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 1

November 1998

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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.

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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

The Commission has previously noted that, as part of the review of site characterization activities specified in the U.S. Nuclear Regulatory Commission's (NRC) geologic repository regulations, it contemplates an ongoing review of information on site investigation and site characterization activities, particularly those activities with long times to completion, 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 the U.S. Department of Energy (DOE), 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. This approach attempts to reduce the number of, and to better define, issues that may be in dispute during the NRC licensing review, after the filing of a license application, by obtaining input and striving for consensus from the technical community, interested parties, and other groups on such issues.

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 the 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 the 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: (1) a reduction in Congressional budget appropriations for NRC in FY 1996; (2) the reorganization of DOE's geologic repository program at Yucca Mountain, Nevada; and (3) 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 Yucca Mountain. 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 DWM approach is to focus most activities on issue resolution of the respective KTIs, at the staff level. DWM activities have been subsequently reprioritized, and organizations have been restructured to support, improve integration of, and streamline the technical work necessary to achieve staff-level resolution. Identifying KTIs, integrating their activities into a risk-informed approach, and evaluating their significance for post-closure repository performance helps 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 Viability Assessment. *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 currently has comments or questions. Feedback is also contained in the staff's Annual Progress Report (e.g., Sagar, 1997), which summarizes the significant technical work toward resolution of all KTIs during the preceding fiscal year. Finally, open meetings and technical exchanges with DOE provide additional opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

In addition to providing feedback, the IRSRs will guide the staff's review of information expected to be included in DOE's Viability Assessment. The staff is currently using the IRSRs to develop the *Yucca Mountain Review Plan* for any potential repository license application.

This IRSR contains six sections, including this introduction in Section 1.0. Section 2.0 defines the KTI, all related subissues, and the scope of the particular subissue or subissues addressed in the IRSR. Section 3.0 discusses the importance of the subissue to evaluation of repository performance. Section 4.0 provides the staff 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 staff technical basis for its acceptance criteria will also be 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.

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

The DOE demonstration of compliance with applicable standards for disposal of high-level waste in a geologic repository at Yucca Mountain (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 total system performance assessment (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

[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.104, passed by the Senate on April 15, 1997, and H.R. 1270, passed by the House on October 30, 1997). 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.

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 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.

(1) Demonstration of the Overall Performance Objective — This subissue focuses on the role of the performance assessment 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.

(2) Demonstration of Multiple Barriers — This subissue focuses on the demonstration of multiple barriers and includes: (1) identification of design features of the engineered barrier system and natural features of the geologic setting that are considered barriers important to waste isolation; (2) descriptions of the capability of barriers to isolate waste; and (3) identification of degradation, deterioration, or alteration processes of engineered barriers that would adversely affect the performance of natural barriers.

(3) 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 performance assessment and the integration of those factors to ensure a comprehensive analysis of the total system.

(4) 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. This is a key factor in ensuring the completeness of a TSPA.

(5) Transparency and Traceability of the Analysis—This subissue emphasizes staff expectation of the contents of DOE's TSPA to support a LA. Specifically, it focuses on those aspects of the TSPA that will allow for an independent analysis of the results.

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, technical basis for the acceptance criteria, and adds acceptance criteria for scenario analysis. Succeeding versions of this IRSR will add acceptance criteria related to: (1) use of performance assessment to support demonstration of compliance with the overall performance objective, (2) demonstration of multiple barriers, and (3) transparency and traceability of the performance assessment. These upcoming revisions also will update the acceptance criteria, review methods and status of resolution at the staff level for the model abstraction and scenario analysis subissues.

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. 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 performance assessment in its license application (U.S. Nuclear Regulatory Commission, 1997). 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 the DOE 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 performance assessment 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-VA; (iii) provide a basis for judging the sufficiency of data in DOE's Draft LA for the YM site; (iv) facilitate constructive review and comment on DOE's Draft Environmental Impact Statement; and (v) prepare for an effective and efficient review of a potential LA.

3.2 IMPORTANCE OF SUBISSUES TO TOTAL SYSTEM PERFORMANCE

The five subissues identified in section 2.0 include the essential components of a TSPA and how the TSPA is used to demonstrate compliance with regulatory requirements. Resolution of subissue 1, demonstration of the overall performance objective, ensures that DOE has appropriately executed the performance assessment 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). Resolution of subissue 2, demonstration of multiple barriers, ensures that DOE has: (1) identified the design features of the engineered barrier system and natural features of the geologic setting that are considered important barriers to waste isolation; (2) described the capability of the barriers important to waste isolation; and (3) provided a technical basis for its description of the capability of the barriers. 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, scenario analysis, ensures that the performance assessment appropriately considers likely processes and events in the performance assessment. Resolution of subissue 5, transparency and traceability of the analysis, ensures compliance calculations in DOE's TSPAs are clear and consistent, which builds confidence in the overall analysis and allows the staff to efficiently complete its independent review.

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 3.0. Staff past independent research effort, review of previous DOE TSPAs, information learned during meetings with DOE, approaches used in staff's Total-system Performance Assessment (TPA) Version 3.1 code, 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 3.1 code has been incorporated to the extent feasible.

There are two programmatic acceptance criteria that are applicable to the subissues, but apply directly in the case of subissues three and four (model abstraction and scenario analysis). These programmatic acceptance criteria apply to quality assurance and expert elicitation. The development of data, models, and computer codes — whether they are used for scenario analysis or support development of conceptual models in the performance assessment or to provide input for the performance assessment — 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 DEMONSTRATION OF THE OVERALL PERFORMANCE OBJECTIVE

This section will be developed in revision two of the IRSR. A proposed strategy for developing regulations for the disposal of high-level radioactive waste in a Yucca Mountain 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 Yucca Mountain 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). Demonstration of compliance with the overall performance objective will be supported with DOE's performance assessment, which includes model abstraction (Section 4.3), treatment of scenarios (Section 4.4) and transparency of the analysis (Section 4.5). The final requirements for the overall performance objective will be established after a public rulemaking and the acceptance criteria will be modified (as needed) to be consistent with the final regulations.

4.2 DEMONSTRATION OF MULTIPLE BARRIERS

This section will be developed in revision two of the IRSR. A proposed strategy for developing regulations for the disposal of high-level radioactive waste in a Yucca Mountain repository was outlined in "Proposed Strategy for Development of Regulations Governing Disposal of High-Level Radioactive Wastes in a Proposed Repository at Yucca Mountain" (U.S. Nuclear Regulatory Commission, 1997). This strategy indicates that a demonstration of multiple barriers would be maintained, but would not incorporate the existing subsystem performance objectives in 10 CFR Part 60. In demonstrating compliance with the overall system performance objective, DOE would need to present the results of intermediate calculations, along with their associated uncertainties, to demonstrate the effectiveness and diversity of the barriers as a measure of the resiliency of the repository. Demonstration of multiple barriers will be supported with DOE's performance assessment, which includes model abstraction (Section 4.3), treatment of scenarios (Section 4.4), and transparency of the analysis (Section 4.5). The final requirements for the demonstration of multiple barriers will be established after a public rulemaking and the acceptance criteria will be modified (as needed) to be consistent with the final regulations.

4.3 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 1. 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 1. 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.[2] 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 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

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[2] 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.

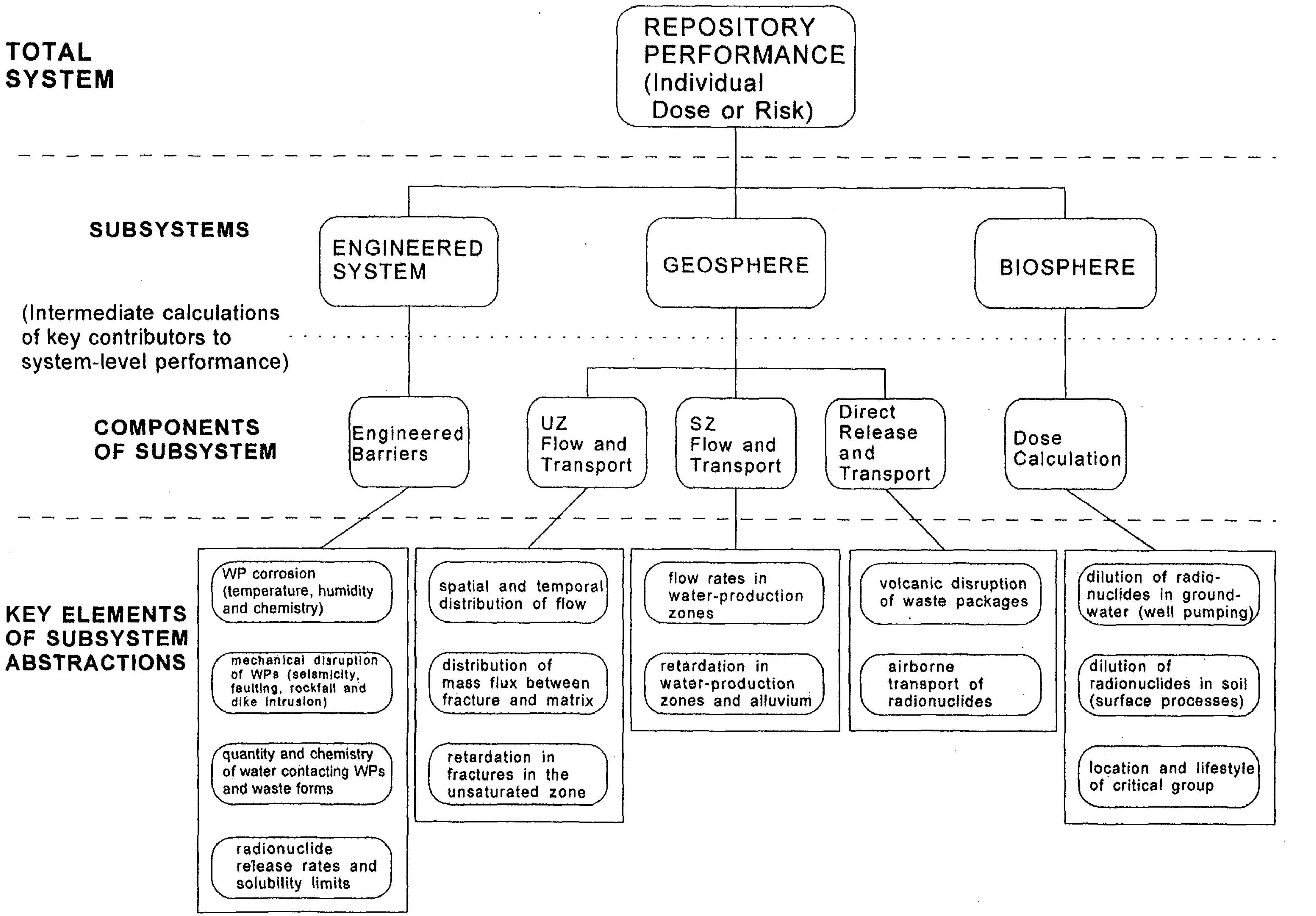

Figure 1. Flowdown diagram for total system performance assessment.

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 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 key elements of subsystem abstraction (KESAs) 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 KESA, 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 KESAs. The general principles underlying the technical criteria apply to all KESAs and are reiterated and customized for each KESA 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.
Criterion T2	Data Uncertainty and Verification - 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 Verification - Models implemented in the TSPA provide results consistent with output of detailed process models or empirical observations, 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 KESAs (see the bottom tier in figure 1). Note that although the AC and RMs are presented by KESA, the intent of criterion T5 is to emphasize the appropriate interfaces among two or more KESAs. In an attempt to be more explicit on the integration aspect, to the extent feasible, potential important interfaces between the various KESAs are identified under T5. Successful application of criterion T5 ensures that consistent assumptions, data, and models have been implemented in the TSPA. For each KESA, those DOE repository safety strategy hypotheses considered pertinent to that KESA can be found in appendix A. Descriptions for the pertinent KTI subissues that have been identified at the beginning of each KESA section are listed in Appendix B. Note also that the relationship of individual KTI subissues to a particular KESA 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.

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 1 (i.e., Waste Package 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, 1998). 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 KESAs are met.

4.3.1.1.1 Waste Package Corrosion (Temperature, Humidity and Chemistry)

Pertinent KTI subissues: CLST1, 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) 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.[3] However, the most recent DOE TSPA (TRW,1995) uses an empirical description of WP corrosion. 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. NRC has previously questioned the adequacy of the approach used by the 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). Specifically, 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[4] can affect WP lifetime.

<u>**Acceptance Criteria with Review Methods**</u>

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.

<u>Criterion T1</u>: Sufficient data (field, laboratory and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the WP corrosion abstraction in TSPA.

<u>Review Method</u>: 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. For example, 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

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

[4] 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.

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 verified through comparison to output of detailed process models and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified the output of WP corrosion 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 WP corrosion abstraction against results produced by the detailed process-level model.

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.[5] For example, if conditions and assumptions used to generate look-up tables or regression equations[6] 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[7] 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 KESAs:

- Seismic (and possibly fault formation) mechanical disruptions may create weak spots on the WP for enhanced corrosion. Nearby dike intrusions into the repository will change, for example, both the near-field temperature and chemistry to which the WP is exposed for some length of time (mechanical disruption of WPs).
- Near-field chemistry (e.g., pH, chloride concentration, dissolved oxygen concentration, 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 2. Staff should verify that DOE's domain-based[8] 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.

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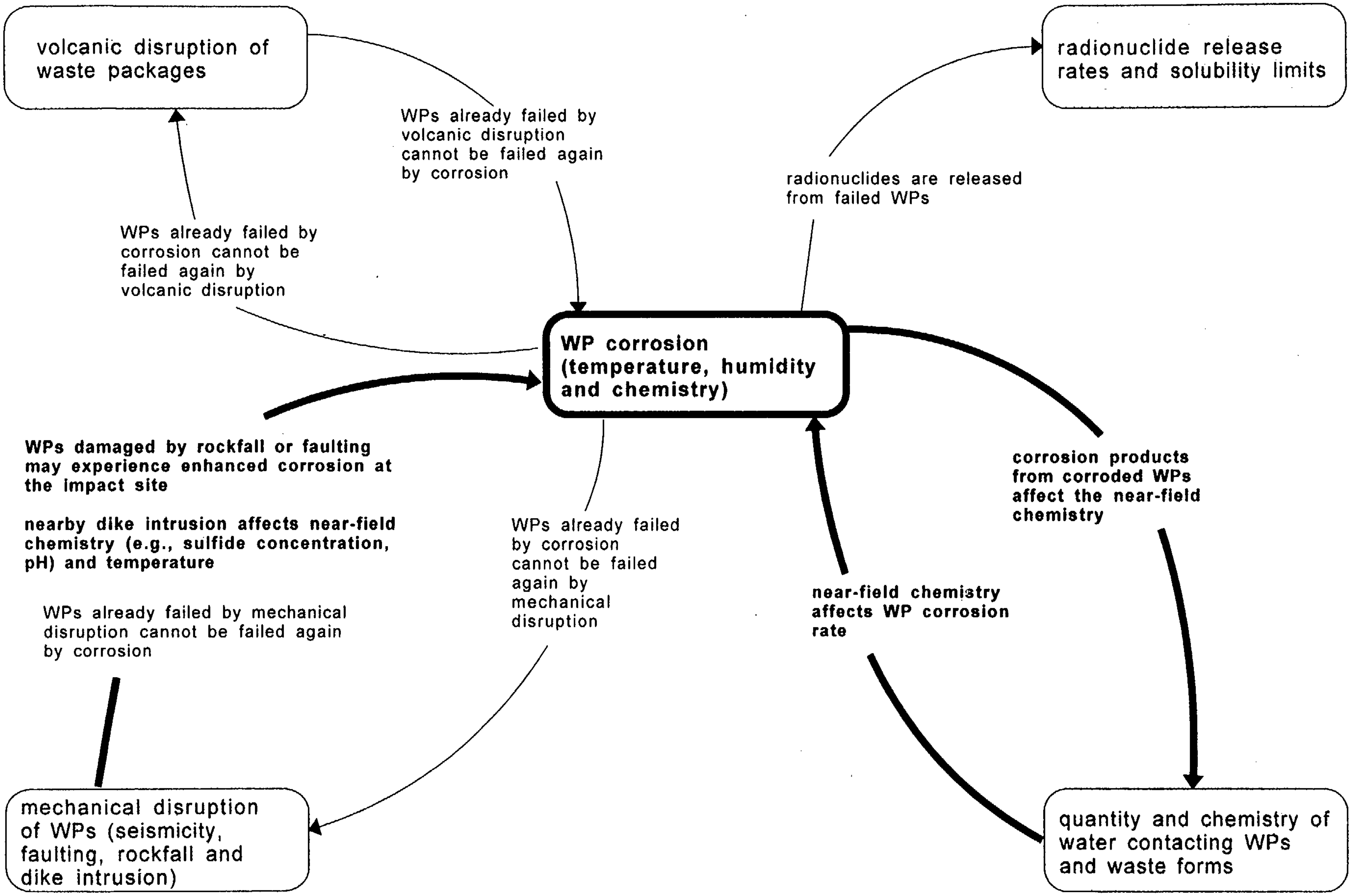
[5] For TSPA-VA, the types of abstraction are defined in section 3.3 of the TSPA-VA Plan (TRW, 1996).

