ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE: TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION

Division of Waste Management
Office of Nuclear Material Safety and Safeguards
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CONTENTS

FIGURES

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1.0 INTRODUCTION

One of the primary objectives of the Nuclear Regulatory Commission (NRC) realigned prelicensing program is to focus all its activities on resolving the 10 key technical issues (KTIs) it considers to be most important to repository performance. This approach is summarized in chapter 1 of staff periodic reports (Sagar, 1996). Other chapters address each of the 10 KTIs by describing the scope of the issue and subissues, path to resolution, and progress achieved during fiscal year (FY) 1996.

Consistent with a 1992 agreement with the Department of Energy (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 the 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 is limited to documenting a common understanding regarding differences in the NRC and the DOE points of view. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staff approach to issue resolution is to provide DOE with feedback regarding issue resolution, before the viability assessment (VA). Issue Resolution Status Reports (IRSRs) are the primary mechanism that the staff will use to provide DOE with feedback on the subissues composing the KTIs. IRSRs comprise (i) acceptance criteria that will be used by the staff to review DOE prelicensing submittals, as well as indicating the basis for resolution of the subissue, and (ii) status of resolution including where the staff currently has no comments or questions as well as where it does. Feedback is also contained in the staff periodic reports, which summarize the significant technical work toward resolution of all KTIs during the preceding FY. Finally, open meetings and technical exchanges with DOE provide 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 serve as guidance for the staff review of information in the DOE VA. The staff also plans to use the IRSRs in the future to develop the Review Plan (RP) for the repository license application (LA).

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. 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.

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; (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

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

analysis is focused on the integrated total system assessment, and the assessment is transparent, traceable, defensible, and comprehensive.

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) 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.

2) Scenario Analysis - This subissue considers the proper inclusion or exclusion of possible features, events, and processes that could affect repository performance, the combination of those events into scenario classes, and presentation of the results generated from various credible scenarios. This is a key factor in ensuring the completeness of a TSPA.

3) 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. For example, the presentation of intermediate calculations or output that would assist in demonstrating the contributions of various components of the system toward the overall system performance thus making the TSPA more transparent and traceable.

Revision 0 of this IRSR addresses the input information and model abstraction parts of subissue 1 (Model Abstraction). Succeeding versions of this IRSR will update the acceptance criteria, review methods and status of resolution at the staff level under subissue 1, and address the third part, overall performance calculation, in subissue 1 and subissues 2 and 3.

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 that will be subject to numerous challenges. 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

Under existing regulations, DOE is required (10 CFR 60.21) to provide a comprehensive performance assessment in its license application. NRC is obligated to ensure in its review of a license application, that the proposed repository will adequately protect public health and safety (e.g., 10 CFR 60.31). The staff strategy for conducting a licensing review of DOE's performance assessment calls for an audit review of the assessment in its entirety, supplemented by more detailed reviews of those sections that are of greatest safety significance. As part of its review process, NRC staff will rely almost exclusively on site 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.

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 IMPORTANT OF SUBISSUES TO TOTAL SYSTEM PERFORMANCE

The three subissues identified in Section 2.0 represent the essential components of a TSPA. Resolution of subissue 1, model abstraction, ensures that the assumptions, conceptual approaches, data, models, and abstractions used in DOE's TSPAs are appropriately integrated and technically defensible, and the output of DOE's TSPAs provides sufficient information for the staff to judge if the repository performance would meet the EPA standards for YM. Resolution of subissue 2, scenario analysis, ensures that the quantitative results [e.g., complementary cumulative distribution function (CCDF) on peak annual individual dose] reasonably considers credible scenarios that can affect the performance of the proposed repository over the compliance period. Resolution of subissue 3, 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. 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.

4.1 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: MODEL ABSTRACTION[2]

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 peak annual individual dose or risk 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, and direct release for the geosphere; 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.[3] 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

[2] This section will be updated after completion of staff's TPA Version 3.1 sensitivity studies in FY98.

[3] 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.

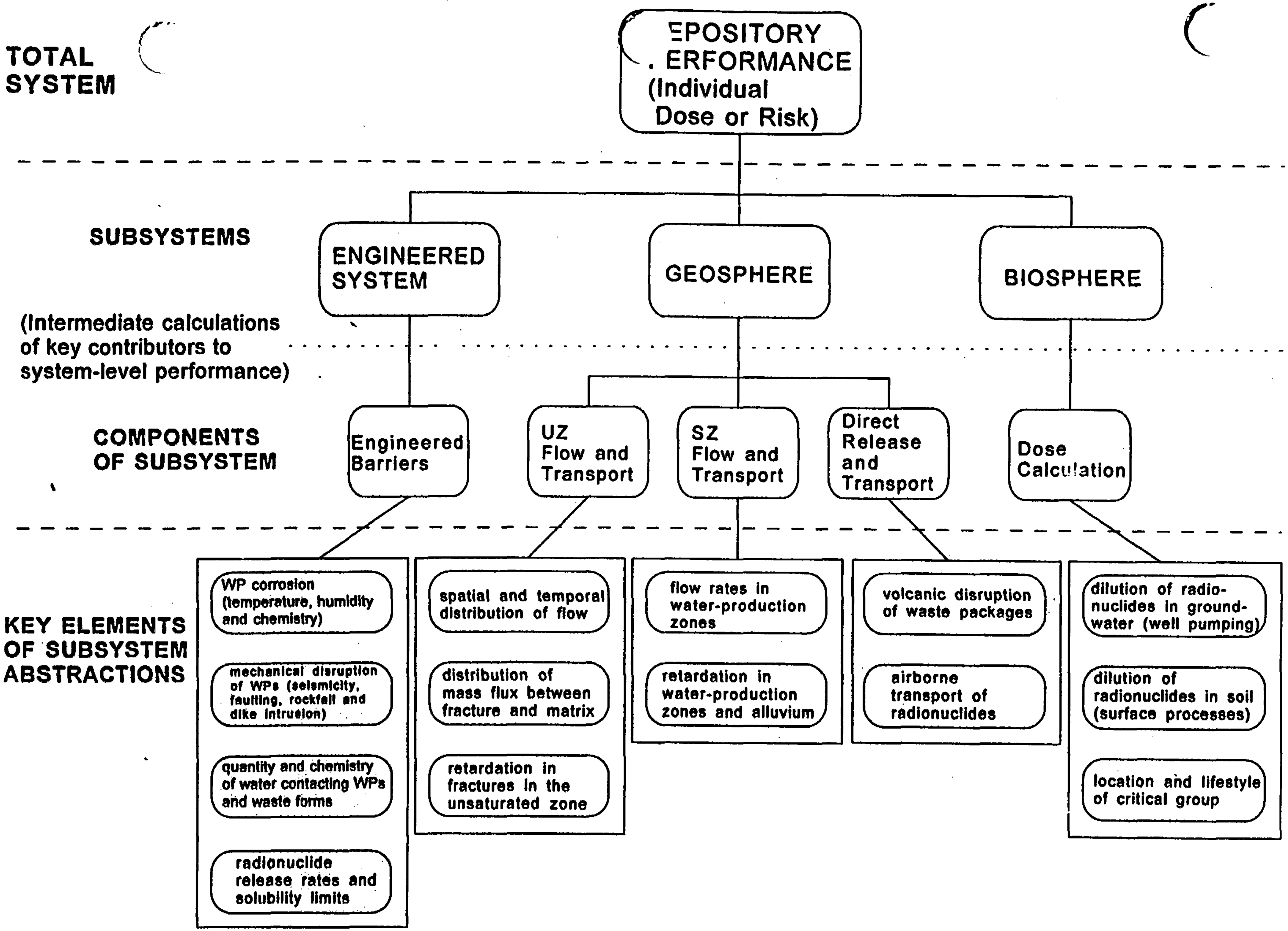

Figure 1. Flowdown diagram for total system performance assessment.

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 contribution to the overall system performance. Therefore, the approach delineated in this section will enable the staff to examine systematically, in the context of the total system performance, whether the engineered designs, site characteristics, and interactions among them have been appropriately identified, incorporated, and analyzed in DOE's TSPA. It should be noted that the staff will focus its review to (i) understand the contribution 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 seven acceptance criteria (AC). The first two AC are programmatic and applicable to all KESAs:

Criterion P1: Abstractions of data and process models are acceptable if they are developed and documented under acceptable quality assurance (QA) procedures.

Review Method: NRC will attend, as observer, activities conducted by DOE related to model/data abstractions and track the progress made in resolving deficiencies/nonconformities in the abstraction activities. If DOE uses peer reviews, staff should review DOE implementation to assure that the peer reviews followed the guidance in NUREG-1297 and NUREG-1298 (Altman *et al.*, 1988a, 1988b) or other acceptable approaches. If staff has concerns, these will be noted at the time of staff attendance at the DOE audit and formally communicated to DOE. Progress in resolving these concerns will be tracked by the staff.

Criterion P2: Use of formal expert elicitations to synthesize data and develop models and input for abstractions in TSPA is acceptable if the elicitations are conducted and documented under acceptable procedures.

Review Method: If DOE uses this approach, NRC staff will attend, as observers, elicitation workshops and review the documentation to ensure the expert elicitations follow the guidance in NUREG-1563 (Kotra *et al.*, 1996) or other acceptable approaches. If staff has concerns, they will be formally communicated to DOE. Progress made in resolving these concerns will be tracked by the staff.

In addition to the two programmatic acceptance criteria noted above, there are five technical acceptance criteria. The general principles underlying these technical criteria apply to all KESAs and are reiterated and customized for each KESA in Sections 4.1.1 through 4.1.3.

Criterion T1 Data and Model Justification
Sufficient data (field, experimental, 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 4.1 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.

4.1.1 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 release rates, as a function of time, of RNs 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.

4.1.1.1 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.

4.1.1.1.1 Waste Package Corrosion (Temperature, Humidity and Chemistry)

Pertinent KTI subissues: CLST1, ENFE2, ENFE3, 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 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 modes considered in assessments of package lifetimes: (i) dry air oxidation, (ii) humid air oxidation, and (iii) aqueous oxidation. 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. NRC has previously questioned the adequacy of this approach, however. 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 several types of WP material under consideration by DOE, the beneficial effect of galvanic coupling[4] can greatly 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, experimental and/or natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the WP corrosion abstraction in TSPA.

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

Review Method: During its review, staff should ascertain that DOE demonstrated that sufficient data exist to support the conceptual models and define relevant parameters in DOE's WP corrosion abstractions. 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 has identified the most important degradation modes and has provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

Criterion T2: Parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the WP corrosion abstraction, such as the critical RH, material properties, pH, and chloride concentration are technically defensible and reasonably account for uncertainties and variabilities.

Review Method: This acceptance criteria will focus on the integrated 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 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 repository, thermal loading strategy, thermal reflux model, deep percolation flux, 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 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 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 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 package for enhanced corrosion. Nearby dike intrusions into the repository will change, for example, both the near-field temperature and chemistry to which the package 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).

[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.

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 nondefensible predictions.

Technical Basis

Approaches to abstracting this key element to system performance have taken two forms: DOE's empirical description of the waste package 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 can greatly affect WP lifetime for inner overpack materials such as alloys 625 and 825.

Corroded WPs have the ability to imbibe percolating groundwater, thereby contaminating it with RNs contained within the package. Specifically, there are currently three corrosion degradation modes considered in assessments of package lifetimes: (i) dry air oxidation, (ii) humid air oxidation, and (iii) aqueous oxidation. These three degradation modes, along with electrochemical or galvanic coupling of package constituents are explained in the follow paragraphs.

