides to the near-field environment
CLST3	Rate of degradation of spent nuclear fuel and the rate at which radionuclides 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 radionuclides 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 radionuclide release

Radionuclide Transport (RT)

RT1	Radionuclide transport through porous rock
RT2	Radionuclide transport through alluvium
RT3	Radionuclide transport 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:

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. The TPA code was developed to evaluate the performance of a potential geologic repository at Yucca Mountain and represents NRC's abstraction of the Yucca Mountain 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 1). The components of the subsystems (i.e., engineered barriers, unsaturated zone flow and transport, saturated zone 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 code version 3.2 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 performance assessment 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 WP, disturbed failure of the WP (also called disruptive failures), radionuclide transport, 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 Yucca Mountain. 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 can then be released from the waste form and into the groundwater. The contaminated groundwater will pass through the unsaturated zone and through the saturated zone before its eventual uptake through a well by a receptor group. In the event of extrusive igneous activity, the groundwater pathway is bypassed and radionuclides are transported through the airborne pathway and are distributed throughout an ash blanket within the biosphere. Radionuclides 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, radionuclide 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 unsaturated zone 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, radionuclide release rates [and solubility limits]**, and the transport of these radionuclides through the near-field. **Waste package 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 and chemistry of percolating water) may be influenced by the **spatial and temporal distribution of flow** through the unsaturated zone. 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 unsaturated zone provides an input (i.e., source term of contaminants entering the saturated zone) into the flow and transport of contamination in the saturated zone.

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 fuel 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 relative humidity.

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 unsaturated zone. 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 **radionuclide 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 relative humidity (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 relative humidity 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 **radionuclide 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 radionuclide transport) 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 **radionuclide 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. Waste package 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 radionuclides from the repository to a receptor location. The primary pathways for radionuclide transport at Yucca Mountain are the groundwater pathway and the air pathway. In both cases, the contamination must pass through the unsaturated zone. 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 unsaturated zone, and the saturated zone before reaching the receptor location. The amount of contamination transported through the unsaturated and saturated zones is affected by the number of failed WPs (**WP corrosion** and **mechanical disruption of WPs**)and the **radionuclide release rates (and solubility limits).** In the unsaturated zone, the amount of radionuclides transported is dependent on the **quantity and chemistry of water contacting WPs and waste forms** and the **radionuclide release rates and solubility limits**. Transport of RNs in the unsaturated zone 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 unsaturated zone**; whereas, transport in the saturated zone 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 radionuclides 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 radionuclides 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 spent fuel 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 spent fuel 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 spent fuel matrix, the amount of contamination released to the water depends on solubility limits and the extent to which the spent fuel is wetted. The extent of spent fuel wetting varies by subarea for initial, seismic, and corrosion failures, while the spent fuel 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 radionuclide. Radionuclides flow from the WP into the unsaturated zone 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 radionuclide travel through the invert assumes steady-state flow through the invert and constant and uniform invert material properties. The flow through the unsaturated zone 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 unsaturated zone; 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 saturated zone is considered to be transported along streamtubes that are one-dimensional representations of the saturated zone flow. The dimensions of the streamtubes are based upon 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 saturated zone. For each subarea, the center of the unsaturated zone streamtube is used to determine which one of the four saturated zone streamtubes is utilized in calculations for transporting contamination downgradient to the receptor group location. Matrix diffusion within fractures is considered in the saturated zone as part of the TPA 3.2.

The radionuclides 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 Yucca Mountain region. The attributes of the event and the wind velocity determine the areal distribution of the volcanic ash and spent fuel deposition. The model described in Suzuki (1983) has been modified to calculate the distribution of the released inventory within the biosphere. The time-dependent radionuclide 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 performance assessment and requires the input of earlier components. These earlier components will establish the temporal and spatial distribution of radionuclides at the receptor location. The arrival of radionuclides 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 radionuclides** after a volcanic event (when other gaseous releases are neglected), and the **dilution of radionuclides in soil**. The processes within the biosphere will then result in the redistribution, dilution, and uptake of radionuclides. 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 radionuclides 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 km of the repository that use contaminated groundwater only for drinking and are exposed to surface contamination through inhalation and direct exposure. The second group is comprised of individuals located at least 20 km 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 (TEDEs) 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 radionuclides from surface processes.