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

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

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



* Relationships in bold are identified in the text

Figure 2. A diagram illustrating the relationships between "waste package corrosion" and other key elements of subsystem abstractions.

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), 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). However, 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 the current DOE design (U.S. Department of Energy, 1996), 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 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 performance assessments. 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. Because the inner 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 waste package 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. 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 outer 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). It is noted that 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.

After the carbon steel outer overpack is penetrated, the aqueous corrosion of the inner overpack material is determined by the chemistry of the environment contacting the inner overpack, the critical potential for localized corrosion of the inner overpack material, 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).

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).

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.

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 the most recent DOE TSPA (TRW Environmental Safety Systems, Inc., 1995) did not address disruptive scenarios, future DOE TSPA iterations (e.g., TSPA-VA) will include these disruptive events.[9] Previous 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, however. 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.[10]

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[9] DOE/NRC Technical Exchange on Performance Assessment, July 21-22, 1997, Center for Nuclear Waste Regulatory Analyses, San Antonio, TX.

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

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.

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. For example, 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.[11]

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.

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

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 verified through comparison to output of detailed process models, and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified 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.

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 KESA:

- 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 3. 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. It is noted that the 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). TSPA should address the effect of seismicity on the engineered barrier system. Specifically, the effects of low frequency seismic events of large magnitude, and the cumulative effect of repeated episodes of seismic loading due to high frequency low magnitude events on the stability of emplacement drifts are of potential concern (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. It is noted that 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 deflection that the WP experiences due to rock falls; if the deflection reaches a threshold value, the WP is considered to be failed.[12]

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 (Ghosh *et al.*, 1997) use probabilistic techniques to

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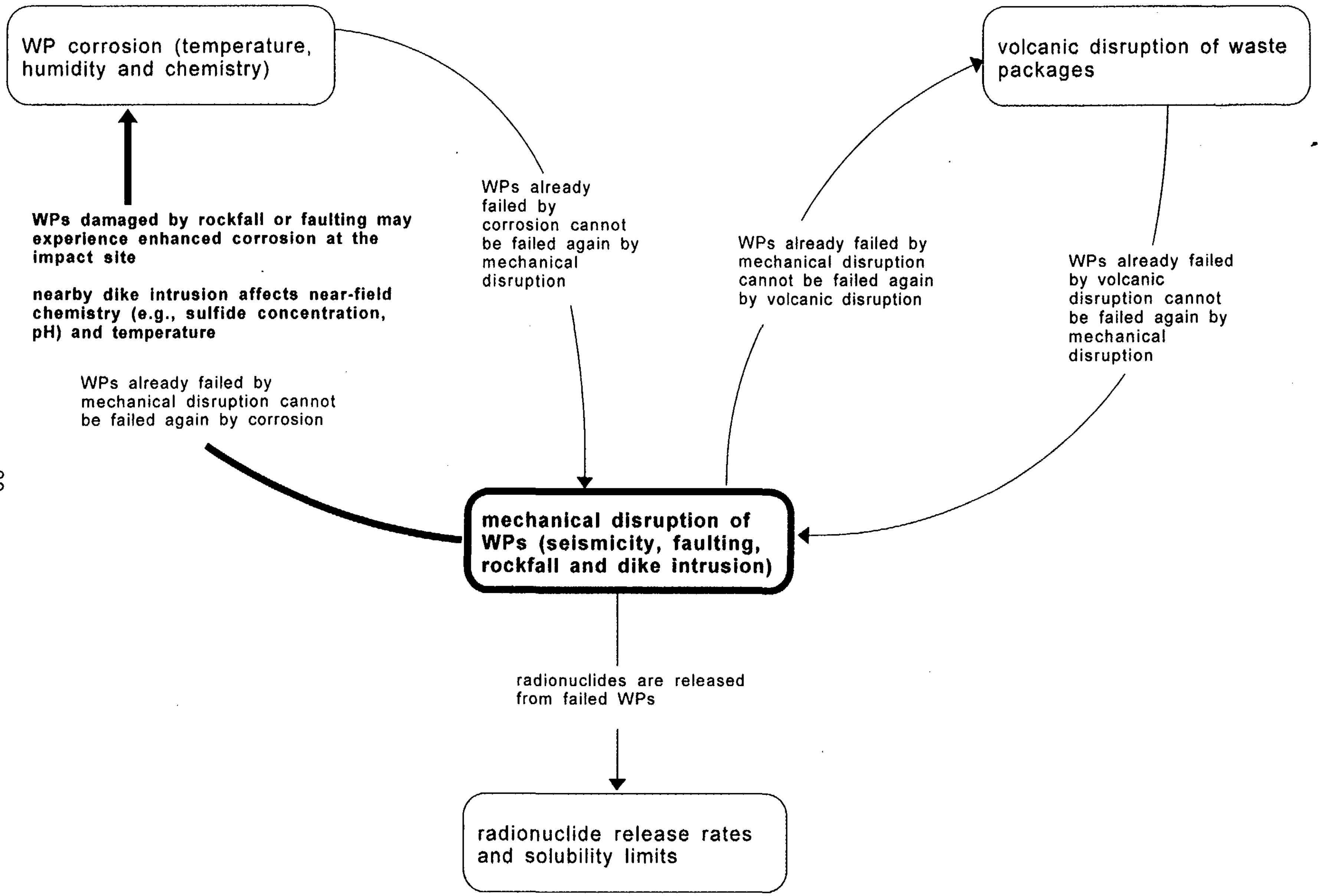
[12] In the latest version of the NRC TPA code, a maximum allowable strain failure criterion is adopted for WP failure (see appendix C).



* Relationships in bold are identified in the text

Figure 3. A diagram illustrating the relationships between "mechanical disruption of waste packages" and other key elements of subsystem abstractions.

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 waste package 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 (1) the critical faulting region, (2) the recurrence rate of faulting, and (3) the percent of faults in the critical region that also intersect the repository. Center for Nuclear Waste Regulatory Analyses (1998e) 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.

Formation of volcanic dikes in the repository footprint at future times may also need to be incorporated into the performance assessment. Magma forming the dike, typically at temperatures of about 1,100°C, may result in the premature failure of WPs. Although most recent efforts in performance assessment have not modeled the indirect effects of volcanism from dike formation (TRW Environmental Safety Systems, Inc., 1996), previous iterations 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. If future sensitivity studies show dike formation to be a significant contribution to WP failure (not bounded by other failure mechanisms) this may be an area for future TSPA improvements.

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. TSPA should address the possible degradation of the mechanical properties of the material (i.e., fracture toughness) combined 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 C119-22 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. Although cladding protection was not considered in TSPA-95. DOE may include cladding as an additional metallic barrier in the TSPA-VA. Although several mechanisms have been identified for the failure of Zircaloy cladding, such as damage due to rock fall, unzipping due to volume expansion from fuel oxidation, localized corrosion, creep, delayed hydride cracking, hydrogen embrittlement, SCC, and cladding oxidation; the TSPA-VA abstraction may be limited to the potentially significant processes. 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. It is expected that for the mechanical failure calculation, existing defects in the cladding and propagation of cracks as a function of time will be taken into consideration. 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.

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

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

RN release rates from breached WPs (corrosion or mechanical disruptions) are dependent on the quantity and chemistry of water contacting the WPs and subsequently the waste forms. The quantity of water contacting waste forms is a major factor in determining RN migration to the accessible environment. The quantity 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 performance assessments (PAs) would be dry air oxidation and humid air corrosion. Also for this case, the groundwater release would be largely eliminated, even if WP failures were to occur 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 currently under investigation by NRC and DOE.

The chemistry of water contacting the waste plays an important role in determining the source term for the exposure from the groundwater pathway. For example, solubilities of RNs in water are dependent upon pH and oxygen content (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 are dependent upon pH (Turner, 1993, 1995).

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.

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. For example, 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 verified through comparison to output of detailed process models and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified the output of quantity and chemistry of water contacting WPs and waste forms abstraction reasonably 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.

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 KESAs:

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

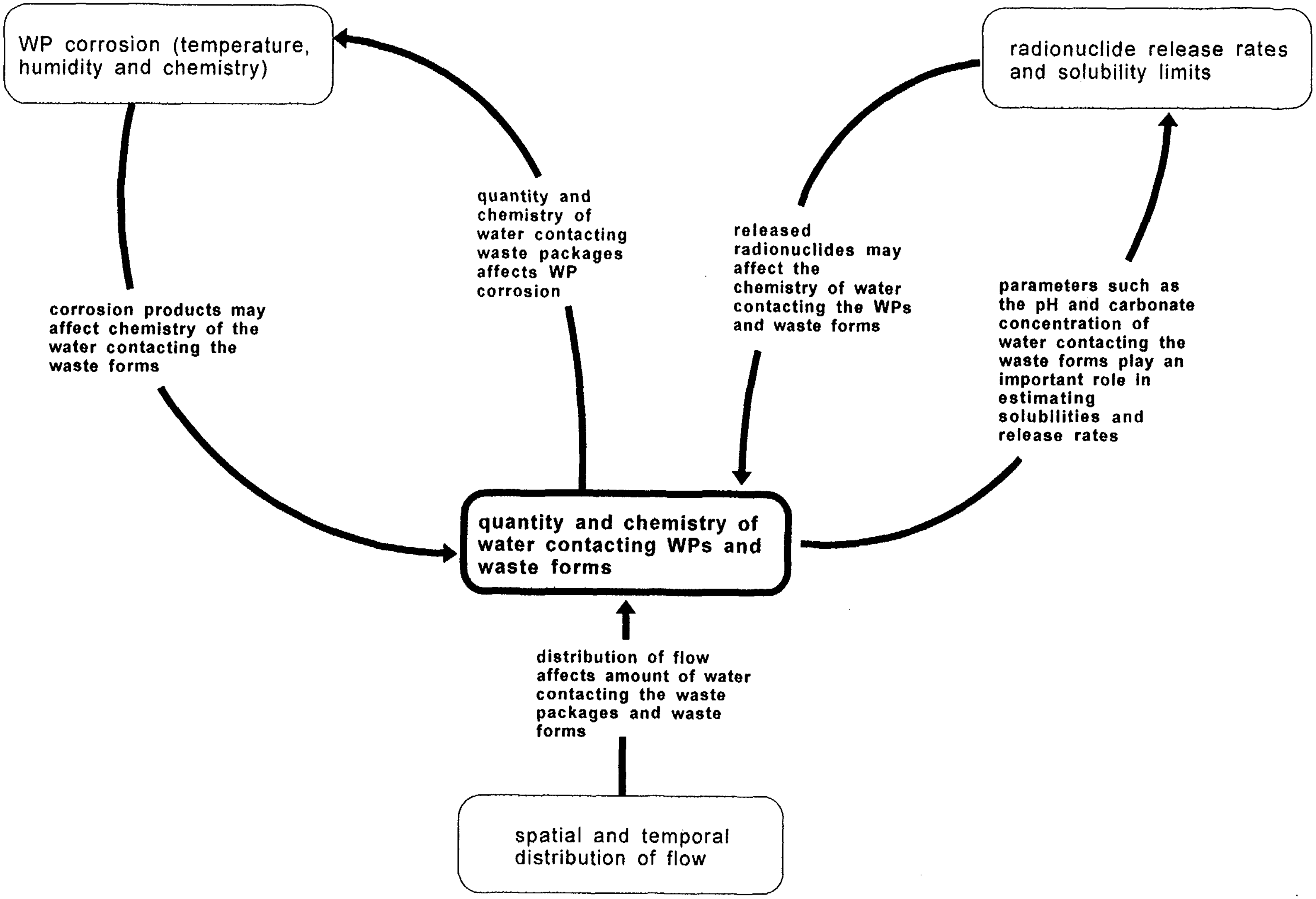
- Corrosion products may affect chemistry of the water contacting the waste forms. Quantity and chemistry of water contacting WPs affects WP corrosion (WP corrosion).

- 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 4. 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

The quantity of water contacting WPs plays an important role in determining the lifetime of the WP and the release rates of RNs after the WPs have failed. Current models for predicting WP lifetimes have several regimes for the predominant failure mechanism 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 the release of RNs is dissolution rate limited, a large flow of water contacts waste forms such that not all the water can be saturated with a given RN (due to limited waste surface areas). In this case, RN releases in performance assessment are usually calculated by multiplying the WP RN inventory by a maximum fractional release rate for that RN (Mohanty *et*



* Relationships in bold are identified in the text

Figure 4. A diagram illustrating the relationships between "quantity and chemistry of water contacting WPs and waste forms" and other key elements of subsystem abstractions.

al., 1997). In the solubility-limited regime, there is sufficient surface area contacted by water and sufficient RN inventory to completely saturate the water with a given RN. In either case, it is necessary to estimate the quantity of water contacting the waste. It is noted that 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; 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 earlier 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 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). In previous DOE TSPAs (Wilson *et al.*, 1993), uncertainties in YM groundwater pH are characterized as providing one of the major sources of uncertainty for predicting RN solubilities. Distribution coefficients for host rock minerals of the repository block and other parts of the repository system are also dependent on pH (Turner, 1993, 1995).

4.3.1.1.4 Radionuclide Release Rates and Solubility Limits

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

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

A typical approach to analyze the radionuclide release rates and solubility limits is as follows. The solubility of the waste matrix, when combined with an amount of water in contact with the waste, determines the annual fraction of RN inventory released to WP waters. If annual releases of RNs to WP water dictate concentrations greater than the solubility limits would allow, then RN concentrations are truncated to the solubility limits. In this manner, both RN solubilities and the waste matrix solubility (determining the release rate for RNs) 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 and/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.

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. For example, 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 is verified through comparison to outputs of detailed process models and/or empirical observations (field, laboratory and natural analog data).

Review Method: Staff should ascertain whether DOE verified 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.