In the present 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. 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

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

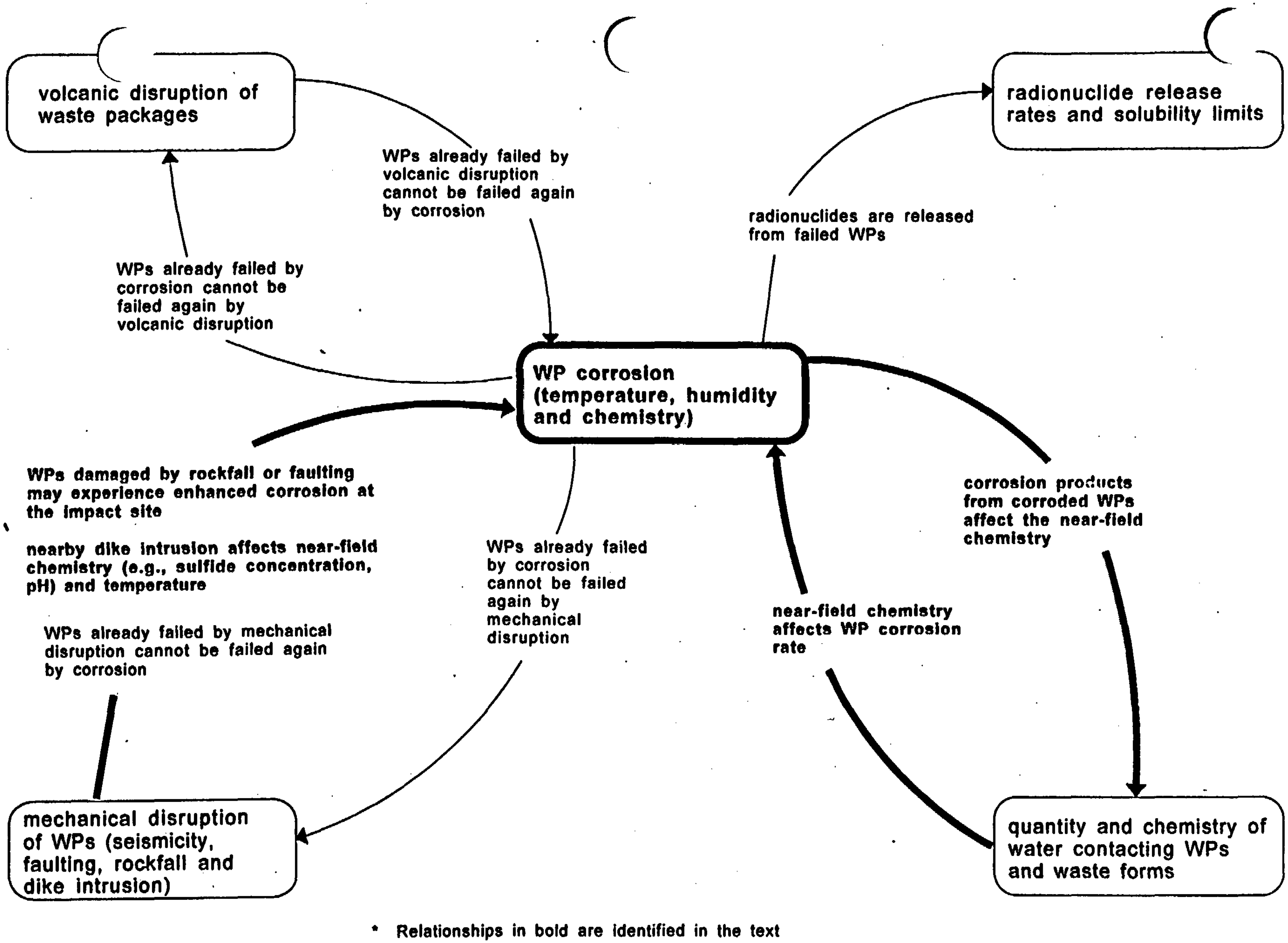

Figure 2. A diagram illustrating the relationships between "waste package corrosion" and other key elements of subsystem abstractions.

corrosion rate can be extremely high where the film is breached. A crucial assumption in DOE's WP design is that the outer overpack material will protect the inner overpack material from localized corrosion. If the outer barrier is breached by localized corrosion, DOE may seek to take credit for galvanic protection of the inner barrier to extend the period of time where the waste package has retained its integrity. 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), this penetration may affect its subsequent performance in an aqueous environment. This decreased performance may occur due to a thickening of the protective oxide film, which, in turn can result in an increase in corrosion potential (Sagar, 1996); 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 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 an arbitrary number dependent 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 concentrations in the alloy $\left(E_{crit}^{825} < E_{crit}^{625} < E_{crit}^{c22}\right)$. 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 form a conservative lower-bound estimate of the long-term critical potential of an alloy in a given environment (Sridhar *et al.*, 1995). Localized corrosion is 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. Such a reduction of corrosion potential through galvanic contact depends on the low-electrolyte resistance in the solution simultaneously contacting both the steel and the inner overpack and low-electronic resistance in the contact between the steel and the alloy (Dunn and Cragnolino, 1997). The electrolyte resistance depends on the solution concentration and can be considered to be relatively insignificant for the solution chemistry anticipated to be present in the pits of the steel overpack. The contact resistance between the steel and the inner alloy overpack may be increased by the presence of oxide scale or corrosion products.

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

Pertinent KTI subissues: CLST2, IA1, 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.[9] 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.[10] 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

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[9] Volcanic disruption is discussed in Section 4.1.2.3, Direct Release and Transport.

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

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.[11]

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, experimental 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.[12]

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,

[11] Section 4.2 will address the scenario analysis subissue in more detail.

[12] The acceptance criteria and review methods for the proper inclusion or exclusion of disruptive scenarios will be provided in Section 4.2.

staff should evaluate DOE input values by comparison to corresponding input values in the staff data set and use the TPA code to test sensitivity of the system performance to the input values and correlations used by DOE.

Criterion T3: Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations appropriately factored into the mechanical disruption of WPs abstraction.

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

Criterion T4: Mechanical disruption of WPs abstraction output is 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 other KESA:

- Seismic (and possibly other) mechanical disruptions may damage the package 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 nondefensible 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 4.1.2.3. If future modeling efforts by DOE's 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; Manteufel *et al.*, 1997). The potential effects of drift instability (i.e., rock falls) on WP performance include (i) breach of corrosion-weakened WPs and (ii) contribution to local acceleration of WP corrosion through the creation of localized depressions where liquid water may pool on the WP surface. Both processes can shorten WP lifetimes. It is noted that these effects are expected to be more pronounced if emplacement drifts are not backfilled. In current NRC modeling (Manteufel *et al.*, 1997), damage to the WP from a seismic event is estimated by calculating the deflection that the package experiences due to rockfalls, and the cumulative damage is tracked until it reaches a threshold value, above which the WP is considered to be failed.

The possibility of a new (or currently unknown) faults at YM undergoing displacement within the repository footprint at some future time is also of interest for WP performance. 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 scenario (Ghosh *et al.*, 1997; Manteufel *et al.* 1997) use probabilistic techniques to determine the timing, location, and

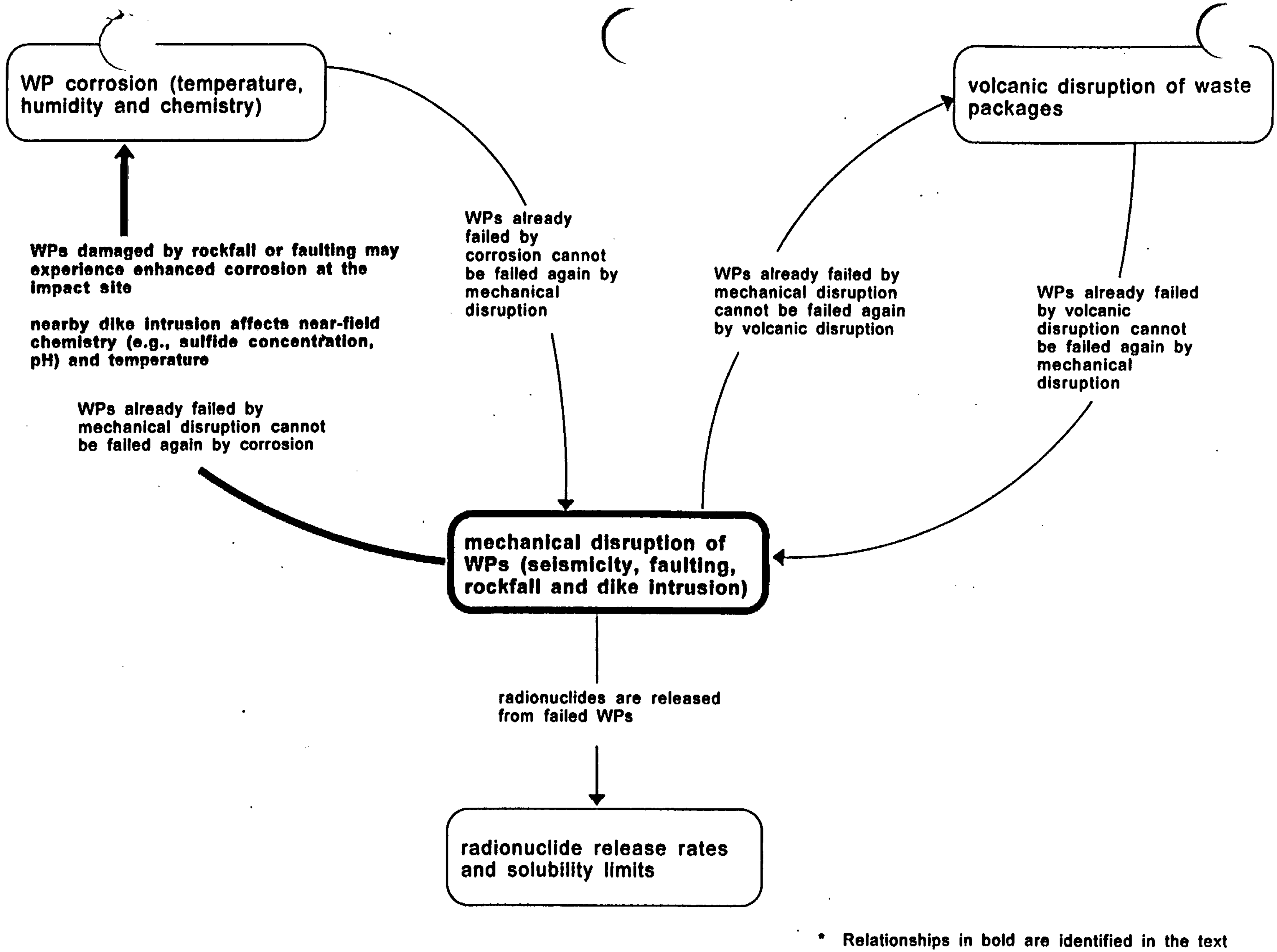


Figure 3. A diagram illustrating the relationships between "mechanical disruption of waste packages" and other key elements of subsystem abstractions.

displacement of faults within a region that includes the repository footprint. 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 takes into consideration that for ductile metallic materials a deformation or strain threshold must be overcome. 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).

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 have the ability to mechanically disrupt and thus prematurely fail a number of WPs. Although most recent efforts in performance assessment have not modeled the indirect effects of volcanism from dike formation (Manteufel *et al.*, 1997; 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 activity event penetrating the proposed repository has been less extensively studied than the annual probability of penetration of the repository by an extrusive event. An intrusive event is defined here as the penetration of the repository by an igneous dike or dike swarm with no cone formation, or the penetration of the proposed repository by an igneous dike (or dike swarm) with a cone that forms outside of the repository footprint. In either case, no waste is directly extruded into the accessible environment, 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. Considering the typical lengths and orientations of YM region intrusions, the probability of an intrusive event is estimated to be at least twice that of cone formation (Hill *et al.*, 1996). 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.

4.1.1.1.3 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, USFIC5

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 package. 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 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 engineered system's contribution to total system performance.

Criterion T1: Sufficient data (field, experimental, 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 abstracting 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 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).