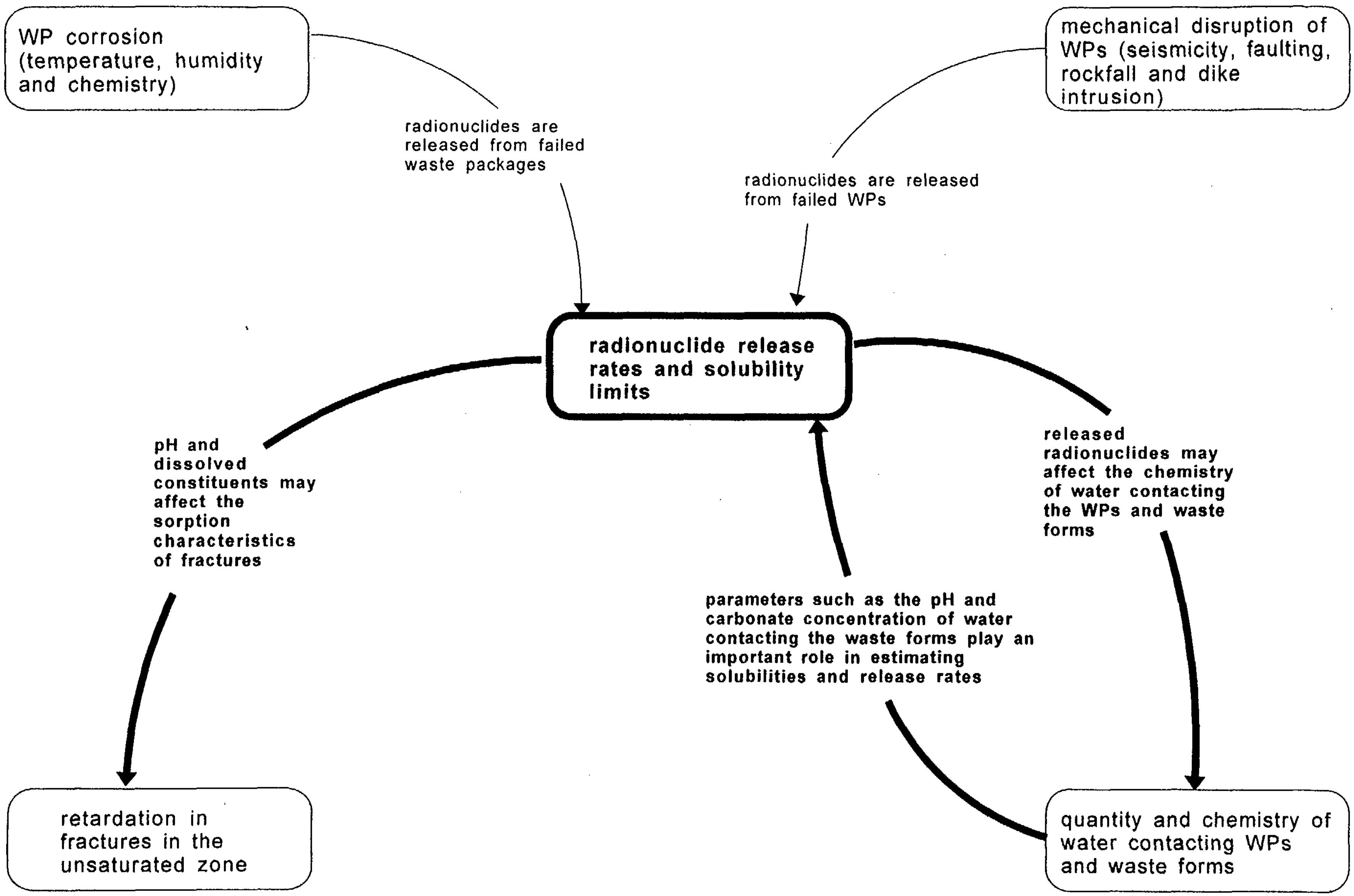
Criterion T5: Important design features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the radionuclide release rates and solubility limits abstraction.

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 KESAs are:

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

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

These relationships and other computational input/output are illustrated in figure 5. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C) or sufficient justification has been provided to exclude these couplings. To



* Relationships in bold are identified in the text

Figure 5. A diagram illustrating the relationships between "radionuclide release rates" and solubility limits" and other key elements of subsystem abstractions.

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 form with liquid water, transport in liquid water, and the solubility limit 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 and 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 waste package at a rate controlled by either (1) the rate of waste form decomposition (i.e., congruent dissolution), (2) the rate of dissolution of secondary mineral into which the RNs have become incorporated (e.g., schoepite), or (3) the solubility of the radionuclides 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). Solubility of radionuclide elements might limit concentrations in WP water if release of radionuclides from the waste form would result in concentrations higher than the solubility limit (although colloid precipitation is also a possibility).

Current NRC performance assessment (PA) models (Mohanty *et al.*, 1997) use what is referred to as the "bath tub" model where a volume of water is stored within a failed WP.[13] Advective and diffusive releases from the WP are estimated, both of which require estimation of time dependent RN concentrations in the water contained within the WP. In advective release, the rate at which water exits the WP is multiplied by the RN concentration to obtain an exit rate for RNs from the WP. In diffusive release, the concentration of RNs in WP waters is used to estimate the concentration gradient necessary for calculating the diffusive flux of RNs from the WP.[14] To estimate time dependent RN concentrations inside a breached WP, alternative expressions for the dissolution rate of RNs in the 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 the dissolution rate multiplied by the RN inventory in the WPs. First order rate equations are used to estimate RN concentrations as a function of time in WP waters, with the upper limit being the solubility of the RN.

In the next version of the NRC's TPA code, the effect of the invert will be taken into consideration. The radionuclides exiting the WP will go through the invert, whose physical properties may have been altered by the cemetitious materials, before leaving the EBS. 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.

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[13] 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.

[14] The diffusive release calculation will be omitted in the subsequent version of TPA code based on preliminary analysis in which diffusive release was found to be several orders of magnitude smaller than advective release.

Models in DOE's TSPA-95 (TRW Environmental Safety Systems, Inc., 1995) used essentially the same model as NRC assessments, however, no credit is taken for portions of the waste not in contact with 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.

Both the RN and waste matrix solubility are strongly dependent upon the near-field environment (i.e., temperature and chemistry of water contacting waste). The chemistry of water contacting the waste affects the oxidation state in which RNs exist and ultimately, the solubility and release rate of the RNs. In an oxidizing environment such as the YM repository setting, UO_2 in the SNF may ultimately exist as U_3O_8 or UO_3, which have markedly different solubilities from UO_2. Similarly, Tc is generally considered to be very soluble under oxidizing conditions but relatively insoluble under reducing conditions (Kerrisk, 1984). Solubility limits are also sensitive to parameters dictated by the chemistry of the near-field environment. For example, the model for dissolution rate of SNF (and hence RNs contained in the fuel) given in Gray and Wilson (1995) and reiterated in Mohanty, *et al.* (1997) contains equations with terms dependent upon pH, carbonate concentration, temperature, and Si and Ca concentrations.

Secondary minerals could precipitate on or near the SNF as a result of homogeneous reaction 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 . Periodic spallation of the dissolution product could occur exposing fresh surface 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 the secondary mineral deposits (Buck et al.,1998; Bates,1998b). While it is recognized that DOE does not take credit for SNF surface masking by secondary minerals, consideration should be given to the easy access of some nuclides to the water contacting the SNF.

In spite of small volumetric inventory of HLW glass, its contribution to performance assessment 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 model should reflect data from natural analogs for such long term behavior. The secondary phases on the surface of the glass waste could be released as colloids that could lead to sudden increase in actinide concentration in the near-field environment. DOE's long-term dissolution model should consider the dominant colloid formation processes under anticipated repository conditions and should not underestimate colloidal releases. Microbes can also change the solubilities of radionuclides by the increased production of organic acids.

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

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 1 (i.e., spatial and temporal distribution of flow, distribution of mass flux between fracture and matrix, retardation in fractures 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 KESAs 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

Various hypotheses have been advanced as to how shallow infiltration and deep percolation are related. Most PAs assume that flow is primarily vertical and considered to be uniform over large spatial dimensions (typically averaged over 0.1 to 1 square kilometer). Therefore, when considering transport, deep percolation and shallow infiltration are numerically equal. 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. Bodvarsson and Bandurraga (1996), using a three dimensional site-scale model of the UZ, suggest that relative proportions of shallow infiltration being laterally diverted at the PTn may become smaller as fluxes increase. The possibility of nonvertical flow under the PTn layer from Solitario Canyon has not been considered in YM PAs to date.

Matrix properties of the low-permeability zeolitic units underlying YM have the potential to retard movement of many RNs owing to the highly adsorptive properties of the zeolites. The benefit, derived from the geochemical properties of the matrix, of the 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, 1996) or increase the potential for fracture flow within the low-permeability unit, or both, resulting in limited contact of RNs with the zeolites. Temporal (i.e., episodic nature of deep percolation) flow and the presence of low-permeability zones such as the zeolitic units influence lateral diversion. The effect of lateral diversion on the spatial distribution of flow and the potential for fracture flow has not been considered in YM PAs to date.

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.

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. For example, 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., 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 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 verified through comparison to output of detailed process models, and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain that DOE verified 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.

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 KESAs:

- 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).

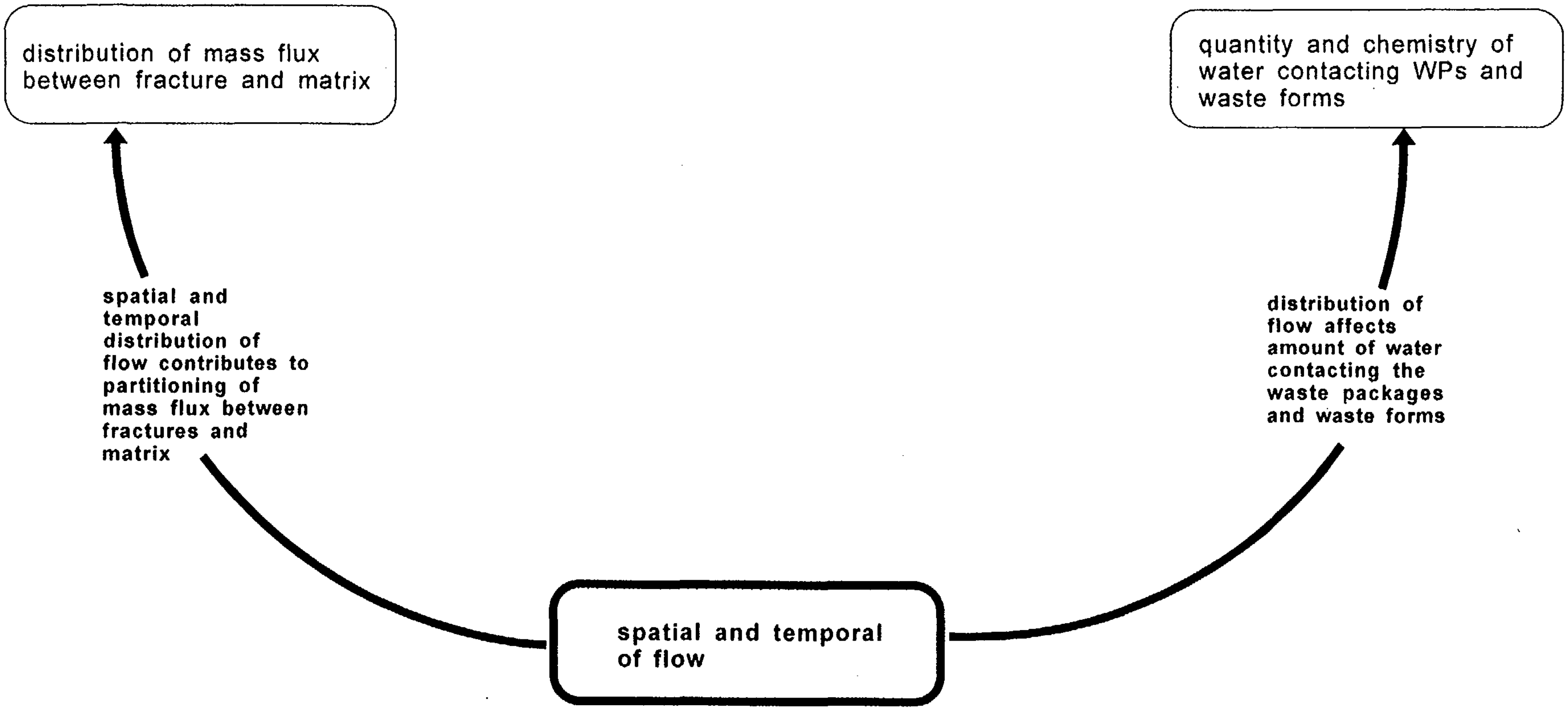
These relationships are illustrated in figure 6. Staff should verify that DOE's domain-based and temporal abstractions appropriately handled the physical couplings (T-H-C-M) or sufficient justification has been provided to exclude these couplings. To the extent feasible, staff should use the TPA code 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). 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. Shallow infiltration is not spatially or temporally uniform, occurring in pulses following precipitation with a magnitude dependent on factors such as soil cover, evapotranspiration, and type of bedrock. Flow paths may also be focused by heterogeneities such as fracture and fault zones (U.S. Nuclear Regulatory Commission, 1998b). As water moves deeper, wetting pulses attenuate and spread to become more temporally uniform. 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). A vertically oriented 2D model may be necessary below the repository (U.S. Nuclear Regulatory Commission, 1998b) to account for lateral flow diversion.

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.

DOE's TSPA-95 also assumes that infiltrating waters proceed through the repository horizon to the water table with negligible lateral diversion, and deep percolation is assumed to adjust quickly to climatic variation. DOE also links the periodicity of MAI to glacial cycles, but does not provide a mechanistic link between MAI and climate. MAI is assumed to vary linearly between current and peak conditions. In effect, DOE's model assumes that the fraction of Full Glacial Maximum (FGM) varies linearly between minimum and maximum, and that MAI is linearly dependent on FGM.



* Relationships in bold are identified in the text

Figure 6. A diagram illustrating the relationships between "spatial and temporal distribution of flow" and other key elements of subsystem abstractions.

For time periods beyond 10,000 years, even for identical NRC and DOE current-climate estimates of MAI, NRC estimates of future-climate MAI are expected to be considerably larger than DOE estimates for two reasons: (i) NRC estimates that the wetter and cooler glacial conditions will be more common than DOE's estimates, and (ii) the NRC estimates that MAI changes exponentially with climatic change whereas DOE's estimates that MAI changes linearly. Increased MAI can lead to earlier and larger RN releases and faster transport of RNs to receptors.

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. When the capacity of the rock matrix to conduct water is larger than the total amount of flow, little or no water will flow in fractures owing to capillary forces acting on the water. When the total flow is at or above the matrix flow capacity, fractures conduct fluid in excess of the matrix capacity. 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 (TRW Environmental Safety Systems, Inc., 1995).

Transport of RNs is strongly affected by the proportion of flow within the rock matrix. Subsurface flow that is predominantly through the matrix ensures relatively slow movement of water. In addition, owing to enhanced contact with rock constituents, RNs may be more highly retarded when transported within the rock matrix than within fractures. In contrast, subsurface flow within well-interconnected fractures is more likely to provide (i) liquid flux into drifts, (ii) rapid pathways through the UZ, and (iii) minimal sorption onto rock constituents.

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

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.

<u>Criterion T1</u>: 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.

<u>Review Method</u>: 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. For example, 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 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 verified through comparison to output of detailed flow process models, and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain that DOE verified 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.