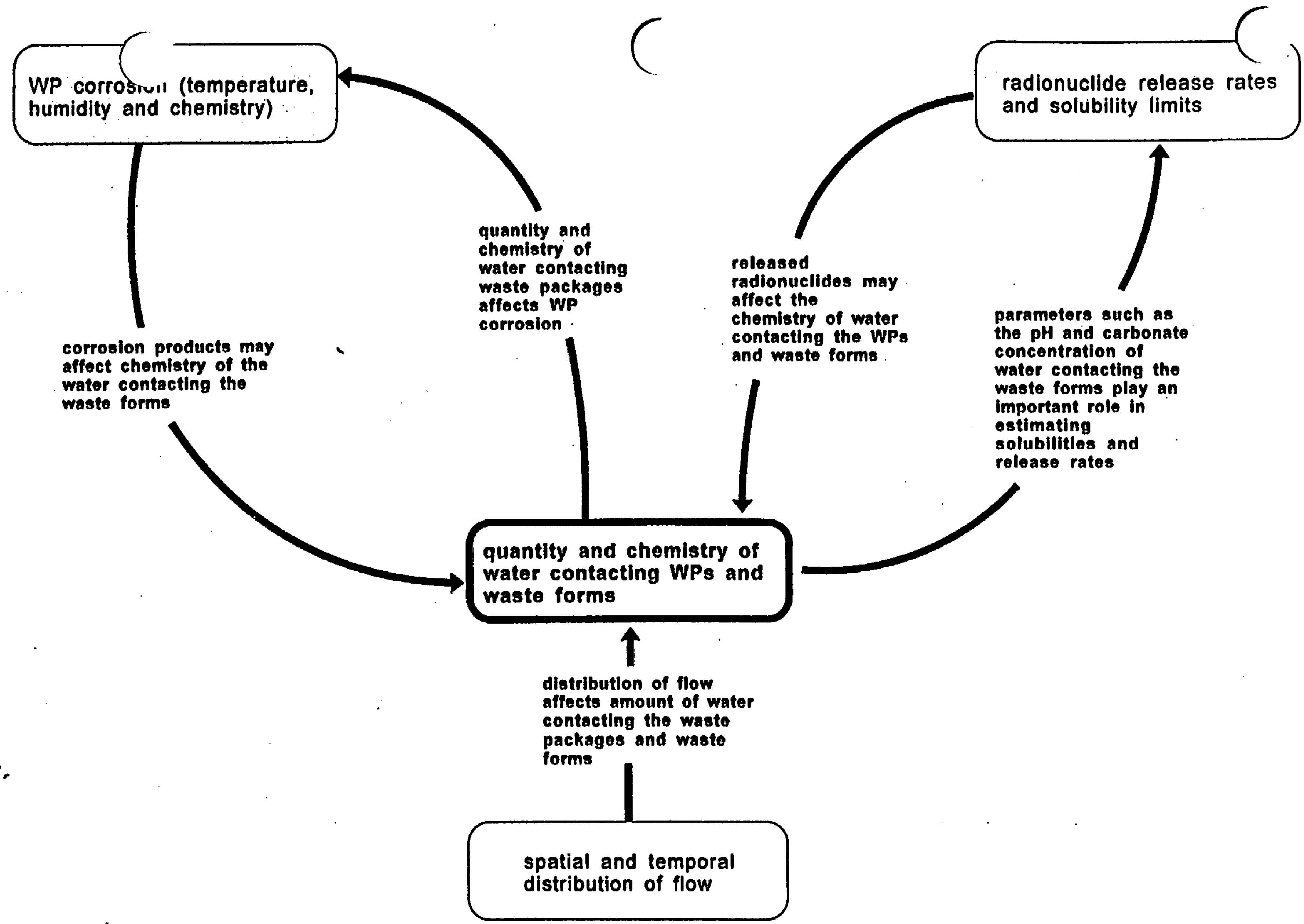
- Parameters such as the pH and carbonate concentration of water contacting the waste forms play an important role in estimating solubilities and release rates. Released RNs may affect the chemistry of water contacting the WPs and waste forms (radionuclide release rates and solubility limits).

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 packages 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 4.1.1.1.1. 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 4.1.1.1.1.

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 rate limited, a large flow of water contacts waste forms such that not all the water can be saturated in a given RN (due to limited waste surface areas). In this case, RN releases in performance assessment are usually calculated by multiplying the package RN inventory by a maximum fractional release rate for that RN (Manteufel *et al.*, 1997; Mohanty *et 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



* 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.

waste. It is noted that maximum fractional release rates and RN solubilities are discussed in Section 4.1.1.1.4. 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 packages; 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 4.1.1.1.1, 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 assessments (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).

4.1.1.1.4 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 spent fuel (SF) 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 package water and depend on parameters describing 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 package 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.

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

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.

<u>Criterion T1</u>: Sufficient data (field, experimental 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 should be 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 (laboratory testings or natural analogs, or both).

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 SF, waste forms, thermal loading strategy (for temperature 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 the

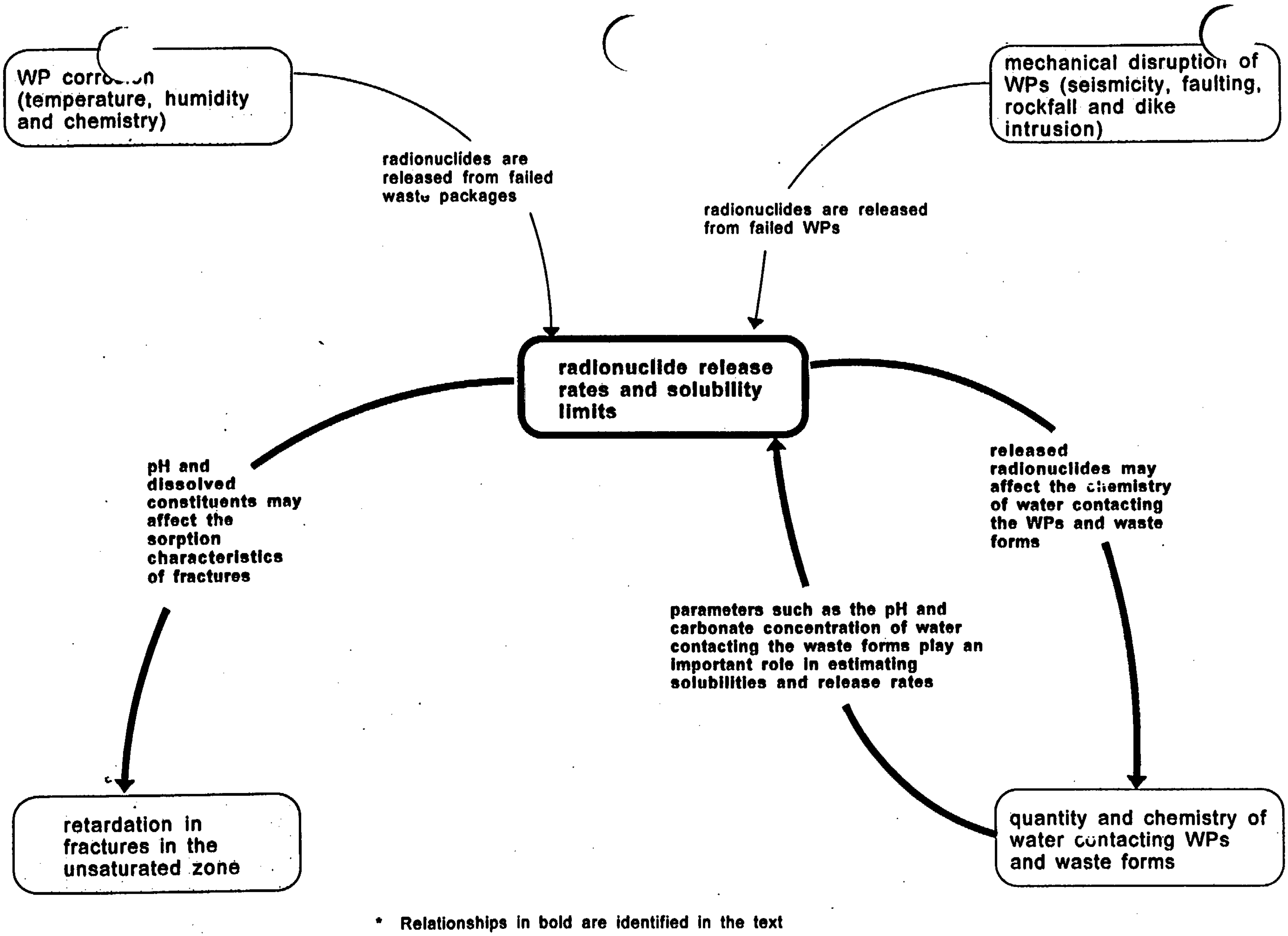


Figure 5. A diagram illustrating the relationships between "radionuclide release rates" and solubility limits" and other key elements of subsystem abstractions.

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

This section describes the technical basis for the abstraction of the radionuclide release rates and solubility limits with respect to repository performance. Specifically, how these processes are captured in PA models and their dependence upon the near-field environment are discussed.

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. 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 package. In advective release, the rate at which water exits the package is multiplied by the RN concentration to obtain an exit rate for RNs from the package. In diffusive release, the concentration of RNs in package waters is used to estimate the concentration gradient necessary for calculating the diffusive flux of RNs from the package. To estimate time dependent RN concentrations inside a breached WP, an expression for the fractional release rate of RNs from the spent fuel (SF) to package waters from Gray and Wilson (1995) is utilized and a mass balance is performed. The total release rate of RNs to package waters is the fractional release rate multiplied by the package inventory. First order rate equations are used to estimate RN concentrations as a function of time in package waters, with the upper limit being the solubility of the RN.

Current DOE PA models (TRW Environmental Safety Systems, Inc., 1995) use 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 SF 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 SF (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.

4.1.2 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.

4.1.2.1 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.

4.1.2.1.1 Spatial and Temporal Distribution of Flow

Pertinent KTI subissues: ENFE1, IA2, RDTME1, RDTME3, SDS1, SDS2, SDS3, SDS4, TEF1, TEF2, TEF3, USFIC1, USFIC2, USFIC3, USFIC4, USFIC5

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 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) of 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 geosphere's contribution to total system performance.

Criterion T1: Sufficient data (field, experimental 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).

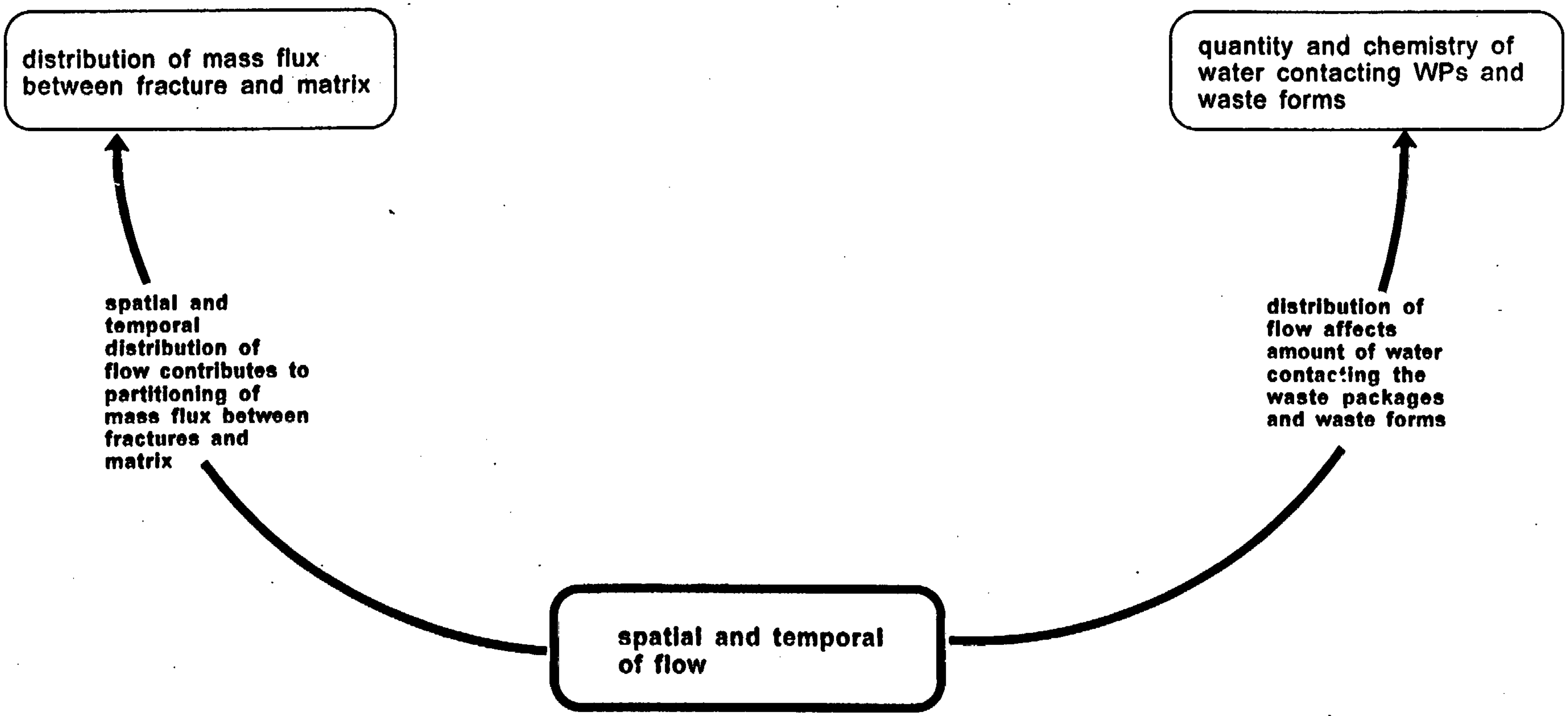
Review Method: Staff should ascertain that DOE verified the output of spatial and temporal distribution of flow abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible, staff should evaluate the output of DOE's 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 seals of shafts and boreholes, thermal loading strategy, drift size and spacing, 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:

- 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



* :'elationships 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.

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) focussed 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 magnitude dependent on factors such as soil cover, evapotranspiration, and type of bedrock. As water moves deeper, wetting pulses attenuate and spread to become more temporally and spatially 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 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).

The current NRC model assumes that infiltrating waters proceed through the repository horizon to the water table with negligible 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.

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.

4.1.2.1.2 Distribution of Mass Flux between Fracture and Matrix

Pertinent KTI subissues: ENFE1, ENFE4, RDTME1, RDTME3, SDS1, SDS3, TEF1, TEF2, TEF3, USFIC3, USFIC4, USFIC5

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 capacity, fractures conduct flow 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, experimental, 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.

<u>Criterion T2</u>: 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 abstracting 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:

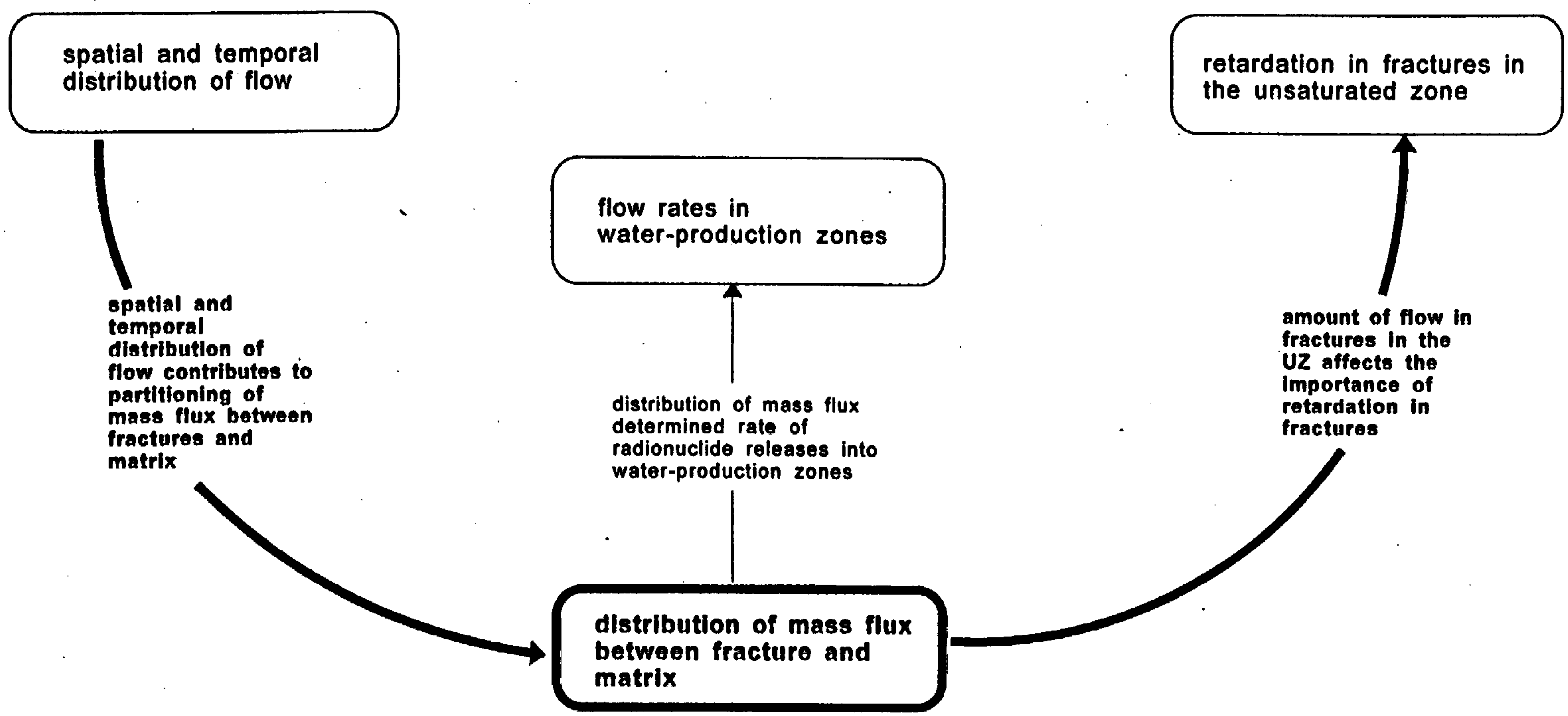
- Spatial and temporal distribution of flow contributes to partitioning of mass flux between fractures and matrix (spatial and temporal distribution of flow).
- Amount of flow in fractures in the UZ affects the importance of retardation in fractures (retardation in fractures in the UZ).

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 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



* 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.

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 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) 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.

4.1.2.1.3 Retardation in Fractures in the Unsaturated Zone

Pertinent KTI subissues: ENFE4, RDTME1, RDTME3, RT1, RT2, RT3, RT4, USFIC3, USFIC4, USFIC5, USFIC7

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 to which RNs can migrate from the repository.

Currently, neither DOE's nor NRC's PAs (TRW Environmental Safety Systems, Inc., 1995; Wescott *et al.*, 1995; Manteufel *et al.*, 1997) 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, experimental, 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 DOE's dimensionality 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 in retardation in fractures in the UZ for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

There remains uncertainty regarding the distribution of unsaturated zone groundwater flow between fractures and matrix. Aside from issues of advective flow, this distinction is critical to

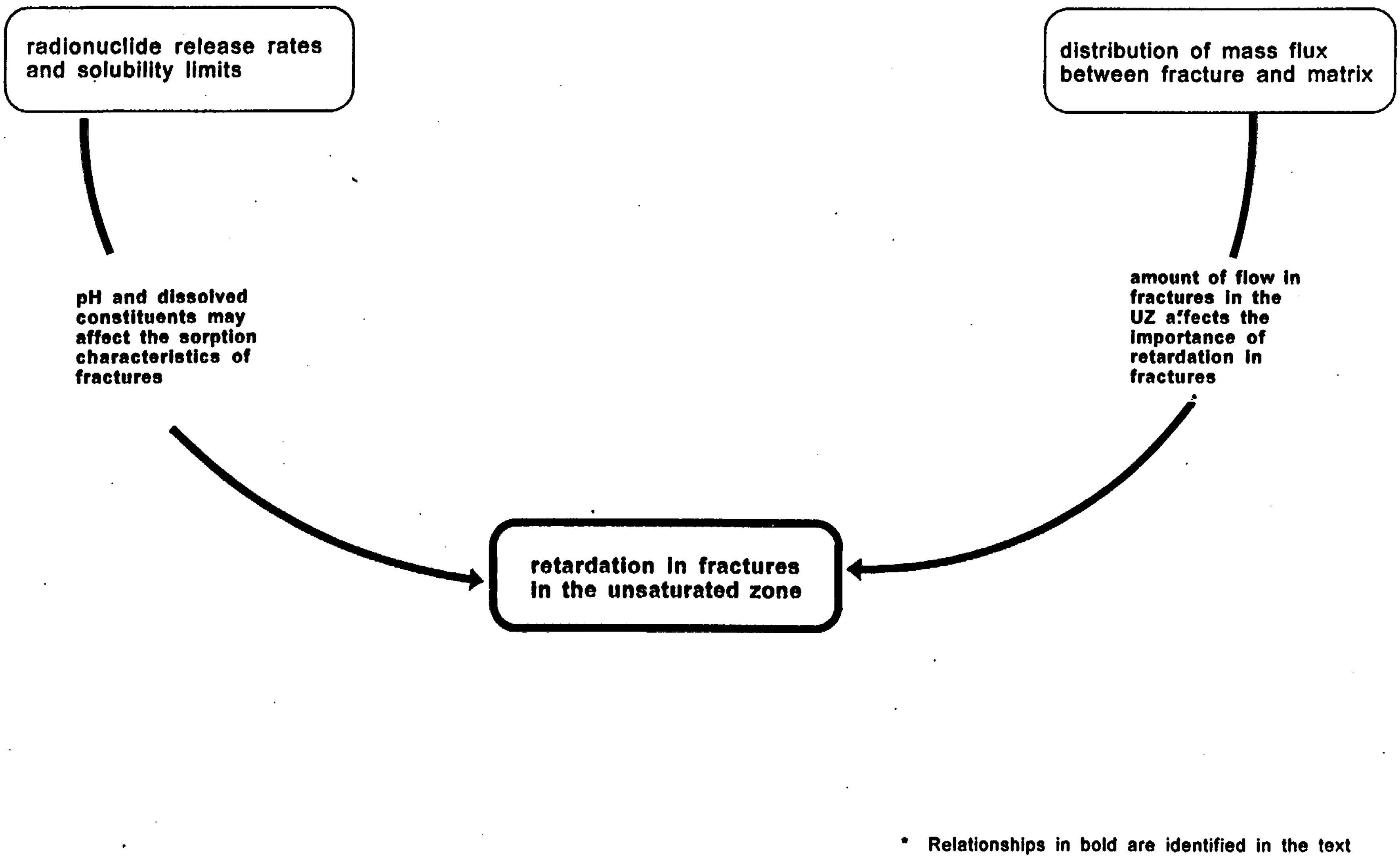


Figure 8. A diagram illustrating the relationships between "retardation in fractures in the unsaturated zone" and other key elements of subsystem abstractions.

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). 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.

4.1.2.2 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.

4.1.2.2.1 Flow Rates in Water Production Zones[13]

Pertinent KTI subissues: IA2, SDS1, SDS3, USFIC2, USFIC6, USFIC8

A necessary step in estimating the dose to a receptor group is determining the average RN concentrations in the pumping well. If a receptor group location is less than 10 km, then the extent and thickness of groundwater production zones in the tuff aquifer may be important for estimating the dose. At distances of less than 15 km downgradient from the site, the SZ occurs entirely in volcanic tuffs. Beyond a distance of about 15 km, the water table occurs in thick alluvial deposits. RN concentrations in the well are functions of plume dilution (i.e., entrainment of pristine waters), geometry of the plume near the well, and the well capture area. One approach for estimating the average RN concentrations is to use a borehole dilution factor. Such dilution factors can be computed by using groundwater flow models (Fedors and Wittmeyer, 1998).

RNs introduced into the groundwater below the repository horizon travel in the SZ by convection and dispersion. It is currently expected that longitudinal and transverse dispersion will be relatively small in the tuff production zones. Groundwater flow patterns in the tuffaceous aquifer are likely to be complex and largely controlled by high-permeability features such as faults and zones with interconnected fractures. Although the flow fields within the tuffaceous aquifer may be complicated and difficult to define, 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). These production zones can transmit varying amounts of water depending on their thicknesses and transmissivities. Near a pumping well, the flow in the production zones also will be affected by the amount and distribution of pumping, the well diameter, the screen interval, degree of aquifer penetration, and the radius of influence of the well(s).