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 KESAs:

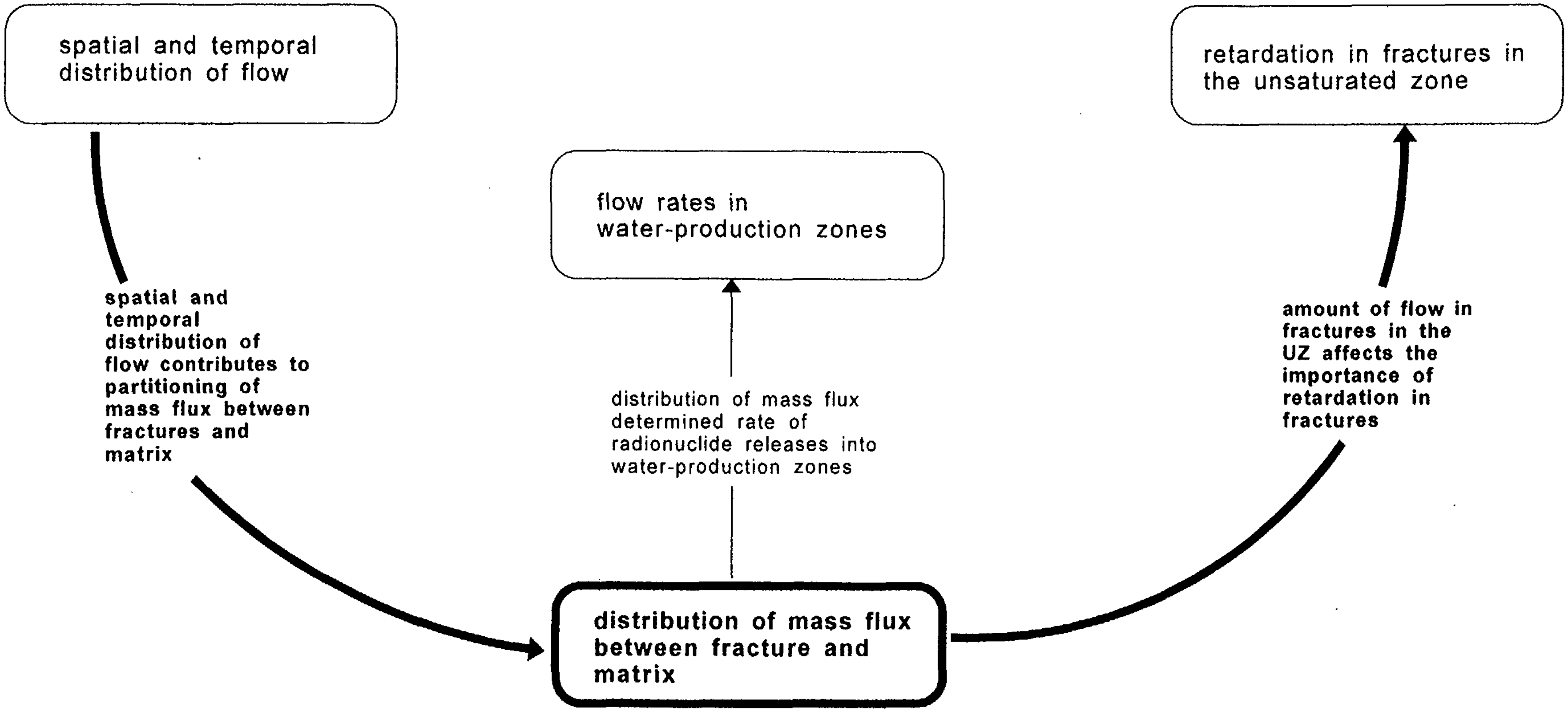
- Spatial and temporal distribution of flow contributes to partitioning of mass flux between fractures and matrix (spatial and temporal distribution of flow).
- Amount of flow in fractures in the UZ affects the importance of retardation in fractures (retardation in fractures in the UZ).

These relationships and other computational output are illustrated in figure 7. 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; TRW Environmental Safety Systems, Inc., 1995; Kessler and McGuire, 1996). Partitioning of deep percolation flux into matrix and fracture flow is important because the partitioning; (i) determines the quantity of water flowing past the WP, and (ii) affects the flux of dissolved RNs moving through the unsaturated zone.

The current NRC model for unsaturated zone flow and RN transport assumes that gravity drainage occurs in the rock below the PTn layer, with flow preferentially partitioned into the matrix up to a limiting saturation. Above the limiting saturation, flow is conducted by fractures. Baca and Jarzemba (1997) note that significant fracture flow is expected when matrix saturation exceeds 95 percent. It is noted that because fractures are generally not continuous from the surface to the repository horizon, nor from the repository horizon to the SZ, that a portion of the flow path for a given volume of percolating groundwater may be in fractures and a portion may



* Relationships in bold are identified in the text

Figure 7. A diagram illustrating the relationships between "distribution of mass flux between fracture and matrix" and other key elements of subsystem abstractions.

be in the rock matrix. Baca and Jarzemba (1997) also estimate that an infiltration rate of 2 mm/yr may cause 26 to 73 percent of the total flow to occur in fractures within the TSw hydrogeologic unit. 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 unit is either entirely within the matrix (if no fracture flow occurs in the time period of interest) or entirely within the fractures (if any fracture flow occurs). Thus, RNs completely bypass the rock matrix in any formation within which fracture flow occurs.

DOE's TSPA-95 report used a conceptually similar method to divide flow between fractures and the rock matrix. Fracture flow is assumed to be initiated when the matrix saturation exceeds a limiting value, σ, which is stochastically sampled in the range of 0.95 to 1.0.

4.3.2.1.3 Retardation in Fractures 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, precipitation, ion exchange, and filtration of particulates. Sorption (a term encompassing the first three processes in the preceding list) onto mineral surfaces is the most widely recognized process for retardation; in fact, a key favorable condition often cited for YM has been the potentially large retardation effects of the zeolite-rich strata underlying the repository horizon. 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 fractures 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, neither DOE's nor NRC's PAs (TRW Environmental Safety Systems, Inc., 1995; Wescott *et al.*, 1995) take credit for retardation in fractures owing to lack of data. 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, once diffused into water contained in the rock matrix, can be sorbed onto rock constituents. Matrix diffusion 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 fractures in the UZ abstraction in TSPA.

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and to define relevant parameters in DOE's abstractions. For example, 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 fractures 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. 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 fractures 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 fractures in the UZ 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 fractures in the UZ abstraction output is verified through comparison to output of detailed process models, and/or empirical observations (laboratory testings or natural analogs, or both).

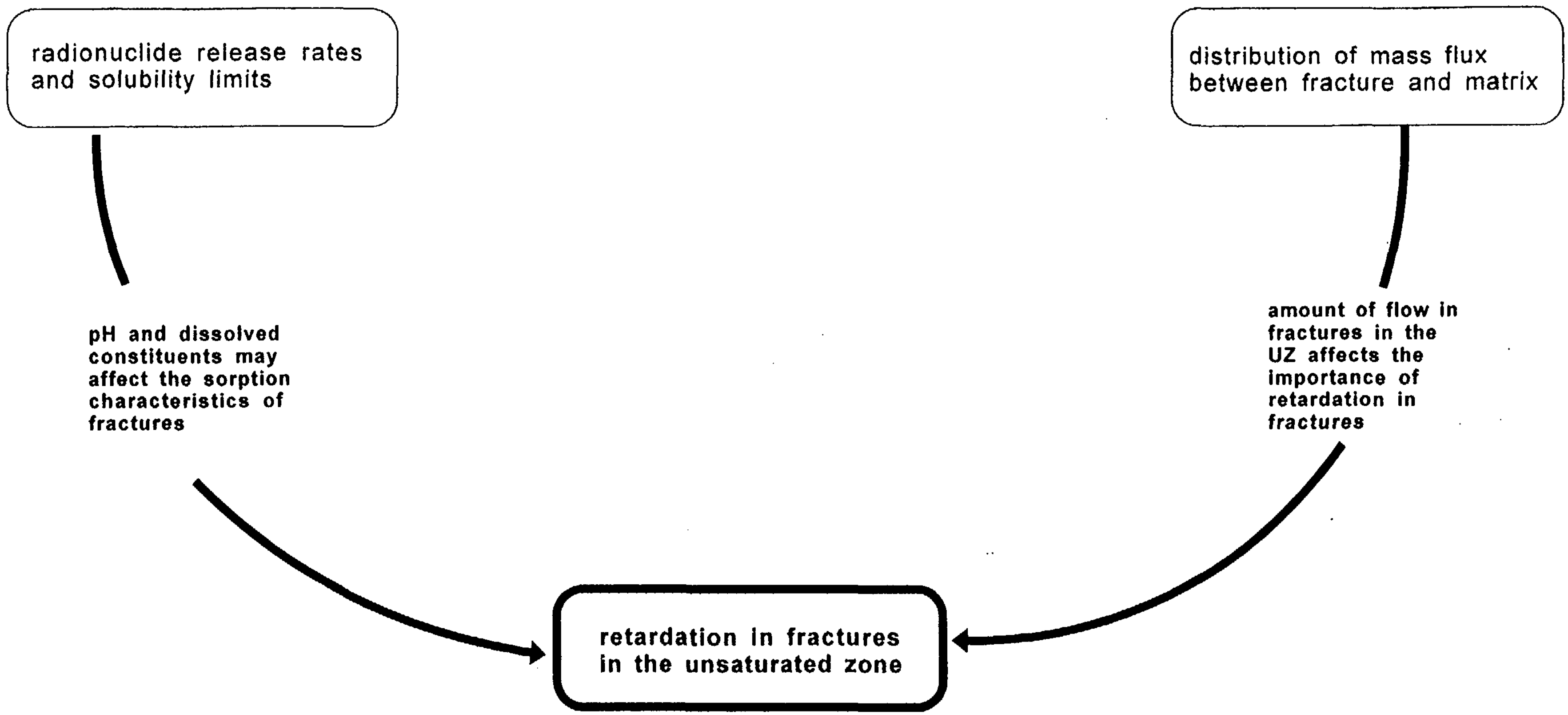
Review Method: Staff should ascertain whether DOE verified the output of retardation in fractures in the UZ abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's retardation in fractures in the UZ abstraction against the results produced by the process-level models developed by the staff.

Criterion T5: Important physical phenomena and couplings and consistent and appropriate assumptions are incorporated into the consideration of retardation in fractures 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 fractures 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 KESAs:

- 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 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 to retardation in fractures in the UZ for potential inconsistency in the analysis and nondefensible predictions.



* Relationships in bold are identified in the text

Figure 8. A diagram illustrating the relationships between "retardation in fractures in the unsaturated zone" and other key elements of subsystem abstractions.

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) and the available surface area for adsorption. The key aspects of this KESA are:

- 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 an equilibrium R_d. It must be resolved whether or not the equilibrium 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. 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 achieved by a physical process such as 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 R_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 1 (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: IA2, SDS1, SDS3, USFIC2, 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.

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; for example, 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 verified through comparison to output of detailed process models, and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified 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.

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.

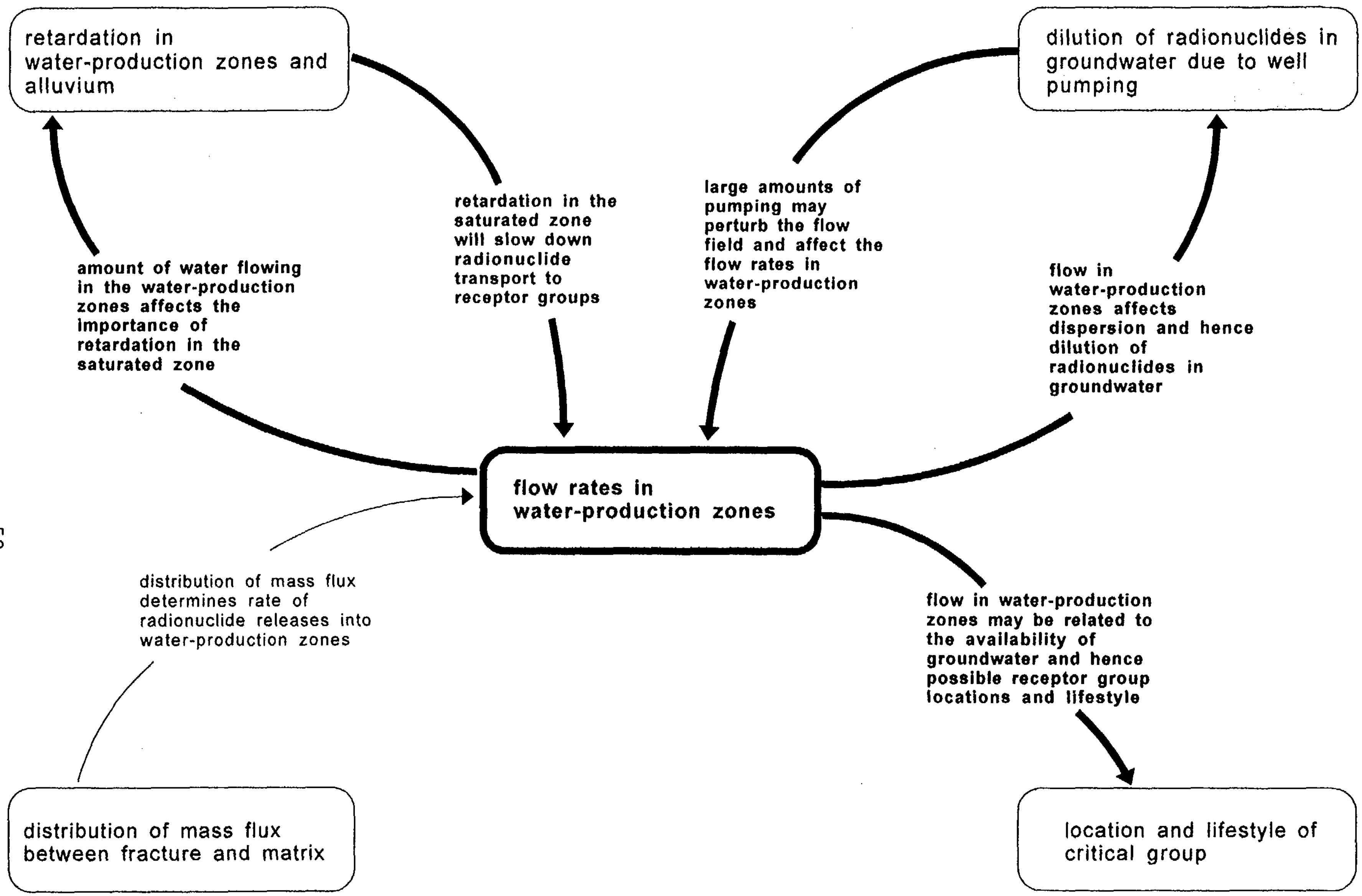
Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches; for example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent 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 KESAs:

- 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 9. 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. The last published DOE TSPA (TRW Environmental Safety Systems, Inc., 1995)



* Relationships in bold are identified in the text

Figure 9. A diagram illustrating the relationships between "flow rates in water-production zones" and other key elements of subsystem abstractions.

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.

Information gleaned from recent technical exchanges with the DOE and at DOE presentations to the Nuclear Waste Technical Review Board (NWTRB) indicate that the latest SZ transport modeling approach adopted by DOE in their TSPA-VA may use significantly smaller dilution factors along the SZ flow path. For the TSPA-VA DOE has implemented a simplified SZ transport model that consists of six streamtubes from which convolution integrals or transfer functions are developed. While longitudinal dispersion is incorporated into the transfer functions, the effects of transverse dispersion are accounted for in a dilution factor, which is applied to resident aquifer RN concentrations at the receptor location. This dilution factor—which does not account for well pumping—is sampled from a probability distribution, whose form is based on information DOE obtained from the Saturated Zone Expert Elicitation (SZEE). SZEE panel members generally dismissed the significance of transverse dispersion as a mechanism for reducing RN concentrations during transport and suggested that the dilution factors due solely to dispersion may have a median value of approximately 10, when accounting for spreading of the plume in the SZ.

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 KESA 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 some RNs, such an assumption may be overly conservative and would yield unrealistic results.

In DOE's TSPA-95 report (TRW Environmental Safety Systems, Inc., 1995), the authors did not differentiate between sorption properties (e.g., K_ds) assigned to stream tubes near the repository and portions of the stream tube in the vicinity of the Amargosa Farms (e.g., 30 km); hence the retardation in production zones and alluvium was treated identically to that in fractured rock (i.e., beneath the repository). The current version of the TPA code allows different properties for distinct portions of the stream tube, 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.

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. For example, 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 verified through comparison to output of detailed process models, and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified the output of 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.

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 KESAs:

- 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 10. 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.