Groundwater flow in the tuffaceous aquifer is predominantly horizontal, except where the production zones are offset across faults. Therefore, the volumetric flow in the production zones will govern the availability of groundwater for RN transport. One of the primary mechanisms for reducing RN concentrations in the tuffaceous aquifer is dilution induced by pumping wells. In this case, the mass of RNs entering the well casing are mixed with the total inflow of water from one or more production zones. 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 geosphere's contribution to total system performance.

[13] Current NRC approach assumes that a limited amount of leachate flows into production zones.

Criterion T1: Sufficient hydrogeologic data (field, experimental, 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.

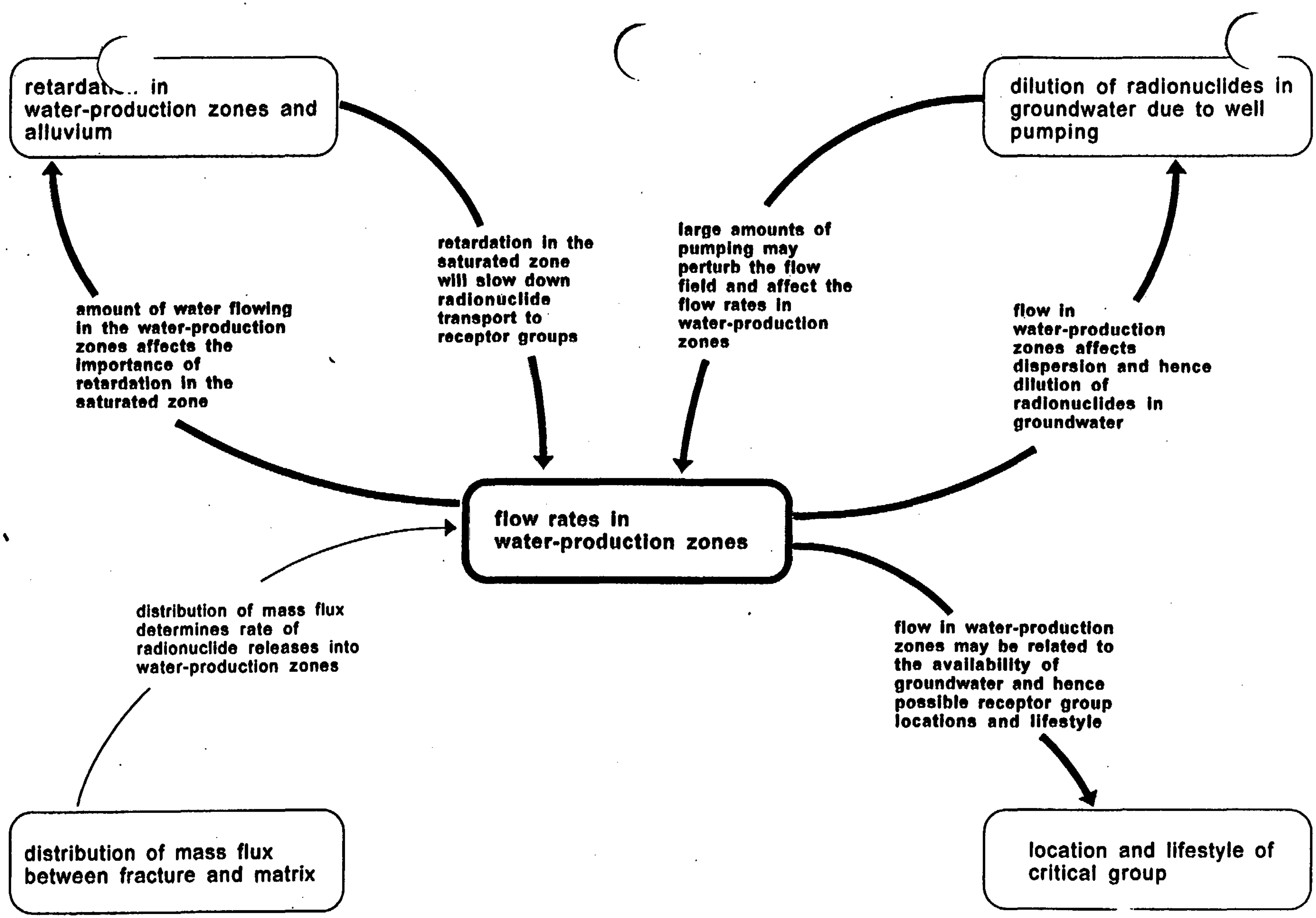
Review Method: Staff should ascertain that consistent and appropriate assumptions and initial and boundary conditions have been propagated throughout DOE's abstraction approaches; for example, if the conditions and assumptions used to generate the look-up tables or regression equations are consistent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



* 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.

in water-production zones for potential inconsistency in the analysis and nondefensible predictions.

Technical Basis

Current NRC and DOE assessments differ in the amount of credit taken for mixing and volumetric flow in the SZ beneath the repository (i.e., dilution). This difference is seen by examining dilution factors used by these assessments. The most recent DOE TSPA (TRW Environmental Safety Systems, Inc., 1995) estimates dilution factors (defined as the ratio of RN concentration in unsaturated zone waters beneath the repository just above the water table to centerline concentrations at a distance) on the range of [4.5×10^3, 1.9×10^5] at 5 km, to the range of [3.1×10^4, 1.3×10^6] at 30 km. Although NRC/CNWRA assessments do not use dilution factors per se[14], a similar quantity can be estimated from these assessments. Results obtained with preliminary runs of the TPA code (Manteufel *et al.*, 1997) indicate that the actual dilution factors may be orders of magnitude lower than those estimated in TSPA-95. These preliminary results agree with other auxiliary calculations (Baca *et al.*, 1996) that estimate dilution factors on the order of 5 to 50 in the Amargosa Farms area. They also agree with the dilution factor computed by the Electric Power Research Institute (Kessler and McGuire, 1996), which ranges from 6 to 44.

4.1.2.2.2 Retardation in Water Production Zones and Alluvium

Pertinent KTI subissues: ENFE4, IA2, RT1, RT2, RT3, RT4, USFIC7

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 results in diminishment of RN concentrations in groundwater. Because if lack of sufficient 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 4.1.2.1.3. 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.

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[14] Latest NRC/CNWRA assessments assume that all RNs released to the SZ are captured by a well at the compliance point after migration through the SZ. RN concentrations are estimated by diluting these releases into the volume of water pumped by the well.

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, experimental, 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 plume dispersivity, sorption in tuff, and sorption in alluvium, 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).

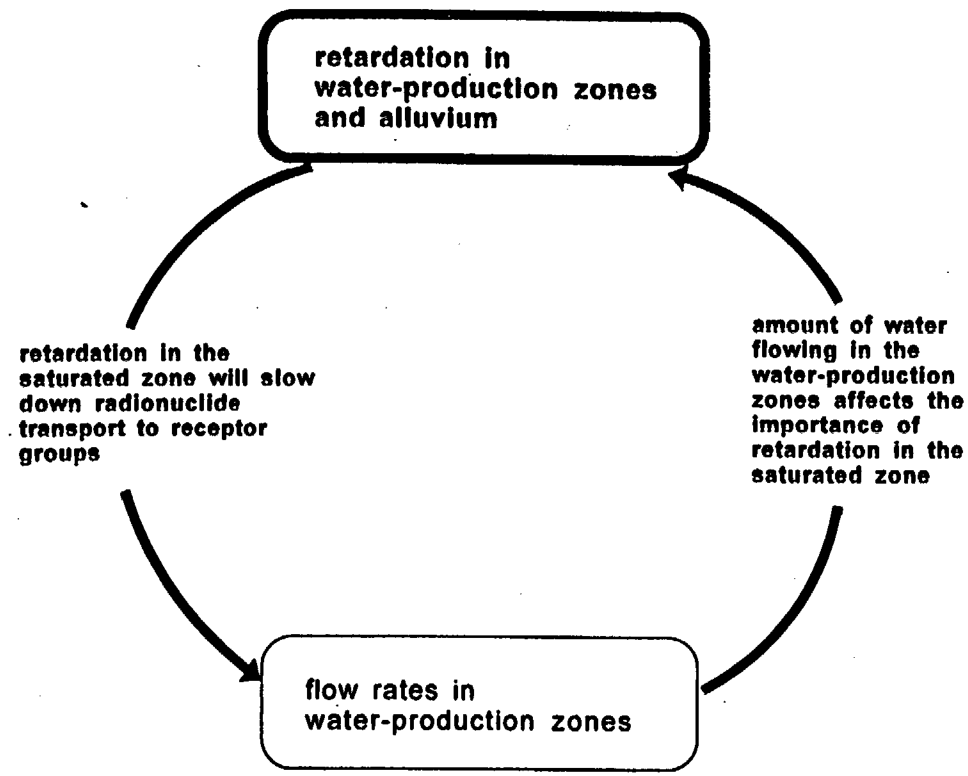
Review Method: Staff should ascertain whether DOE verified the output of retardation in water-production zones and alluvium abstraction reasonably reproduces or bounds the results of the corresponding process-level models or empirical observations. To the extent feasible and applicable, staff should 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 DOE's dimensionality 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:

- Amount of water flowing in water-production zones affects the importance of retardation in SZ. Retardation in SZ will slow down RNs transport 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.



* 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.

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 sorption of RNs on different minerals to limit migration velocities of RNs 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 4.1.2.1.3, one of the key geochemical processes that may lower RN concentrations—and thus enhance repository performance—is retardation. Section 4.1.2.1.3 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 4.1.2.1.3 discusses the others. Also included here are subjects specific to possible saturated flow in alluvium.

As in the case of the unsaturated zone, 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.

It has recently become apparent that flow in alluvium may have a significant effect on groundwater evolution in the YM region. Furthermore, it is possible that flow in alluvium may have a favorable influence on the potential for RN retardation. For example, alluvium more closely represents a porous medium than fractured tuffs do, and probably has much higher effective porosities. 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. Therefore, there is a paucity of data on the hydraulic and mineralogic properties that are 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.

4.1.2.3 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.

4.1.2.3.1 Volcanic Disruption of Waste Packages

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

If magma (i.e., molten rock) from volcanic events penetrates the repository, it will likely have the ability to incorporate SF particulates from canisters breached in the event. The SF particulates may range in size from micrometers (Ayer *et al.*, 1988) to approximately 1 cm (the size of fuel pellets prior to irradiation) (Knief, 1992). Assuming the magma has incorporated SF particles, and hence RNs contained within the SF, the tephra (i.e., ash) formed from the fragmented magma will also contain RNs. As will be discussed in Section 4.1.2.3.2, the contaminated tephra particles can be transported to receptor locations via atmospheric dispersion, thus exposing receptor groups to RN contamination. Preliminary calculations conducted by NRC/CNWRA indicate that expected doses in a 10,000-year period from extrusive volcanic events to a receptor individual (LaPlante *et al.*, 1995) at 20 km south from the repository could be as high as several to perhaps several tens of mrem/yr, indicating that volcanism should be included in PAs of the proposed repository. Therefore, NRC has included volcanism as a disruptive scenario in its TPA code to estimated 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

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[15] DOE/NRC Technical Exchange on Performance Assessment, July 21-22, 1997, CNWRA, San Antonio, TX.

calculations to demonstrate the effect of direct release and transport on the total system performance.

Criterion T1: Sufficient data (field data or natural analog data, or both) are available to adequately define relevant parameters and conceptual models necessary for abstracting the volcanic disruption of WPs 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 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 the 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 hence 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. Staff should verify that DOE appropriately distinguishes between the probabilities of intrusive and extrusive volcanism and associates these probabilities with corresponding consequence results for estimating risk. To the extent feasible, staff should use the TPA code to selectively probe DOE's approach in probability of volcanism for potential inconsistency in the analysis and nondefensible predictions.

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 entrainment of waste in ash are presented.