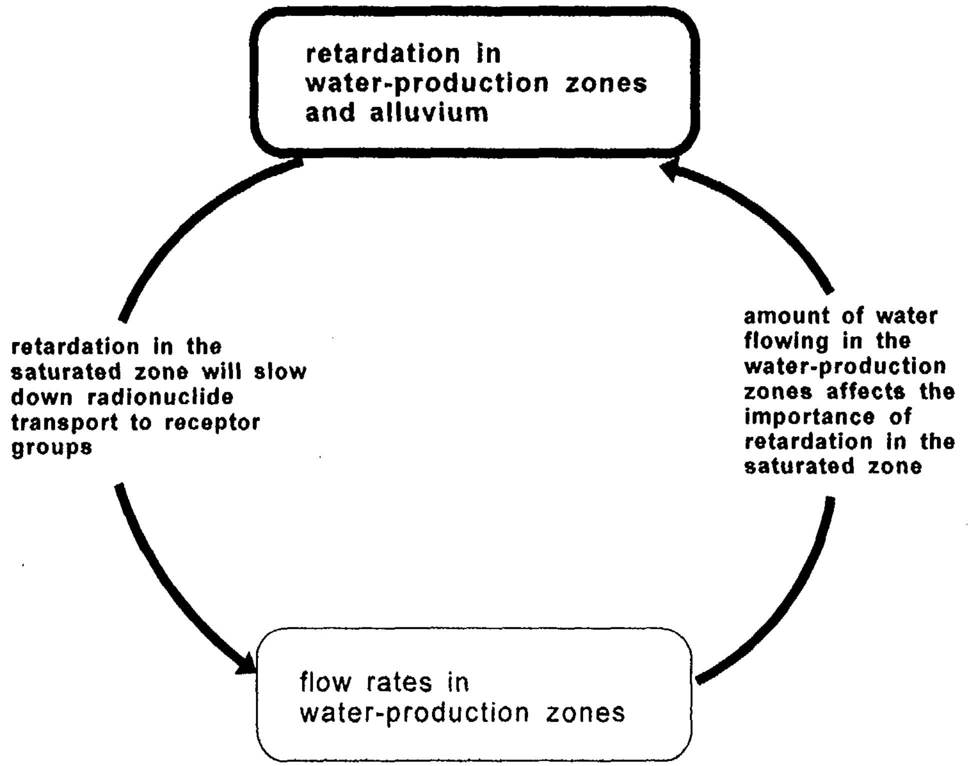
Technical Basis

This section describes the technical basis for the abstraction of retardation in production zones and alluvium to repository performance assessments. 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 alluvium, 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 KESA 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.



* Relationships in bold are identified in the text

Figure 10. A diagram illustrating the relationships between "retardation in water-production zones and alluvium" and "flow rates in water-production zones" key elements of subsystem abstractions.

It has recently 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 and oxyhydroxides. However, previous efforts to characterize groundwater host rocks at YM have tended to overlook alluvium so there are few data 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.

4.3.2.3 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 1 (i.e., volcanic disruption of waste packages 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.

4.3.2.3.1 Volcanic Disruption of Waste Packages

Pertinent KTI subissues: IA1, IA2, SDS1, SDS2, SDS4

An eruption at Yucca Mountain could involve dense magma at high temperatures impacting waste packages at high velocities for days to weeks, which could result in the mechanical disruption of waste packages. NRC has included volcanism as a disruptive scenario in its TPA code to estimate the repository performance. Although the most recent DOE TSPA (TRW Environmental Safety Systems, Inc., 1995) did not include disruptive scenarios such as volcanism, DOE has indicated that disruptive scenarios will be included in future DOE TSPAs.[15]

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

DOE's approach in abstracting the volcanic disruption of waste packages 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.

<u>Criterion T1</u>: 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.

[15] DOE/NRC Technical Exchange on Performance Assessment, July 22, 1997, CNWRA, San Antonio, TX.

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; for example, 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 or features in its conceptual models.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in abstracting the volcanic disruption of WPs, such as the probability of volcanism, number of WPs affected, and the amount of spent fuel particles incorporated into the tephra and ejected, are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated volcanic disruption of WPs input/data in the performance calculations. Staff should ascertain that the input values used in estimating the volcanic disruption of WPs in TSPA are reasonable based on data from the YM region and other applicable laboratory tests and natural analogs. Staff should also verify that these values are consistent with the initial and boundary conditions (e.g., structural control, repository layout and waste emplacement) and the assumptions of the conceptual models for the YM site (e.g., the spatial and temporal variations of future volcanic events should be consistent with the tectonic models proposed for the YM region, and the amount of waste available for airborne transport to the surface should be based on the repository area overlapped by the dike and conduit, and hence related to the number of WP affected). 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 volcanic disruption of WPs abstraction.

Review Method: Staff should ascertain that DOE considered plausible alternative recurrence rates models for future volcanic events and provided supporting information for the approaches used in the volcanic disruption of WPs 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: Volcanic disruption of WPs abstraction outputs are verified through comparison to output of detailed process models and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE has verified the outputs of its volcanic disruption of WPs abstraction to ensure that it 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 volcanic disruption of WPs abstraction against the results produced by the process-level models developed by the staff.

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.

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 estimate the probability of volcanism are consistent with all other relevant conditions and assumptions in the TSPA. Staff should verify that DOE's dimensionality abstractions appropriately account for the various site characteristics and alternative conceptual approaches. If DOE decides not to take credit for certain site features which 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. Figure 11 illustrates computational input/output for this KESA.

Technical Basis

This section describes the technical basis for the abstraction of volcanic disruption of WPs in repository performance assessments. Specifically, estimates of the probability of the occurrence of volcanism and the physical volcanology of YMR basaltic volcanoes are presented. However, probability of volcanism may be treated through scenario analysis (see Section 4.4)

At this time, volcanism has been determined to be the only mechanism that could lead to direct release of RNs from the proposed repository at YM that could result in significant radiological exposures to an individual. Previous studies have shown that the annual probability of an extrusive volcanic event penetrating the repository is large enough to be considered in TSPAs (Connor and Hill, 1995; Hill *et al.*, 1996; Crowe *et al.*, 1995). A volcanic event is defined here as the formation of a new volcano that penetrates the proposed repository facility after closure. Current 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; Connor *et al.*, 1996). These studies have used geologic information relevant to past patterns of volcanic activity in the YM area to estimate the recurrence rate of extrusive volcanism in the repository footprint for the next 10,000 yr, and estimated that the annual

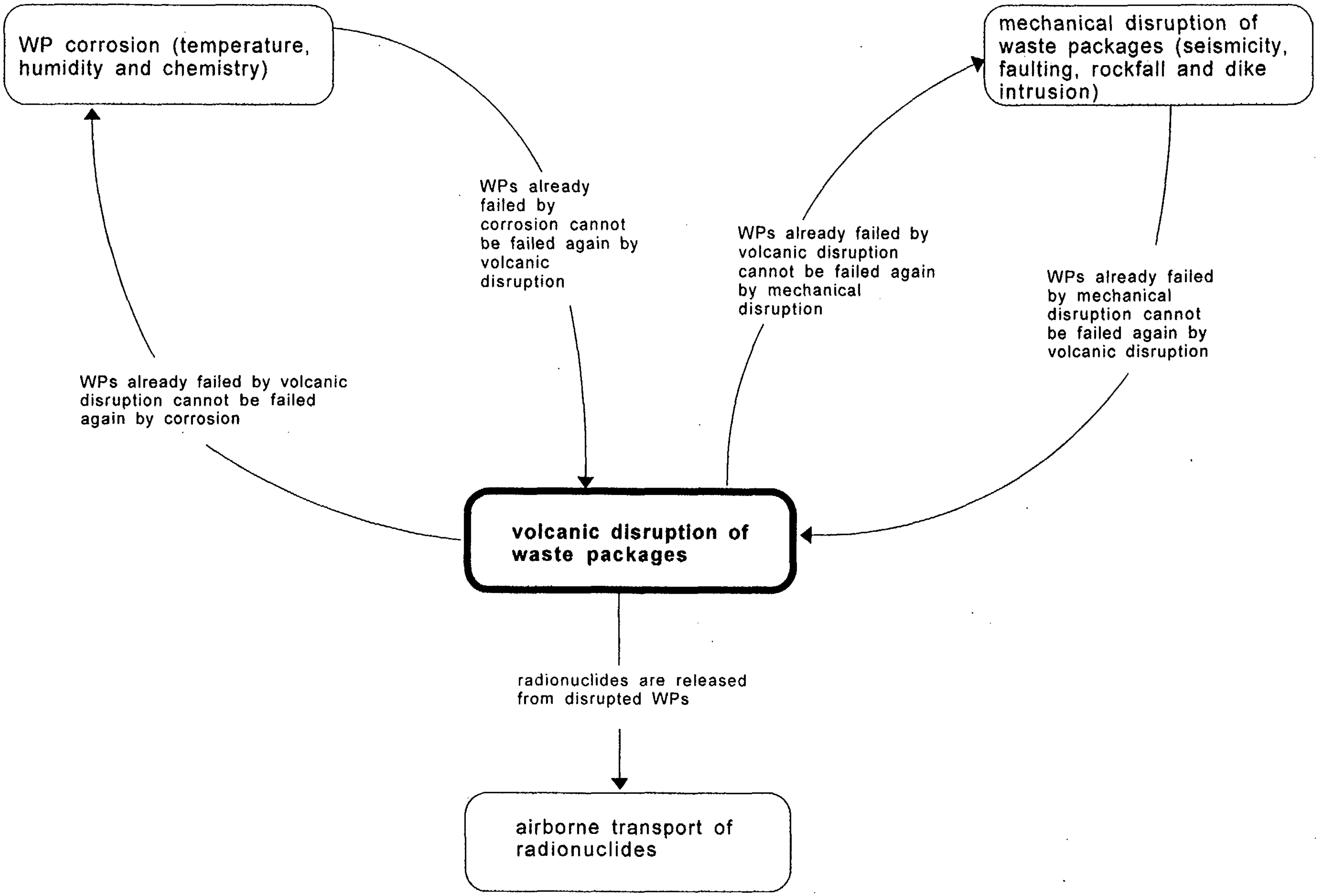


Figure 11. A diagram illustrating the relationships between "volcanic disruption of waste packages" and other key elements of subsystem abstractions.

probability of an extrusive event penetrating the repository generally ranges between 10^{-8} and 10^{-7}. Note that DOE's Probabilistic Volcanic Hazards Assessment (Geomatrix, 1996) 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 deconvolve this probability estimate into extrusive and intrusive components. Scenario Analysis (Section 4.4) addresses the use of probability of occurrence to screen processes and events from the performance assessment.

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 disruptions. Several features of YMR volcanoes at Lathrop Wells and Little Black Peak indicate a violent strombolian eruption style (U.S. Nuclear Regulatory Commission, 1998c). Because recent eruptions in the YMR (<1 million years) appear to exhibit characteristics of violent strombolian activity, models of volcanic eruption through the proposed repository need to encompass this style of volcanic activity. Other parameters, primarily related to interactions between basaltic magma and engineered barrier systems, are difficult to constrain. Because these parameters are important to dose calculations, more data are needed before review of the DOE license application (U.S. Nuclear Regulatory Commission, 1998c). Additionally, emplacement of the repository may affect the shallow subsurface ascent of magma, resulting in potential changes in the eruption style and in intrusion geometry. A technical basis for evaluating these effects has not yet been developed (U.S. Nuclear Regulatory Commission, 1998c), because of the lack of knowledge; it may be assumed conservatively that the waste package will not be an effective deterrent to the transport and dispersion of HLW during volcanic eruptions. Furthermore, analysis presented by U.S. Nuclear Regulatory Commission (1998c) indicates that during a volcanic eruption, HLW particle fragmentation will occur, reducing the average HLW particle size.

DOE's TSPA-95 (TRW Environmental Safety Systems, Inc., 1995) for the YM site did not include volcanism or associated entrainment of waste in ash. Future TSPAs by DOE will include volcanic exposure scenarios (U.S. Nuclear Regulatory Commission, 1998c).

4.3.2.3.2 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, 1996). DOE's TSPA-95 (TRW Environmental Safety Systems, Inc., 1995) did not include volcanism, and hence the airborne transport of radionuclides. Future PAs by DOE will include volcanism. It is uncertain how these assessments will model entrainment of HLW an airborne transport of ash. Specifically, this KESA 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.

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. For example, 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 verified through comparison to output of detailed process model or empirical observations (i.e., natural analogs), or both.

Review Method: Staff should ascertain whether DOE verified the output of airborne transport of radionuclides 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 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 KESAs:

- 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 12. 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 13. Current NRC/CNWRA assessments address this KESA 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).

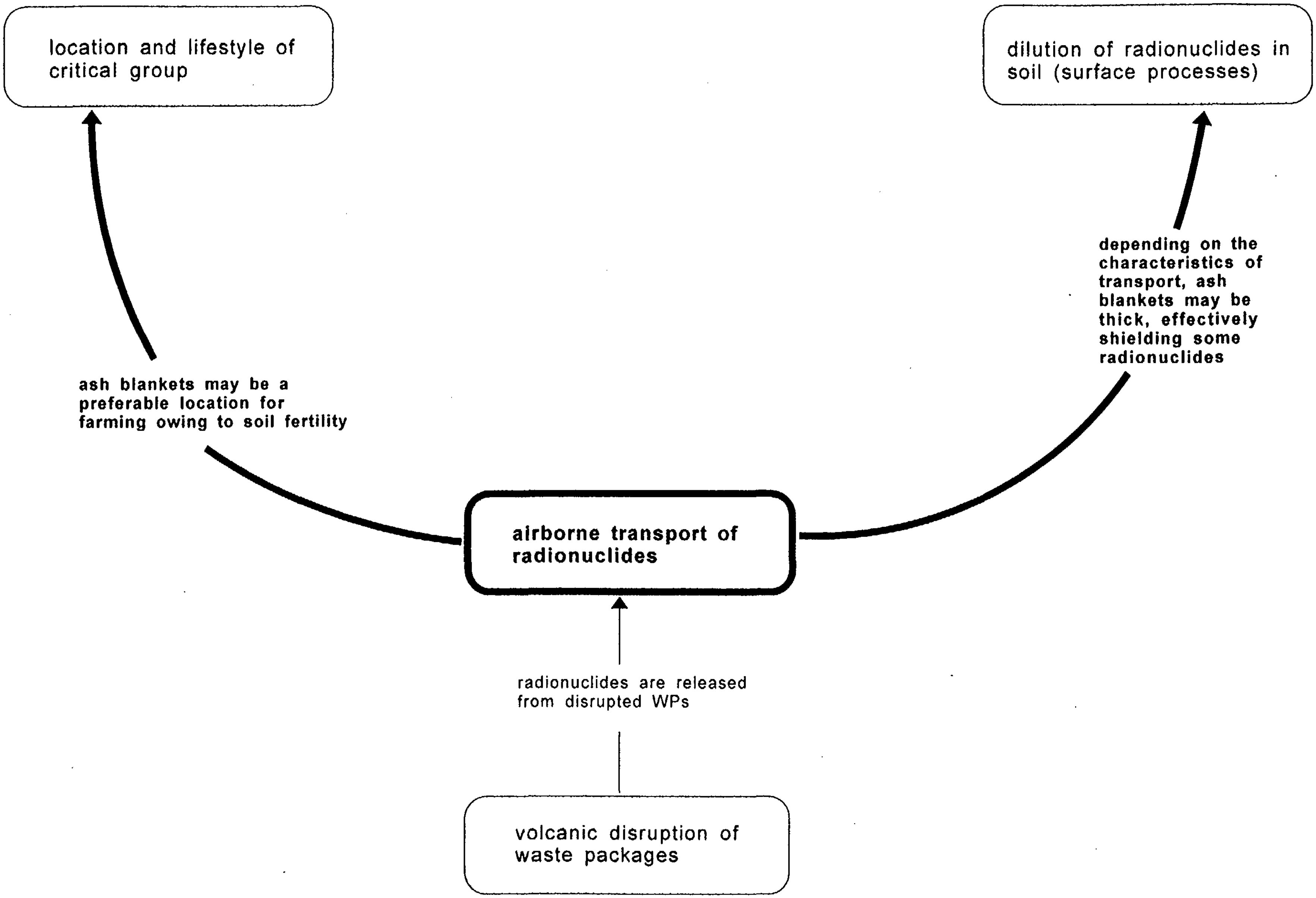
Numerical models that quantify the physics of basaltic eruptions have been developed (Sparks et al., 1997); however, there is considerable uncertainty in how to simulate the entrainment and dispersal of HLW in the eruption column. Physically accurate eruption column models provide an opportunity to extend 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 1 (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.



* Relationships in bold are identified in the text

Figure 12. A diagram illustrating the relationships between "airborne transport of radionuclides" and other key elements of subsystem abstractions.

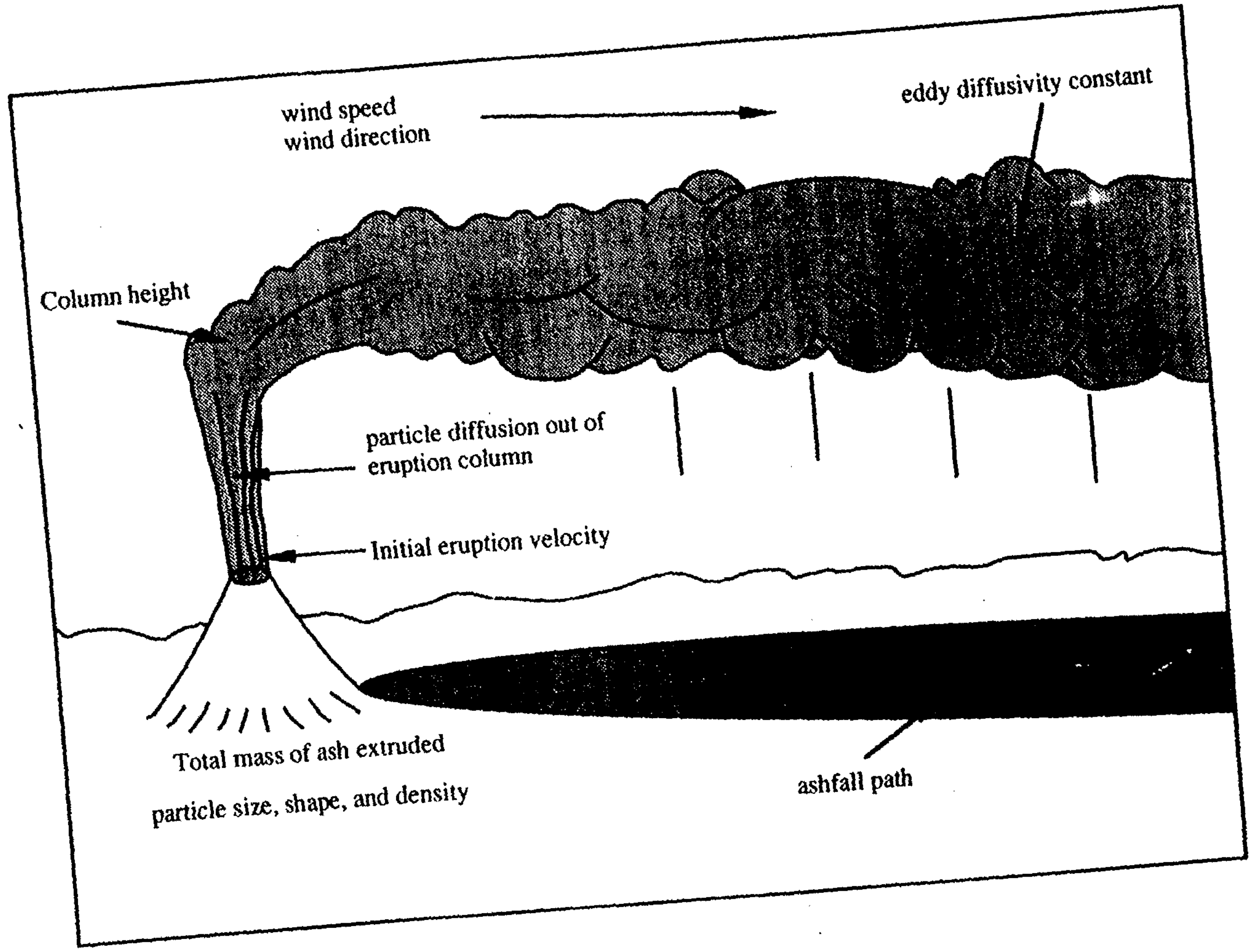


Figure 13. **A diagram illustrating the important processes and parameters for estimating airborne transport of tephra.**

4.3.3.1.1 Dilution of Radionuclides in Groundwater due to Well Pumping

Pertinent KTI subissue: USFIC5

This KESA 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 3.1.4 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. Alternatively, if a simple, 1D stream tube 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. Note that 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-95 (TRW Environmental Safety Systems, Inc., 1995) 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. However, in DOE's TSPA-95 very large aquifer dilution factors were employed to take credit 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 noted in Section 4.3.2.2.1, more recent information obtained from DOE suggests that this approach will be abandoned for the TSPA-VA, and that DOE will instead use a much smaller dilution factor to account for transverse macro-dispersion. It is unclear whether DOE will or will not explicitly account for borehole dilution in computing borehole RN concentrations in the TSPA-VA.

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.

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; for example, 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 verified through comparison to outputs of detailed process models and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified 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.

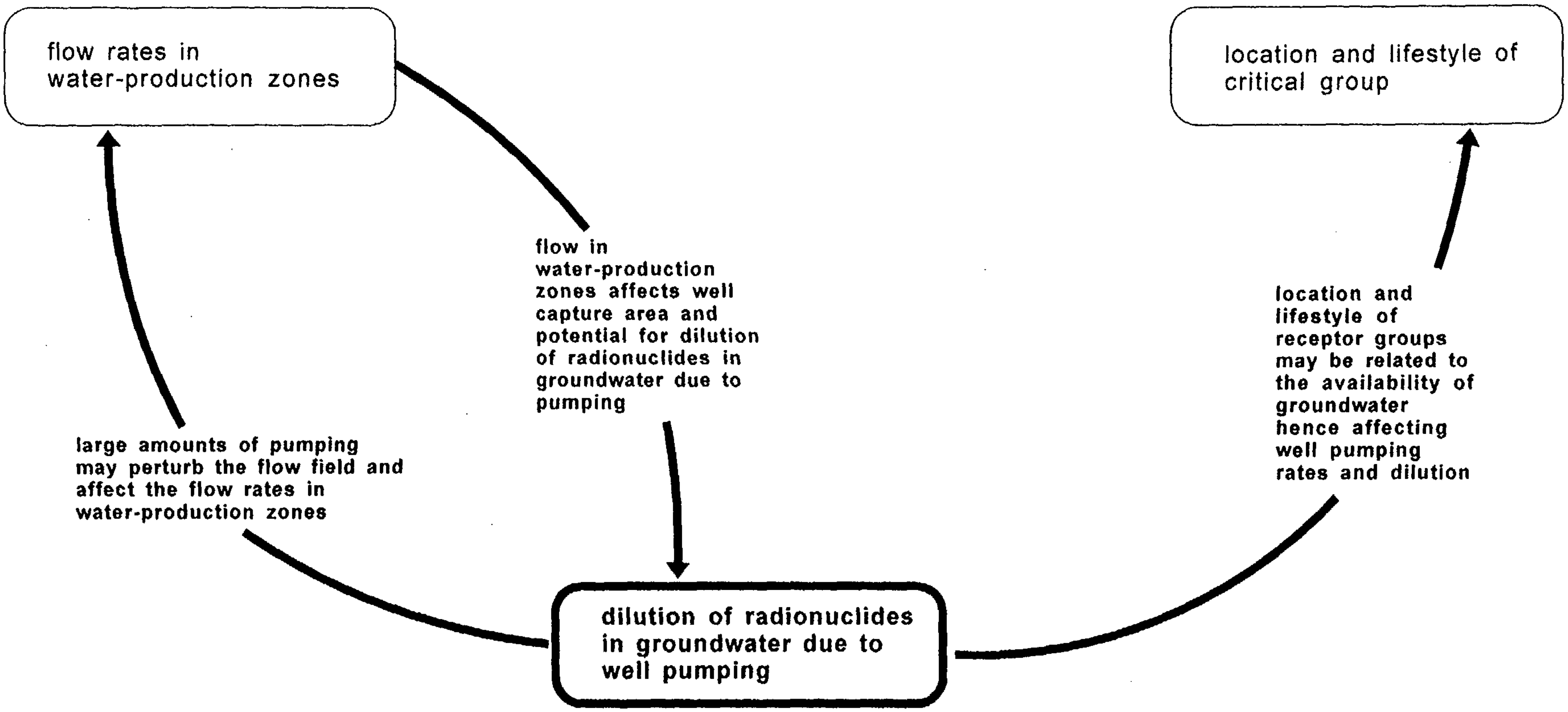
Criterion T5: Important hydrogeologic features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the dilution of radionuclides in groundwater due to well pumping abstraction.

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 KESAs:

- 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 14. 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.



* Relationships in bold are identified in the text

Figure 14. A diagram illustrating the relationships between "dilution of radionuclides in groundwater due to well pumping" and other key elements of subsystem abstractions.

Technical Basis

This section describes the technical basis for the abstraction of dilution of RNs in groundwater due to well pumping in repository performance assessments. 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

The most recent DOE's TSPA (TRW Environmental Safety Systems, Inc., 1995) calculated doses to the receptor individual based solely on consumption of 2 L/day drinking water. DOE has not accounted for dose resulting from the surface-related exposures. The NRC/CNWRA assessments use the models in the GENII-S code (Napier *et al.*, 1988; Leigh et al., 1993) and the ASHRMOVO module to perform calculations for the surface leaching of RNs out of the biosphere. DOE will also be using GENII-S when performing dose calculations.

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) and, 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. Neglecting the removal of RNs may be overly conservative for nonsorbing, highly soluble RNs such as ^{99}Tc.

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.

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. For example, 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 verified through comparison to output of detailed process models and/or empirical observations (laboratory testings or natural analogs, or both).

Review Method: Staff should ascertain whether DOE verified 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.

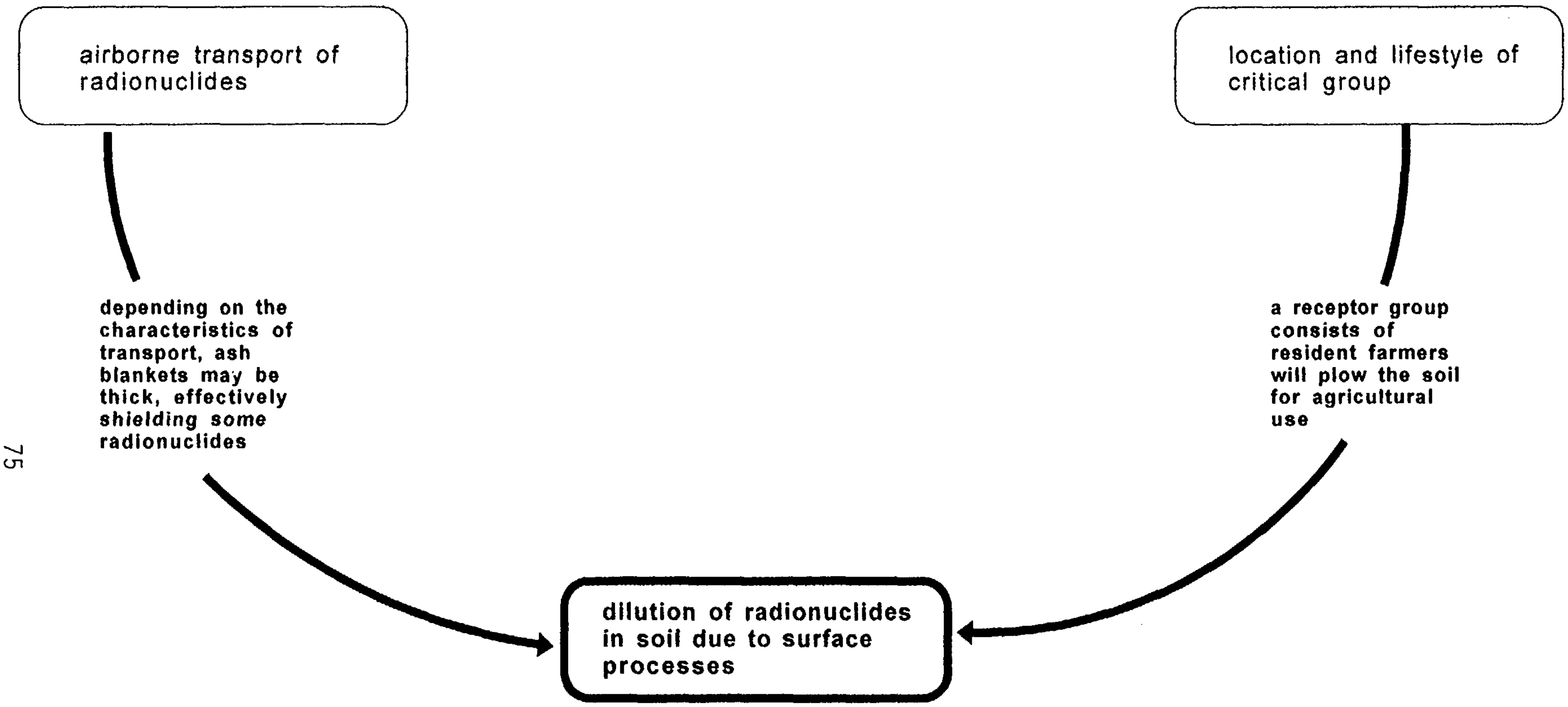
Criterion T5: Important site features, physical phenomena and couplings, and consistent and appropriate assumptions are incorporated into the dilution of radionuclides in soil due to surface processes abstraction.

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 KESAs:

- 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 15. 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



* Relationships in bold are identified in the text

Figure 15. A diagram illustrating the relationships between "dilution of radionuclides in soil due to surface processes" and other key elements of subsystem abstractions.

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 performance assessments. 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).[16] 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 redistribution by plowing (e.g., the plowed layer is deeper than the root zone for the particular crop grown in that soil). The second process is leaching of RNs from surface layers. Water falling 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.

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

4.3.3.1.3 Location and Lifestyle of Critical Group

Pertinent KTI subissues: USFIC1, USFIC2, USFIC5

The critical group is defined 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 RNs. Homogeneity is defined by the ICRP and reiterated by the NAS (National Research Council, 1995):

> *"A group can be considered homogenous if the distribution of individual risk within the group lies within a total range of a factor of ten and the ratio of the mean of individual risks in the group to the standard is less than or equal to one-tenth. If the ratio of the mean group risk to the standard is greater than or equal to one, the range of risk within the group must be within a factor of 3 for the group to be considered homogenous. For groups with ratios of mean group risk to the standard between one-tenth and one, homogeneity requires a range of risk interpolated between those values."*

One of the primary recommendations made by the NAS (National Research Council, 1995) is that the average member of the critical group be the individual whose dose (or risk) should be estimated in TSPAs for the proposed YM repository.

This KESA is directly related to repository performance in that parameters associated with the lifestyle and location of receptor groups and the biosphere in which they exist will enable performance assessors to transform groundwater and ground surface RN concentrations into individual doses. Depending on details of this transformation (i.e., the locations and lifestyles assumed for the receptor groups), the final calculated doses may differ. Although DOE has not previously addressed this issue, it is currently sponsoring telephone surveys of the Amargosa Desert region concerning the lifestyles of area inhabitants (Cannon Center for Survey Research, 1997). An NRC/CNWRA study to update parameters that characterize the range of lifestyles in the area was also completed in 1997 (LaPlante and Poor, 1997).

Acceptance Criteria with Review Methods

It is anticipated that the forthcoming EPA Standards for YM will establish the compliance point. Furthermore, development of the implementing regulations for the YM site is currently underway. Therefore, acceptance criteria and review methods for this KESA will be developed at a later time.

Summary of Relevant Technical Work

> ** Technical basis will be developed concurrently with the development of the acceptance criteria and review methods for this KESA. Some relevant work is included here for information only. **

Defining the critical group, and hence its average member, is subdivided into two main tasks: (i) defining the lifestyle characteristics of group members, and (ii) defining the groups location in the biosphere. In practice, a number of receptor groups may be modeled in performance assessments; the maximally exposed group would be the critical group.