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. 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

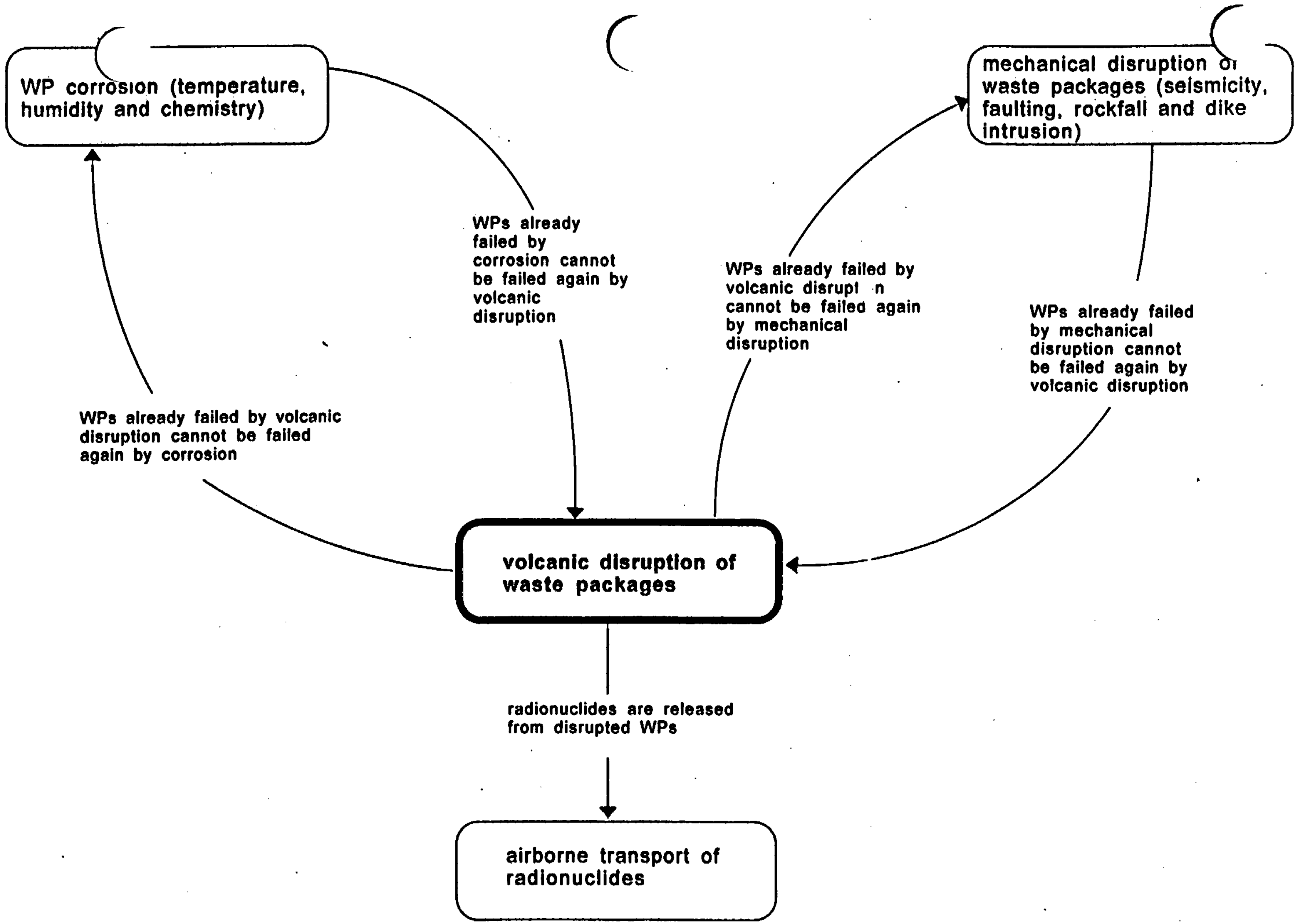

Figure 11. **A diagram illustrating the relationships between "volcanic disruption of waste packages" and other key elements of subsystem abstractions.**

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 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.

As will be discussed in Section 4.1.2.3.2, extrusive events that penetrate the repository will likely result in transporting some amount of tephra to receptor locations via the airborne pathway. Tracking the radioactive material contained within these tephra particles is a necessary step in estimating radiation doses incurred by individuals at the receptor locations. Also, the tephra particles at the receptor likely will not be uniformly contaminated, and estimating the level of contamination of the particles as a function of their size also will be important in performance assessments of the proposed repository. 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.[16] However, it is uncertain how these future TSPAs will model entrainment of waste in ash. Current NRC/CNWRA assessments address this issue by using a particle-scavenging model in which the fuel particles are incorporated into the ash particles as they are being formed (Jarzemba and LaPlante, 1996; Manteufel *et al.*, 1997).

Volcanoes of the type found in the YM region have the capability to disrupt, entrain, and eject subsurface wall-rock during an eruption (e.g., Valentine and Groves, 1996; Hill, 1996). The amount of subsurface rock disrupted can range from <0.01 percent (e.g., Valentine and Groves, 1996) to about 1 percent (Crowe *et al.*, 1986; Hill, 1996) of the total eruption volume. Using stratigraphic constraints, Hill (1996) concluded the subsurface conduit for an analog volcano in Russia widened from several meters to about 50 m in diameter during the later stages of a 1975 eruption. Field evidence indicates similar degrees of late-stage conduit widening likely occurred at some YM region volcanoes (Hill, 1996). The ability of YM region volcanoes to disrupt, entrain, and eject subsurface wall-rock during past eruptions is used as an analog process to estimate the ability of future volcanic eruptions that penetrate the repository to entrain HLW into tephra and transport this material to the accessible environment.

In a previous study that modeled this process (Jarzemba and LaPlante, 1996), the incorporation of spent-fuel particles into tephra particles was modeled as a particle-scavenging process in which the tephra particles were required to be at least a predetermined factor larger than the incorporated spent-fuel particles. Tephra particles have a density of about 1,400 kg m^{-3}, whereas spent-fuel particles are roughly 10,000 kg m^{-3}. Empirically, all but the smallest tephra

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[16] NRC-DOE Technical Exchange on performance assessment, July 21-22, 1997, CNWRA, San Antonio, TX.

particles containing more than about 10 volume percent spent fuel will be too dense to transport great distances (i.e., 20–30 km) from the event. An incorporation ratio can be used to simulate this process, such that tephra particles must be 2 to 10 times as large as the diameter of the spent-fuel particle to transport the fuel particle. Volcanic tephra have a limited range of grain sizes and thus a limited ability to transport relatively large (i.e., ≥1 mm) spent-fuel particles. It is envisioned that, regardless of the mathematical model used to analyze the extrusive volcanic eruption scenario in performance assessments, the entrainment of waste in magma, and hence tephra, will be an important process for estimating the amount of RNs that is available to be transported to the various receptor locations.

4.1.2.3.2 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 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). These estimated consequences can be combined with probability assessments to determine the overall risks to receptor individuals from basaltic volcanism. Previous studies suggested that risks from this exposure scenario may not be negligible (Jarzemba and LaPlante, 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.[17] It is uncertain how these assessments will model airborne transport of ash. Specifically, this KESA relates to model abstractions for evaluating the consequences of volcanic activity within the repository-controlled area.

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, experimental, 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

[17] DOE/NRC Technical Exchange on Performance Assessment, July 21-22, 1997, CNWRA, San Antonio, TX.

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 DOE's dimensionality 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:

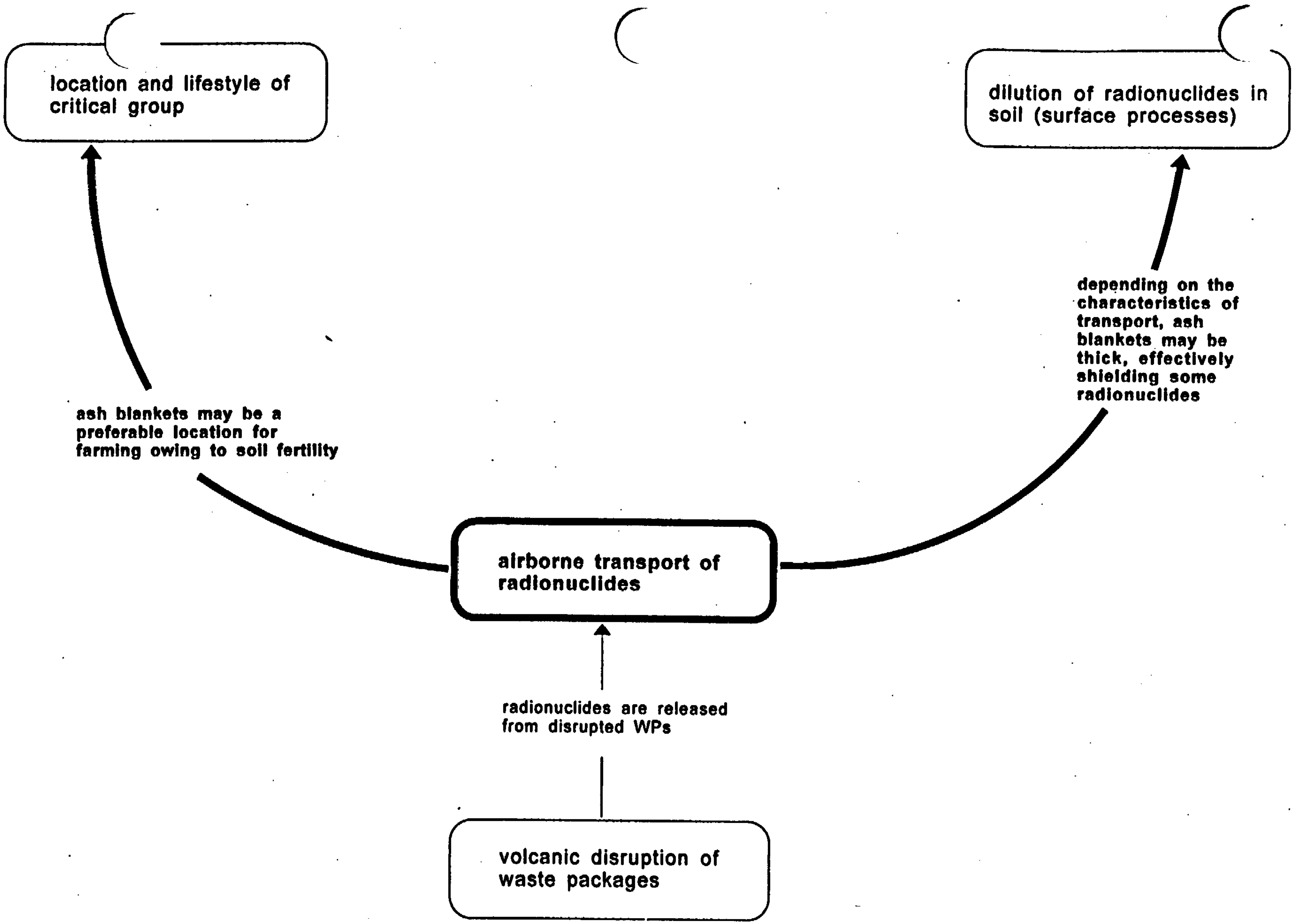
- Depending on the characteristics of transport, ash blankets may be thick, effectively shielding some RNs (dilution of RNs in soil due to surface processes).

- 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). 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



* 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.