To date, NRC/CNWRA investigations into understanding the lifestyles of 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 water use is limited to consuming two liters per day (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 performance assessment.

The preceding two paragraphs assume that the cited receptor groups exist in today's biosphere. The biosphere is defined as the environment in which the critical group exists, and descriptions of the biosphere include details such as where and how people obtain their food and the type of climate. Perhaps the most significant feature of the biosphere with respect to dose calculations for YM is the type of climate that a biosphere exhibits because the type of climate dictates lifestyle parameters such as the types of crops being farmed, the length of the growing season, etc. 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 modern day MAP (DeWispelare *et al.*, 1993; Stablein, 1997a) over the next 10,000 yr. 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). At this time, little information exists that shows the possible locations for the two receptor groups previously profiled is likely to change in a pluvial biosphere.

4.4 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: SCENARIO ANALYSIS

An important element of a total system performance assessment (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.[17] Most uncertainty analyses use a combination of these two approaches.[18] 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: (1) a postulated sequence of events (or may be characterized by the absence of events) and (2) assumptions about initial and boundary conditions. Because there is inherent uncertainty in both the: (i) repository system and (ii) processes and events that can effect the repository system, many different evolutions are possible. The yet-to-be promulgated Yucca Mountain-specific EPA standard and the NRC implementing regulations will likely specify a quantitative overall total system performance criterion in terms of individual dose to the average member of a critical group. The demonstration of compliance is expected to require a probabilistic assessment of repository performance, which would include the consideration of multiple scenarios. A probabilistic approach in which scenario classes[19] 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 performance assessment 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: (1) identification of an initial list of processes and events; (2) classification of processes and events; (3) screening this initial list of processes and events; (4) formation of scenario classes using the reduced set of processes and events; and (5) screening scenario classes. Models of processes and events included within the performance assessment will be evaluated against the model abstraction acceptance criteria. Steps (1) - (3) apply to the screening of processes and events from the performance assessment on a general level; those processes and events that are not excluded from the performance assessment 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.

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[17] 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.

[18] 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.

[19] 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.

4.4.1 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 Yucca Mountain (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.

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

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

<u>Criterion T1</u>: DOE has identified a comprehensive list of processes and events that: (1) are present or might occur in the Yucca Mountain region and (2) includes those processes and events that have the potential to influence repository performance.

<u>Review Method:</u> 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 the DOE 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.[20]

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

Technical Basis

An *event*[21] is an occurrence at a discrete location in space and during a specific interval of time. Examples for the Yucca Mountain 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 performance assessment. Generally, the behavior of the components within the system boundary (e.g., degradation of waste packages, flow through fractures, propagation of thermal pulse, gravity refluxing of pore water) is modeled as a response to processes and events acting on the repository system. A comprehensive list of processes and events needs to be identified to demonstrate that sufficiently likely processes and events have been considered in the analysis.

4.4.2 Classification of Processes and Events

After a comprehensive list of processes and events has been established, processes and events may be grouped into categories.[22] 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.

[21] 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).

[22] 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.

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 performance assessment. 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 performance assessment. 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 performance assessment. Narrowly defined categories of processes and events that result in the inappropriate screening of processes or events from the performance assessment are unacceptable, because they result in an incomplete assessment of repository performance.

NRC uses a Latin Square approach to categorizing processes and events. This approach is useful for evaluating completeness. In the NRC Latin Square approach, a finite set of *event classes*[23] is defined, where each event class contains fundamentally similar events which differ only in detailed characteristics. For example, the set of all igneous events (say ***I***) may form an event class, the set of all fault-related movement (say ***F***) events may form another, and the set of seismic events (say ***S***) a third. In this approach, event classes also are used to represent the absence of a processes or events. For example, igneous events may occur (i.e., ***I***) or they may not (i.e., $\bar{I}$). 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 performance assessment. The event classes also can be used as the basis for forming scenario classes.

4.4.3 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 performance assessment. Categories of processes and events that are sufficiently likely to be included in the performance assessment may be omitted from the performance assessment, 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 Yucca Mountain repository because of waste characteristics, repository design,

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

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 geologic processes in space and time in developing Yucca Mountain-specific probabilities. Staff will compare the DOE-determined probabilities with its own independently developed probabilities through the iterative performance assessments 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 performance assessments, and those categories that have: (1) probabilities close to the screening criteria on probability and (2) 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 performance assessment 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 performance assessment 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 performance assessment 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 performance assessment, 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 performance assessment. However, igneous processes, when they are addressed together, may be sufficiently likely to be included in the performance assessment 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 ***I***⁻; ***F*** and ***F***⁻; and ***S*** and ***S***⁻), must equal one. This property is used to calculate the probability of event classes defined by the absence of a process or event occurring. Probabilities are assigned to event classes, whereas variability in the attributes of processes and events (e.g., time of occurrence, location, duration, amount of energy released, rates of propagation of disturbance) are treated through parameter distributions as part of model abstraction. In the NRC approach, event classes are defined broadly to avoid eliminating potentially important processes and events from the analysis (e.g., fault displacement occurring within the period of regulatory interest). Narrowly defined categories of processes and events that result in the inappropriate screening of processes or events from the performance assessment 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 performance assessment. It is possible to exclude from the performance assessment 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 performance assessment; 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 performance assessment may vary from one category to another, based on the processes and events involved.

4.4.4 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 performance assessment (see Section 4.4.5).

<u>**Acceptance Criteria with Review Methods**</u>

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

Criterion T1: DOE has provided adequate documentation identifying: (1) whether processes and events have been addressed through consequence model abstraction or scenario analysis and (2) 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 performance assessment 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 performance assessment. The response of the repository to these events is addressed through model abstraction. This results in event classes such as faulting (F and F^-), seismicity (S and S^-), and igneous activity (I and I^-). These event classes can be combined into scenario classes such as FSI, FSI^-, FS^-I, FS^-I^-, F^-SI, F^-SI^-, F^-S^-I, and $F^-S^-I^-$. The Latin Square approach provides a complete set of scenario classes and ensures that the scenario classes are mutually exclusive. Scenario classes are broadly defined and distinct, which is useful for screening scenario classes. This formulation of scenario classes does not make a distinction between event sequences, which requires that differences in consequences associated with the timing of events has to be addressed through model abstraction. Narrow scenario class definitions that result in the inappropriate screening of scenario classes from the performance assessment are unacceptable, because they result in an incomplete assessment of repository performance.

4.4.5 Screening of Scenario Classes

Categories of processes and events may be combined into scenario classes. Scenario classes may be omitted from the performance assessment if: (1) they are not credible, (2) they are not sufficiently likely to warrant inclusion in the performance assessment, or (3) their omission would not significantly change the calculated expected annual dose. Probabilities for scenario classes must be appropriately assigned when screening is to be based on the probability of occurrence or the significance to the expected annual dose.

Acceptance Criteria and Review Methods

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

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

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

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

Review Method: Staff will evaluate DOE's documentation of the probabilities assigned to the different scenario classes. Staff will determine whether probabilities assigned to these scenario classes are consistent with geologic data and appropriately account for dependencies and correlations. Staff will compare the DOE-determined probabilities with its own independently developed probabilities through the iterative performance assessments 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 performance assessments, and those scenario classes that have: (1) probabilities close to the screening criteria on probability and (2) 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 performance assessment on the basis of their probability of occurrence, provided: (1) the probability used for screening the scenario class is defined from combinations of initiating processes and events and (2) 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: (1) categories of processes and events and (2) 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 Yucca Mountain 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 performance assessment 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 performance assessment 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 performance assessment, 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 performance assessment. Scenario classes with very low probabilities of occurring during the period of regulatory concern do not need to be considered in the performance assessment. Scenario classes that are not credible should not be included in the performance assessment. 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 performance assessment 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 performance assessment 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 performance assessment 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., $\boldsymbol{F}$ and $\boldsymbol{F}^{-}$) must equal one. The NRC approach is demonstrated using a simple example, where event classes associated with the independent processes $\boldsymbol{\Theta}$ and $\boldsymbol{\Psi}$ are used to form scenario classes. The assumption of independence simplifies the example, but may not be appropriate for all combinations of event classes.

The following probabilities for the two event classes will be assumed in this illustration of the Latin Square method: $\boldsymbol{\Theta}$ (P=0.9) and $\boldsymbol{\Psi}$ (P=0.05); where the probabilities are for the processes or events within the event class either being present or occurring within 10,000 years. Each of these event classes has a probability greater than 10^{-4}, so they may not be screened on the basis of probability. The probability of $\boldsymbol{\Theta}$ or $\boldsymbol{\Psi}$ not being present or not occurring within 10,000 years can be found using the principles of probability; that is $\boldsymbol{\Theta}^{-}$ (P=0.1) and $\boldsymbol{\Psi}^{-}$ (P=0.95). These event classes can be combined to form scenario classes (e.g., $\boldsymbol{\Theta\Psi}$, $\boldsymbol{\Theta\Psi}^{-}$, $\boldsymbol{\Theta}^{-}\boldsymbol{\Psi}$,$\boldsymbol{\Theta}^{-}\boldsymbol{\Psi}^{-}$). 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

4.5 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: TRANSPARENCY AND TRACEABILITY OF THE ANALYSIS

To be developed in revision two.

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 also included. Note that these discussion points are not open items at this time and are so designated. NRC will continue to interact with DOE on issues related to TSPA and will close open items as appropriate. NRC will use DOE's TSPA-VA to reevaluate unresolved open items and the prospective discussion points identified in the TSPA Technical Exchanges. 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 – see DOE, 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.[24] The status of the resolution of TSPAI open items is summarized in table 3, including scenario-related open items.

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. In the 1995 *Mined Geologic Disposal License Application Annotated Outline* (DOE, 1995) and the 1996 *TSPA-VA Plan* (TRW Environmental Safety Systems Inc., 1996), DOE provided no new information on its plans for how these two open items would be addressed.

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[24] 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.

The forthcoming *Viability Assessment* (VA) is the next major DOE program milestone to be reviewed by the staff. In a recent technical exchange on the TSPA-VA, the staff noted the need for DOE to address SCA Comments 95 and 105 (and others) as its program proceeds beyond the VA (see Bell, 1997). An NRC/DOE Appendix 7 meeting on disruptive events was held in October 1998. DOE's current approach to scenario analysis, if effectively implemented, will address open items related to scenario analysis, as indicated by discussions held during the Appendix 7 meeting. The staff will consider closing items after reviewing documentation of the progress and implementation of DOE's current approach. It is the staff's understanding that DOE's current approach to scenario analysis will not be documented in the supporting documents to TSPA-VA,[25] so the staff may not be able to close scenario analysis open items on the basis of TSPA-VA.

[25] As currently defined, the VA consists of four elements: (1) *Preliminary Design Concept*; (2) *TSPA* (or *TSPA-VA*); (3) *License Application Plan and Cost Estimate*; and, (4) *Costs of Construction and Operation*. Because of resource constraints, the staff's review of VA elements 1, 3, and 4 will be limited; the principal focus of the staff's review will be the TSPA-VA and the *License Application Plan and Cost Estimate*.

Status of Total System Performance Assessment and Integration Open Items

Table 2. Resolution summary for TSPAI KTI open items.

Status of TSPAI KTI Open Items	Number
Resolved	18
Open	13

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 Yucca Mountain
OSC0000001347C003	Resolved	Reliance on formal use of expert judgement 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)

Table 3. Summary of TSPAI KTI open item status (cont'd).

Item ID	Status	Title	Comment
OSC0000001347C101	Resolved	The equation (8.3.5.13-21) used to estimate the partial performance measure for the j^{th} scenario class involving water pathway releases may be in error	Austin (1996)
OSC0000001347C103	Resolved	The ross sequence numbers 59 through 62 and 64 through 69 do not characterize scenarios	Austin (1996)
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)

Table 3. Summary of TSPAI KTI open item status (cont'd).

Item ID	Status	Title	Comment
OSC0000001347Q048	Resolved	Question selection procedures for peer review panel	
OAO028MAY1993C001	Open	PACs may not be appropriately considered in compliance demonstration with overall performance objectives	
OAO028MAY1993C002	Open	Consideration of present PAC/FACs may be inappropriately restricted to scenario development	
OSC0000001347C001	Open	Incomplete program for Issue Resolution Strategy	NRC(1989), DOE(1990), Bernero (1991)
OSC0000001347C002	Open	Deficiencies in performance allocation	
OSC0000001347C009	Open	Lack of criteria for using expert judgement and lack of traceable and defendable procedures for expert judgement elicitation	
OSC0000001347C095	Open	Underlying logic for, and implementation of, scenario development and screening is deficient for generating a CCDF and deficient for guiding site characterization	NRC(1989), DOE(1990), Bernero (1991), Austin (1996)
OSC0000001347C098	Open	Weighting alternative conceptual models according to judgement 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
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)
OSC0000001347C102	Open	Performance assessment flow models are inconsistent with current understanding of site hydrology	

Table 3. Summary of TSPAI KTI open item status (cont'd).

Item ID	Status	Title	Comment
OSC0000001347C105	Open	Site characterization should provide data, analyses, or justification to substantiate elimination of scenarios	NRC (1989), DOE (1990), Bernero (1991), Austin (1996)
OSC0000001347C116	Open	Incorrect assumption that absence of significant sources of groundwater sources at site precludes consideration of environmental pathways for individual dose calculations	
OSC0000001347C117	Open	Current approach for C14 exposure will not provide the information needed to calculate residence time	
OSC0000001347Q022	Open	Rationale for selection of performance goals needed for establishing that technologies pertaining to repository construction, operation, closure, and decommissioning are sufficiently	RDTME is also evaluating this open item

Table 4. Discussion points identified in recent DOE/NRC performance assessment technical exchanges. These discussion points are not open items but are more prospective than the established open items.

	Questions
TE1	What is meant by DOE's definition of "importance sampling" and what approach will be used to determine importance?
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?
TE3	How is DOE calibrating its use of abstracted data and response surfaces from process-level modeling results in the performance assessment calculations?
TE4	What radionuclides will DOE use for its dose calculations? How has DOE screened radionuclides from inclusion into the dose calculation?
TE5	How will DOE represent results from alternative conceptual models?
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.
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)?
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? In the unsaturated zone?
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)
TE10	How is the flow from the saturated zone being represented and treated in the flow and transport model? (see OSC0000001347C102)

Table 4. Discussion points identified in recent DOE/NRC performance assessment technical exchanges. These discussion points are not open items but are more prospective than the established open items (cont'd).

	Questions
TE11	What is the significance of colloids on performance?
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?
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?
TE14	What basis is DOE using to estimate radionuclide concentrations in the aquifer?
TE15	What basis is DOE using to support its estimates of Neptunium solubility?
TE16	DOE plans to take credit for degraded waste packages. How much credit will DOE take for the contribution of degraded waste packages? What technical basis will DOE use to support taking this credit?
TE17	If DOE is to take credit for galvanic protection, what basis will be used to support this?
TE18	What data is DOE using to support its modeling of C-22 behavior (e.g., uniform corrosion rate and stress corrosion cracking susceptibility)?
TE19	What basis is DOE using for establishing and applying the near-field environments for waste package corrosion (e.g., corrosion potentials)?
TE20	How is DOE integrating the interactions between the engineered barrier system and the natural system for radionuclide transport?
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?
TE22	How are the consequences of seismic events (i.e., vibratory ground motion and rockfall) on waste packages going to be evaluated? (see also OSP0000831821Q001)

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APPENDIX A:

KEY ELEMENTS OF SUBSYSTEM ABSTRACTIONS
AND
RELEVANT HYPOTHESES IN
DOE'S REPOSITORY SAFETY STRATEGY

Appendix A. Key elements of subsystem abstractions and relevant hypotheses in DOE's repository safety strategy

Key Elements of Subsystem Abstractions	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 corrosion				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
Location and 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 waste packages can be limited.

LONG WASTE PACKAGE LIFETIME

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

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

Hypothesis #7
Double-walled waste packages 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

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).