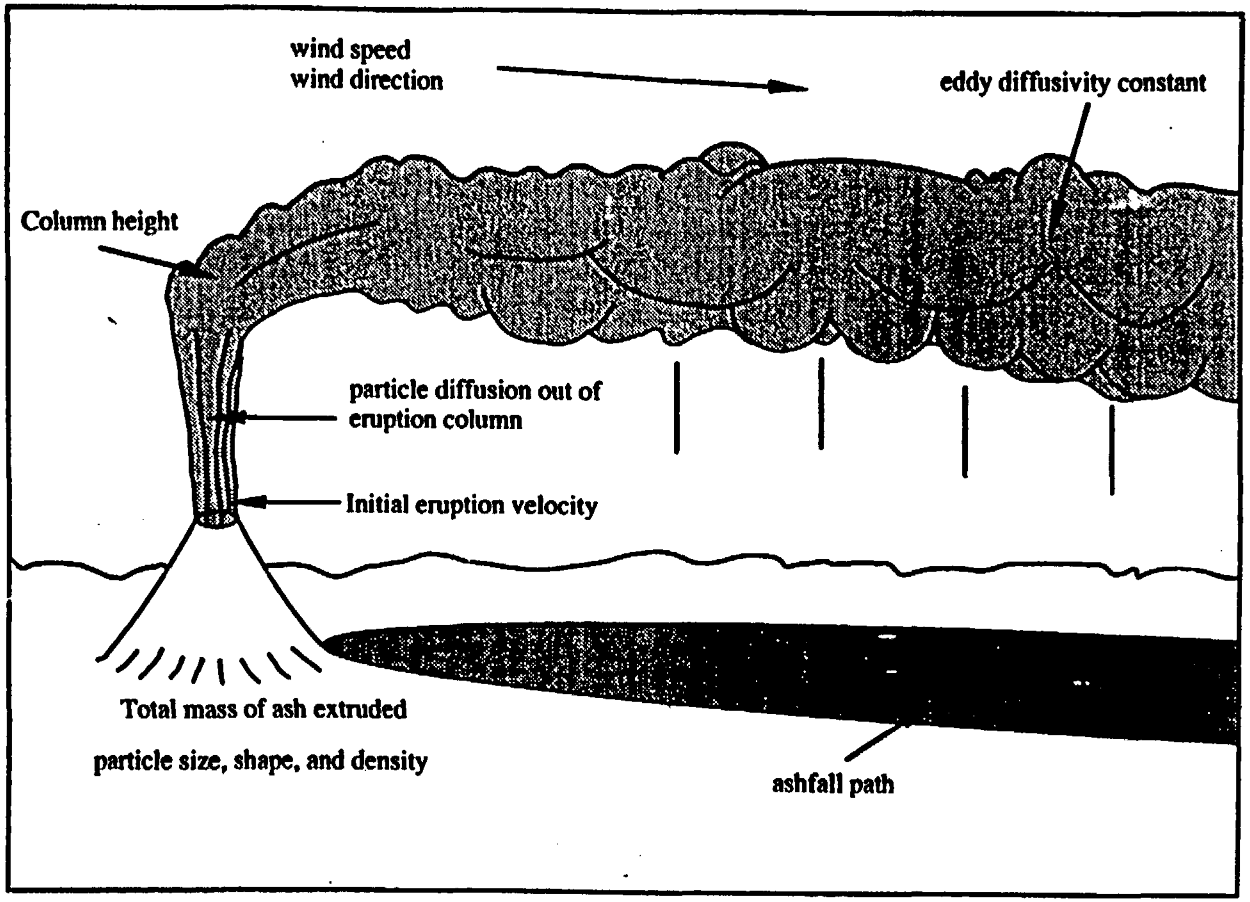


Figure 13. A diagram illustrating the important processes and parameters for estimating airborne transport of tephra.

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; Manteufel *et al.*, 1997).

4.1.3 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.

4.1.3.1 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.

4.1.3.1.1 Dilution of Radionuclides in Groundwater due to Well Pumping

Pertinent KTI subissue: USFIC6, USFIC8

RN dilution factors for pumping are necessary to calculate the dose to exposed populations at the receptor location. The magnitudes of dilution factors are dependent on pumping rate, receptor location, plume geometry, and aquifer characteristics. DOE's TSPA-95 (TRW Environmental Safety Systems, Inc., 1995) did not model dilution due to well pumping. Instead, these authors chose to estimate RN concentrations in well waters by using plume centerline concentrations calculated assuming no perturbation of the flow field due to well interactions. DOE's model abstraction assumed that the well receives only contaminated water from the SZ. In addition, DOE's TSPA took credit for large-scale mixing induced by interbasin groundwater mixing. NRC/CNWRA modeling studies are performed to evaluate a borehole dilution factor appropriate for the Amargosa Desert area (i.e., the ratio of contaminated water to total water received by a representative future well in the region). Specifically, this KESA relates to calculating borehole dilution factors that are used in calculating RN concentrations at the wellhead in PAs of the proposed YM repository.

Acceptance Criteria with Review Methods

DOE's approach in abstracting dilution of radionuclides in groundwater due to well pumping 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, experimental, 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 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 se: .:ivity 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.

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 vertical mixing and plume capture are discussed.

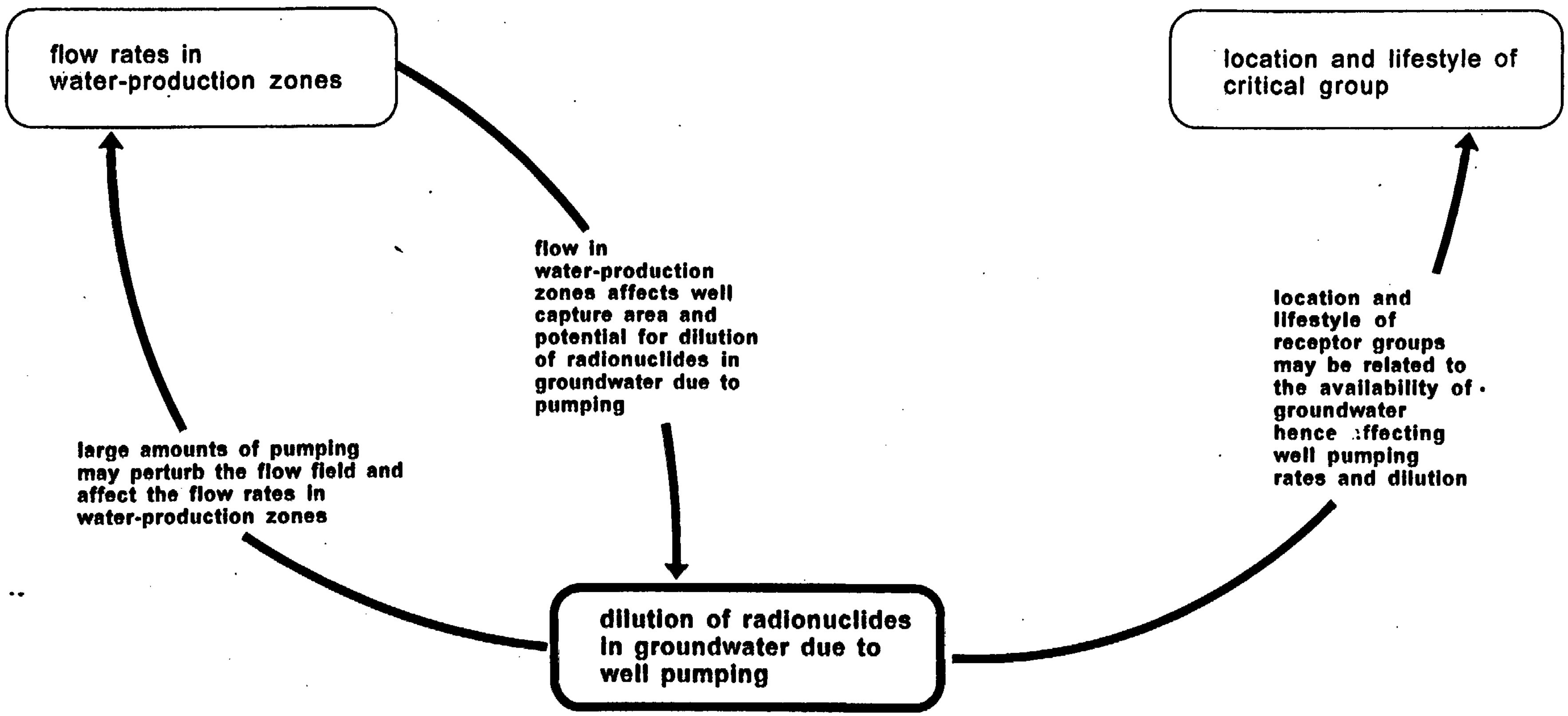
RNs dissolved in SZ groundwater may be intercepted by pumping wells in Amargosa Valley and Jackass Flats. Active pumping of groundwater will create a cone of depression and capture all aqueous phase RNs within its radius of capture. Local groundwater flow in the capture zone will be directed toward the well at a higher velocity than the ambient flow (i.e., flow with the well not present). This increased velocity, and thereby increased volumetric flow, provide an active mixing zone for RNs within the capture zone. The flow into the well casing will be affected by the amount and distribution of pumping, the well diameter, the screen interval, the degree of aquifer penetration by the well, and the radius of influence of the well.

RN dilution due to pumping will be primarily dependent upon placement of the pumping well with respect to the location of the plume. A pumping well with a lateral capture zone completely contained within the boundary of the RN plume will reduce the mean concentration of the plume with vertical mixing. A well that partially captures the plume will reduce the mean concentration of plume in the well casing due to lateral as well as vertical mixing with uncontaminated water. Estimation of the horizontal and vertical extent of the plume at receptor locations will be necessary for capture zone analysis.

4.1.3.1.2 Dilution of Radionuclides in Soil due to Surface Processes

Pertinent KTI subissue: NONE

Plowing of soil or leaching may distribute RN contamination from the surface to deeper soil layers. Accounting for this redistribution of contamination to deeper soil layers will reduce calculated doses (i.e., dose received from direct exposure and inhalation, in PAs of the proposed repository). The most recent DOE's TSPA (TRW Environmental Safety Systems,



* 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.

Inc., 1995) calculated doses to the receptor individual based solely on consumption of 2 L/day drinking water, DOE has not accounted dose resulting from the surface-related exposures. The NRC/CNWRA assessments use the models in the GENII-S code and the ASHRMOVO module (Napier *et al.*, 1988; Leigh et al., 1993; Manteufel *et al.*, 1997) to perform calculations for the surface leaching of RNs out of the biosphere. DOE will also be using GENII-S when performing dose calculations.

As in the case of the groundwater pathway, mixing contaminated ash in soil results in lessening calculated doses. Neglecting the removal of RNs from surface layers to deeper soil layers would be conservative. This approach, however, may be overly conservative for nonsorbing, highly soluble RNs such as ^{99}Tc.

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

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.

<u>Criterion T1</u>: Sufficient data (field, experimental, 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.

<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 provided sound bases for the inclusion or exclusion of certain observed phenomena in its conceptual models.

<u>Criterion T2</u>: 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.

<u>Review Method</u>: 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 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:

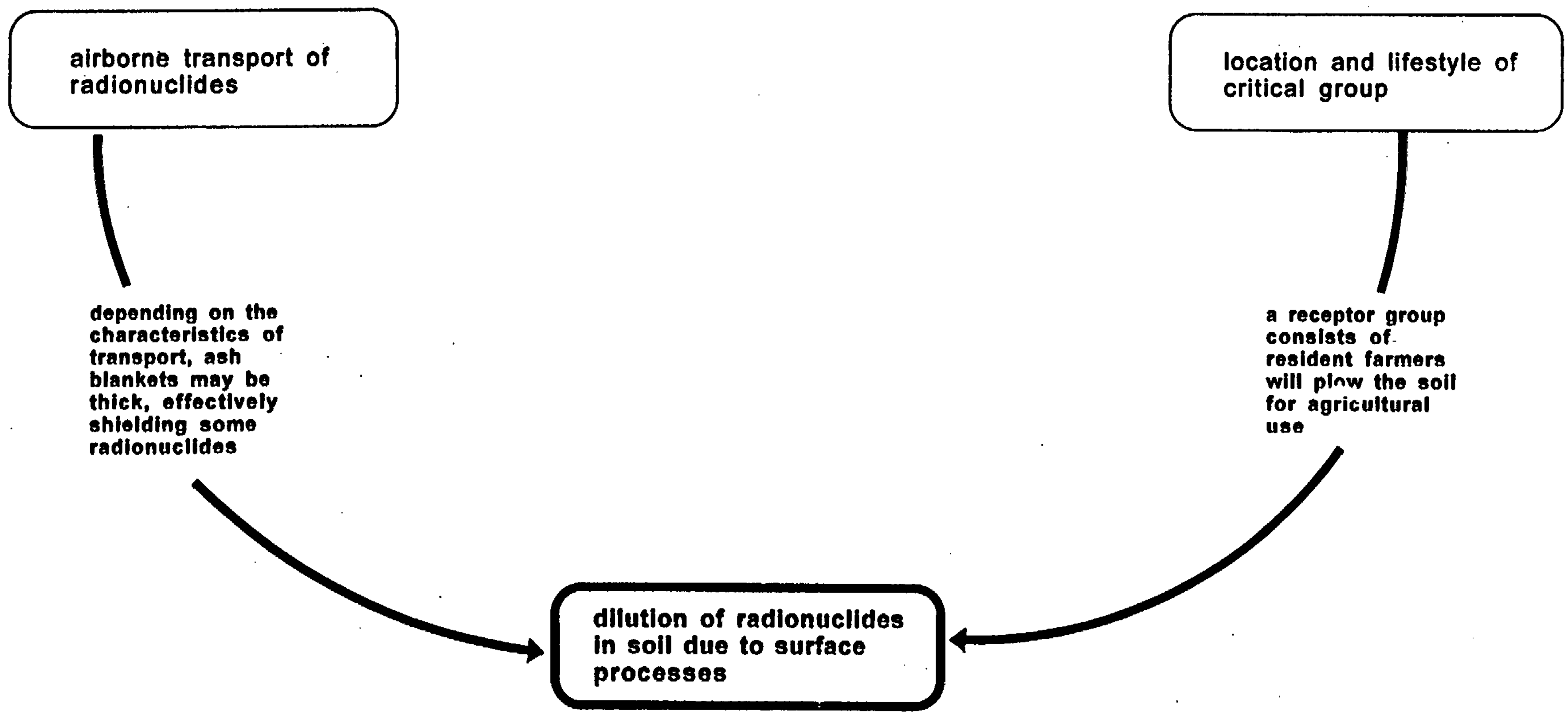
- A receptor group consists of resident farmers will plow the soil for agricultural use (location and lifestyle of critical group).
- Depending on the characteristics of transport, ash blankets may be thick, effectively shielding some radionuclides (airborne transport of radionuclides).