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 waste package and other components of the engineered barrier system for prevention of nuclear criticality

Evolution of the Near-Field Environment (ENFE)

ENFE1 Effects of coupled thermal-hydrologic-chemical processes on seepage and flow

ENFE2 Effects of coupled thermal-hydrologic-chemical processes on waste package chemical environment

ENFE3 Effects of coupled thermal-hydrologic-chemical processes on chemical environment for 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

Igneous Activity (IA)

IA1 Probability of future igneous activity

IA2 Consequences of igneous activity within the repository setting

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

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

Structural Deformation and Seismicity (SDS)

SDS1 Faulting

SDS2 Seismicity

SDS3 Fracturing and structural framework of the geologic setting

SDS4 Tectonics and crustal conditions

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

Total System Performance Assessment and Integration

TSPAI1 Demonstration of the overall performance objective

TSPAI2 Demonstration of multiple barriers

TSPAI3 Model abstraction

TSPAI4 Scenario analysis

TSPAI5 Transparency and traceability of the analysis

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

APPENDIX C:

SUMMARY OF THE CONCEPTUAL APPROACHES IN TPA VERSION 3.1.4 CODE FOR THE KEY ELEMENTS OF SUBSYSTEM ABSTRACTIONS

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 code version 3.1.4 can be found in Mohanty and McCartin (1998). Modifications to TPA code version 3.1.4 is currently underway and the significant changes to the conceptual models are highlighted as appropriate.

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 key elements of subsystem abstraction (KESAs) are addressed with different levels of complexity. The extent that interdependencies are modeled within the TPA 3.1.4 code is also variable. Hereafter the TPA code version 3.1.4 is identified as TPA 3.1.4

The following discussion of the TPA 3.1.4 calculations provides a description of the implemented conceptual model and places the KESAs within the context of the current model abstraction. In the description that follows, KESAs relevant to aspects of the total system performance assessment calculation are identified and the conceptual model for that part of TPA 3.1.4 is presented. The reader should not infer that when a KESA is identified, that all relevant phenomena within that KESA are implemented in TPA 3.1.4. After an overview, the description progresses as follows: infiltration and deep percolation, near-field environment, undisturbed failure of the waste package, disturbed failure of the waste package (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 KESAs in that part of the abstraction. KESAs 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 waste packages are susceptible to corrosion. Waste packages can fail from corrosion or mechanical failure (including disruptive events). After waste package 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, waste package corrosion, radionuclide release rates [and solubility limits],** and the **quantity and chemistry of water contacting waste packages 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 **waste package 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 waste package. 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 waste packages 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 waste package 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 waste package 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 waste package surface temperature and the repository temperature are utilized to compute relative humidity.

The pH and the chloride concentration of the water contacting the waste packages 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 effects 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 between two thermohydrologic models. The first 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 waste package during times when the waste package temperature exceeds the boiling point of water.[27] Only one thermohydrologic model is used during a given simulation.

Undisturbed Failure of the Waste Package

The failure of emplaced waste packages can be considered as occurring from **waste package corrosion** or mechanical failure. Although, waste packages are part of the engineered system, the behavior of the waste packages 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, **waste package corrosion** is a function of temperature, humidity, water chemistry and the thickness of the water film on the waste package; these attributes may be influenced by the **spatial and temporal distribution of flow** through the unsaturated zone. Fracturing or buckling of parts of the waste package can also result in the **mechanical disruption of waste packages**. The failure will allow water to contact the waste form [**quantity and chemistry of water contacting waste packages and waste forms**] and influences the **radionuclide release rates [and solubility limits]**.

[27] Modifications to TPA 3.1.4 include a third model that 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 waste package.

The waste package can fail in one of four ways: waste package fabrication and handling (initial failure), corrosion, mechanical failure or through disruptive events (disruptive failures). Initial failures are considered to occur at the start of the simulation[28]. 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 waste package overpack is penetrated by corrosion. Once one waste package fails by corrosion, all waste packages 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 waste package includes two distinct layers: an inner overpack consisting of a corrosion resistant material (either Alloy C-22, 625 or 825) and an outer overpack consisting of a corrosion allowance material. This approach is consistent with the current DOE conceptual designs for the repository.

Corrosion of the waste package is strongly determined by the following environmental conditions. The temperature (average repository and waste package surface) and relative humidity (RH) are used to determine the extent of the water film on the surface of the waste package. The amount of water dripping onto the waste package 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. The repassivation potential of the inner waste package barrier may be increased through galvanic coupling with the less noble outer barrier.

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 waste packages** can arise from seismicity, faulting, or igneous activity. The failure of waste packages will allow **[quantity and chemistry of] water to contact the waste form** [**and waste packages**] and influences the **radionuclide release rates [and solubility limits]**. The inventory of those waste packages failed by extrusive igneous activity will be transported to the biosphere via the airborne pathway only (discussed below under radionuclide transport) and consequently, these waste packages are not affected by water seeping into the repository. The failure of waste packages 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 waste packages**] 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 waste packages 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 waste packages within the

[28] Revision to TPA 3.1.4 includes an option to specifying non-zero initial failure time

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 waste package. 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 waste packages is estimated from the results of a drift stability analysis using the computer code UDEC (Itasca Consulting Group, Inc., 1996) and joint spacing. This rock is then assumed to fall from the top of an unbackfilled drift to the waste package. The effects of this impact force on waste package deformation and stress within the waste package are calculated for a range of different rock categories and seismic events. Waste package failure from the impact load occurs if the deformation exceeds the initial thickness of the overpacks or if the impact stress exceeds the ultimate tensile strength.[29]

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, **transported through the air** and eventually deposited on the ground surface. 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 unsaturated zone and then through the saturated zone before reaching the receptor location. The amount of contamination transported through the unsaturated zone and saturated zone is affected by the number of failed waste packages (**waste package 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 waste packages 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 waste package failure, whether it be from corrosion, initial failure, mechanical failure or due to disruptive events, it is assumed that one or more holes are formed in the waste package. The waste is then no longer protected from water percolating through the drift and

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[29] In the next version of the TPA code, waste package failure will be assumed to occur 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.

release from the waste package is possible. Releases are modeled to occur by advective and diffusive transport through the remnants of the waste package.[30] For advective releases, the amount of water entering the waste package is apportioned from the water percolating through the repository horizon. For advective release of radionuclides, water must be able to flow through the lowest hole in the waste package. The amount of water that must enter the waste package 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 waste package until the capacity, which is a function of the location of the lowest hole in the waste package, is reached and thereafter the amount of water entering the waste package will equal the amount of water flowing out of the waste package. The height of the water in the waste package determines the fraction of fuel wetted. 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 waste packages; 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 waste package. Water entering the waste package 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 waste package temperature, calculated assuming an intact (i.e., dry) waste package, is used for waste dissolution calculations. Dissolution from the spent fuel matrix may be modeled in one of three ways: release in the absence of Ca and Si, release in the presence of Ca, Si, and a user-defined release rate.[31] The waste package 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 waste package 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 is the same for all subareas and modes of waste package failure.[32] Concentrations within the water flowing out of the waste package are determined assuming a stirred tank model within the waste package.

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 are assumed to flow from the waste package

[30] Revision to TPA 3.1.4 includes the consideration of radionuclide releases from the gap fraction. However, the diffusive release is omitted because of its small contribution to the total release. In the modification to TPA 3.1.4, 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.

[31] Effects of secondary minerals on the waste dissolution is considered in the modifications to the TPA 3.1.4.

[32] In the modifications to TPA 3.1.4, 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.

directly into the unsaturated zone below the repository.[33] 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 3.1.4.

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 waste packages** and the **airborne transport of radionuclides** after a volcanic event (when other gaseous releases are neglected). 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. The approach taken to evaluate the exposure of receptor groups in TPA 3.1.4 is described below.

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[33] Consideration of the invert as a barrier to radionuclide transport is included in the modifications to TPA 3.1.4.

The receptor group may be exposed to contamination transported through the groundwater pathway or released through extrusive igneous activity. Two archetypical 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 20 or greater km from the repository that use the contaminated water for drinking, residential use and agricultural use; they are also exposed to surface contamination through ingestion, inhalation and direct exposure. A set of dose conversion factors (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.

APPENDIX D:

SAMPLE EXPECTED 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 TSPA 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 may be repeated for K scenario classes.

Step 2 A simulation is performed for each of the N vectors. Simulations are also performed for each of the K scenario classes. There is no restriction that the same number of vectors is evaluated for each scenario class. Each simulation provides an evaluation of repository performance under an assumed scenario. A time dependent dose to the average member of the critical group is calculated for each simulation. For example, if there are K scenario classes and N vectors calculated for each scenario class, then there will be a total of $N \times K$ curves.

Step 3 The results from Step 2 then are combined. Each scenario has an associated probability. The expected annual dose to the average member of the critical group is a weighted average of repository performance over all scenarios, where the consequences of each scenario are multiplied by their probability and can be expressed through a single curve. This curve represents the expected repository behavior over time. Repository performance for particular scenario classes or other combinations of scenarios also can be calculated by taking the weighted average over an appropriate subset of scenarios.

A simple example will be described that illustrates the steps described above. Assume that the scenario class $\{\Theta\Psi\}$ is screened out on the basis of its low probability of occurrence so that consequence analysis of only three scenario classes is to be performed, i.e., K=3 and that the probability of $\{\Theta\Psi\}$ is added into the scenario $\{\Theta\Psi^{-}\}$. Also assume that four equally likely simulations (i.e., N=4) are performed for each of the three scenario classes. Tables D-1, D-2, and D-3 show the result of these simulations in terms of annual dose in unspecified units. Although annual dose is a continuous function, these tables show the dose at particular times. Dose versus time plots corresponding to the data listed in tables D-1, D-2, and D-3 also are shown in the 12 graphs in the upper left hand quadrant of figure D-1. Each of these 12 graphs represents the performance of the repository for one scenario. These dose versus time plots are arranged so that each row of plots in figure D-1 corresponds to one of the three scenario classes.

Each scenario has an associated probability. In this example, the probability of each scenario is one fourth the scenario class probability (i.e., each of the four parameter combinations, j = 1 to 4, used to model the scenario are equally probable and the sum of the probability of the four scenarios equals the probability of the scenario class). The lower right hand plot in figure D-1 depicts the expected annual dose. It represents the weighted sum of annual dose from the 12 scenarios and corresponds to the expected dose values in table D-4. Figure D-1 also shows how conditional repository performance can be determined for scenario classes. The upper three plots on the right of figure D-1 illustrates repository performance for each of the three scenario classes (i.e., each curve is weighted by the probability of the scenario class). They were developed by using the relative probability of each scenario within the scenario class. In this example, each scenario within a scenario class has a relative probability of 0.25. A similar approach can be used for other combinations of scenarios (e.g., those scenarios where far-field criticality occurs).

Table D-1. Conditional annual dose at selected times for scenarios within scenario class $\{\Theta^{-}\Psi\}$

Time, t	*Scenario, j = 1*	*Scenario, j = 2*	*Scenario, j = 3*	*Scenario, j = 4*
1,000	0	1	100	5
4,000	10	100	10	0
6,000	100	50	0	10
8,000	10	100	10	50
10,000	100	60	40	100

Table D-2. Conditional annual dose at selected times for scenarios within scenario class $\{\Theta\Psi^{-}\}$

Time, t	*Scenario, j = 1*	*Scenario, j = 2*	*Scenario, j = 3*	*Scenario, j = 4*
1,000	0	5	1	5
4,000	10	100	50	60
6,000	100	200	80	500
8,000	300	400	100	600
10,000	500	600	200	1000

Table D-3. Conditional annual dose at selected times for scenarios within scenario class $\{\Theta^{-}\ \Psi^{-}\}$

Time, t	*Realization, j = 1*	*Realization, j = 2*	*Realization, j = 3*	*Realization, j = 4*
1,000	10	5	1	0
4,000	20	10	5	10
6,000	30	20	10	20
8,000	40	30	20	30
10,000	50	40	30	40

Table D-4. Expected annual dose at selected times

Time, t	*Expected Value*
1,000	5.12
4,000	12.23
6,000	21.19
8,000	30.93
10,000	42.26

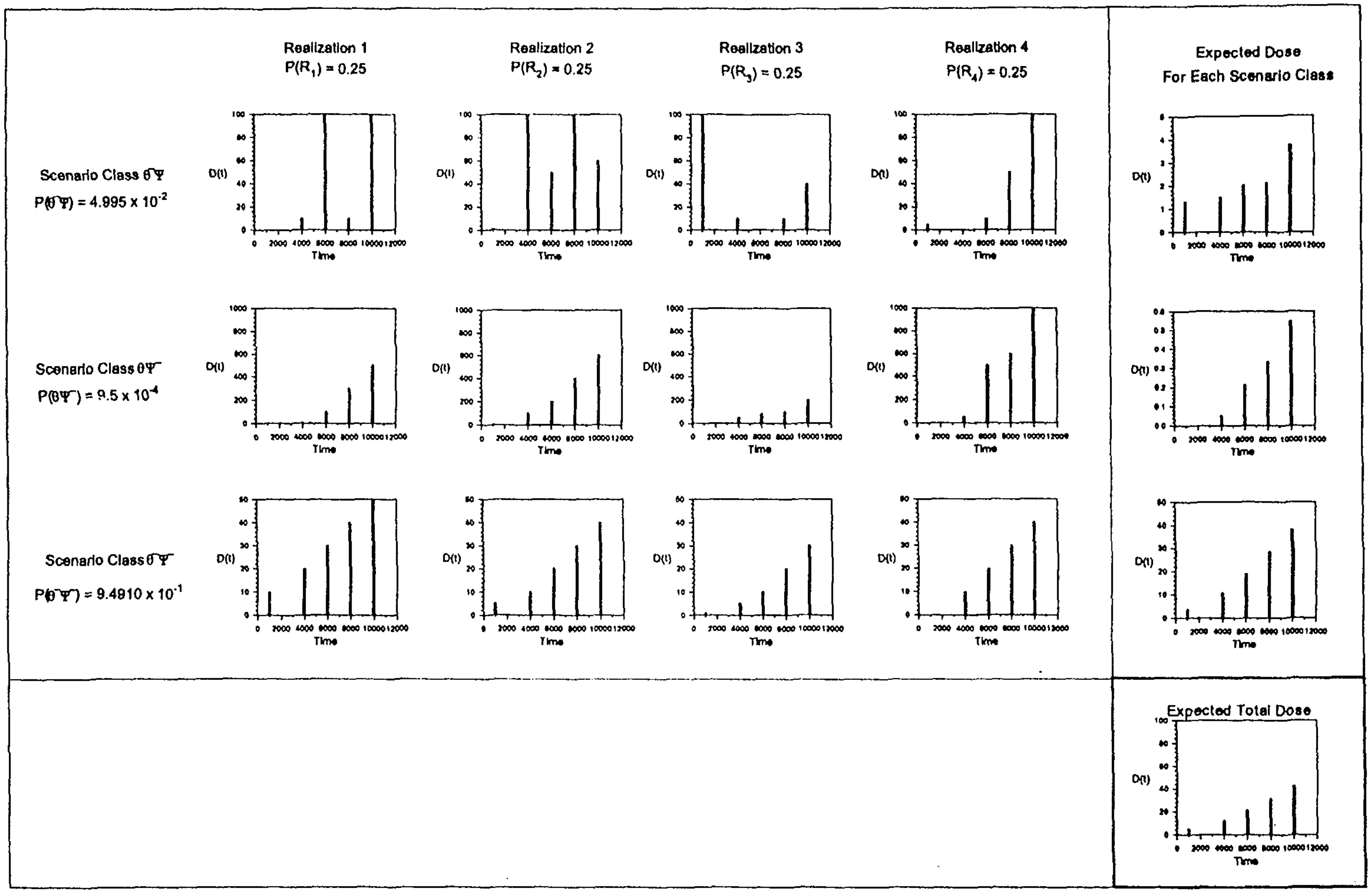

Figure D-1. Illustration of One-Step Method for Computing Expected Total Dose Versus Time