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 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



* 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.

84 percent of the exposure).[18] 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 become infiltrated into deeper soil layers. During the infiltration process, the percolating groundwater may carry some of the surface contamination with it into the deeper soil layers, depending upon such factors as the RN solubility and distribution coefficient. It is noted that these processes may work in conjunction, meaning that RNs would be removed more rapidly due to both processes than either process acting alone.

4.1.3.1.3 Critical Group Location and Lifestyle

Pertinent KTI subissues: USFIC1, USFIC2, USFIC6

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

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

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.

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.

4.2 TOTAL SYSTEM PERFORMANCE ASSESSMENT METHODOLOGY: SCENARIO ANALYSIS

To be developed in revision 1.

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

To be developed in revision 2.

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, NV are promulgated.

Status of Total System Performance Assessment and Integration Open Items

Table1 : Resolution summary for TSPAI KTI Open Items.

Status of TSPAI KTI Open Items	Number
Resolved	13
Open	17

Table 2: 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	
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
OSC0000001347C104	Resolved	Scenario analysis appears to have omitted vitrified high-level waste	
OSC0000001347C107	Resolved	The use of waiting time may preclude accurate representation of clustered phenomena	
OSC0000001347C108	Resolved	Concerns about the use of the expected partial performance measure to screen scenarios	
OSC0000001347C110	Resolved	SCP text is unclear as to how human intrusion will be handled	

Item ID	Status	Title	Comment
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	
OSC0000001347C114	Resolved	Incorrect use of the term -- independent -- in place of -- mutually exclusive	
OSC0000001347Q048	Resolved	Question selection procedures for peer review panel	
OAO017APR1992C003	Resolved	Misplacement of discussion on performance assessments to address 40 CFR 191.13	40 CFR 191.13 No Longer Applicable to Yucca Mountain
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	
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	
OSC0000001347C022	Open	Inadequate saturated zone hydrology sample collection methods	USFIC is also evaluating this open item

Item ID	Status	Title	Comment
OSC0000001347C095	Open	Underlying logic for, and implementation of, scenario development and screening is deficient for generating a CCDF and deficient for guiding site characterization	
OSC0000001347C098	Open	Weighting alternative conceptual models according to judgement they are correct does not provide a conservative estimate of performance	SDS is also evaluating this open item
OSC0000001347C099	Open	Premature limiting of the total system performance consequence analysis may distort performance allocation	
OSC0000001347C101	Open	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	
OSC0000001347C102	Open	Performance assessment flow models are inconsistent with current understanding of site hydrology	
OSC0000001347C103	Open	The ross sequence numbers 59 through 62 and 64 through 69 do not characterize scenarios	
OSC0000001347C105	Open	Site characterization should provide data, analyses, or justification to substantiate elimination of scenarios	
OSC0000001347C115	Open	Statement that CCDF scenario classes can only be expanded if entities are independent is incorrect	
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	

Item ID	Status	Title	Comment
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 3. 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)

	Questions
TE10	How is the flow from the saturated zone being represented and treated in the flow and transport model? (See OSC0000001347C102)
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

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)

<u>CLST1</u> Effects of corrosion on the lifetime of the containers and the release of radionuclides to the near-field environment

<u>CLST2</u> Effects of materials stability and mechanical failure on the lifetime of the containers and the release of radionuclides to the near-field environment

<u>CLST3</u> Contribution of spent fuel resistance to degradation towards controlling radionuclide releases to the near-field environment

<u>CLST4</u> Contribution of HLW glass resistance to degradation towards controlling radionuclide releases to the near-field environment

Evolution of the Near-Field Environment (ENFE)

<u>ENFE1</u> Effects of coupled thermal-hydrologic-chemical processes on seepage and flow

<u>ENFE2</u> Waste package chemical environment

<u>ENFE3</u> Chemical environment for radionuclide release

<u>ENFE4</u> Effects of thermal-hydrologic-chemical processes on radionuclide transport in the near field

Igneous Activity (IA)

<u>IA1</u> Probability of future igneous activity

<u>IA2</u> Consequences of igneous activity within the repository setting

Radionuclide Transport (RT)

<u>RT1</u> Physical and chemical system affecting radionuclide transport

<u>RT2</u> Radionuclide transport through fractured rock

<u>RT3</u> Radionuclide transport through porous rock

RT4 Radionuclide transport through alluvium

Note: IRSR Rev. 0 to be issued in FY98.

Repository Design and Thermal-Mechanical Effects (RDTME)

RDTME1 Design control processes

RDTME2 Seismic design methodology

RDTME3 Thermal-mechanical effects on underground facility design and performance

Structural Deformation and Seismicity (SDS)

SDS1 Fault Slip

SDS2 Seismic Motion

SDS3 Fractures and Site Discontinuities

SDS4 Tectonics and Crustal Conditions

Thermal Effects on Flow (TEF)

TEF1 Sufficiency of thermal-hydrologic testing program to assess thermal reflux

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 Model Abstraction

TSPAI2 Scenario Analysis

TSPAI3 Transparency and Traceability of the Analysis

Unsaturated and Saturated Flow under Isothermal Conditions (USFIC)

USFIC1 Range of future climates

USFIC2 Hydrologic effects of climate change

USFIC3 Amount and spatial distribution of present-day shallow groundwater infiltration

USFIC4 Amount and spatial distribution of present-day groundwater percolation through repository horizon

USFIC5 Amount and spatial distribution of groundwater percolating through repository horizon during period of repository performance

USFIC6 Ambient flow conditions in the saturated zone

USFIC7 Extent of matrix diffusion in unsaturated and saturated zones

USFIC8 Dilution processes and their effectiveness

APPENDIX C:

SUMMARY OF THE CONCEPTUAL APPROACHES IN TPA VERSION 3.1 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. Version 3.1 is the most recent version of the TPA code (Center for Nuclear Waste Regulatory Analyses, 1998).

The TPA code incorporates phenomena within each of the three subsystems -- engineered system, geosphere, and biosphere -- used to focus evaluations of DOE's abstractions (see Figure 1). The components of the subsystems (i.e., engineered barriers, unsaturated zone flow and transport, saturated zone flow and transport, direct release and transport, and dose calculations) are all explicitly included within the TPA code. The key elements of subsystem abstraction (KESAs) are addressed with different levels of complexity. The extent that interdependencies are modeled within the TPA 3.1 code is also variable. Hereafter the TPA 3.1 code is identified as TPA 3.1.

The following discussion of the TPA 3.1 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 TPA3.1 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. 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 the critical 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.

<u>Overview</u>

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 s''barea 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 the critical group. The critical 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 and 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** 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 infiltratior The mean annual infiltration is calculated using estimates of the elevation, soil depth, soil 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. The calculated flux of the repository is normalized to the mean annual infiltration through the repository footprint 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 footprint.

Two models are available to calculate infiltration into the different repository subareas based on spatially variable deep percolation. The first assumes vertical infiltration (i.e., spatially uniform conductivity). The second assumes structural control of the infiltration through fault zones and clustered fractures. Once selected by the user, a single model is used for the entire simulation.

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**, the release of radionuclides 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.

The pH and the chloride concentration of the water contacting the waste packages is estimated using results derived from MULTIFLO (Lichtner and Seth, 1996) calculations. 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. 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 the release of radionuclides from the engineered barrier system.

The waste package can fail in one of four ways: waste package fabrication (initial failure), corrosion, mechanical failure or through disruptive events (disruptive failures). Initial failures are considered to occur at the start of the simulation. Disruptive failures can occur at any time during the simulation where packages remain intact. Corrosion failure is considered to occur at the time of that the inner waste package overpack is penetrated by corrosion. 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 and an outer overpack consisting of a corrosion allowance material (carbon steel). This 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 cc .osion 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 barriers. For example, the **mechanical disruption of waste packages** can arise from seismicity, faulting, rockfall or igneous activity. Igneous activity could also result in failure through **waste package corrosion**. The failure of waste packages will allow **[quantity and chemistry of] water to contact the waste form [and waste packages]** and the release of radionuclides; the occurrence of failure will influence the **[quantity and] chemistry of the water contacting [waste packages and] the waste form**. The inventory of those waste packages failed by extrusive igneous activity will be transported to the biosphere (discussed below under radionuclide transport) and water seeping into the repository is water no longer able to contact either the waste package or the waste form. The occurrence of failure by other modes of mechanical failure from disruptive events (i.e., fault displacement, seismicity and intrusive igneous activity) influence the **[quantity and] chemistry of water contacting [waste packages and] waste form** by providing a path for water to enter the waste package.

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 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 conditions. Waste package failure is assumed to occur if the deformation exceeds the initial thickness of the waste package or the stress exceeds the yield stress of the outer overpack within the zone of rock conditions.

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 groundwater is dependent on the quantity and chemistry of water contacting waste packages and waste forms and the radionuclide release rates and solubility limits. Contaminant transport 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 critical 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 release from the waste package is possible. Releases are modeled to occur through diffusion or through advective transport through the remnants of the waste package. For advective releases, the amount of water entering the waste package is apportioned from the water percolating through the repository horizon, according to considerations related to the capillary barrier between the host rock and the mined opening, impingement of dripping water onto the waste package and hydraulic properties of corrosion holes including corrosion products.

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 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. 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 the 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. Concentrations within the water flowing out of the waste package are determined assuming a mixed tank model within the waste package.

Radionuclides are assumed to flow from the waste package into the unsaturated zone below the repository. The flow through this zone is assumed to be vertical along streamtubes, where one streamtube is assigned to each repository subarea. Flow will occur through the matrix and fractures. The extent 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. Fluid exchange between fractures and the matrix 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. The centers of the unsaturated zone streamtubes are used to apportion the contamination entering the saturated zone among the four streamtubes. Matrix diffusion will be considered in the saturated zones as part of the TPA 3.1 sensitivity studies.

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 Critical Group

The exposure of the critical 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 critical 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 critical group**. The approach taken to evaluate the exposure of the critical group in TPA 3.1 is described below.

The critical group may be exposed to contamination transported through the groundwater pathway or released through extrusive igneous activity. Two archetypical groups are assumed as potential critical groups. The first is comprised of individuals that use contaminated groundwater only for drinking and are exposed to surface contamination through inhalation and direct exposure. The second is comprised of individuals 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. For the groundwater pathway, these DCFs are applied to the concentrations at the well head (i.e., after dilution from well pumping). Similarly, the DCFs for soil contamination reflect the dilution of radionuclides from surface processes.