SECOND INTERIM REPORT

TOTAL SYSTEM PERFORMANCE ASSESSMENT PEER REVIEW PANEL

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Peer Review of the Total System Performance Assessment - Viability Assessment

Second Interim Report

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PREFACE

This report is the second in a series from the Performance Assessment Peer Review Panel. The Panel considers each successive report as an integral part of a series. Issues that have been covered previously will not be repeated unless new information or concerns arise.

In preparing this report, the Panel has directed its primary attention to the methods, data, and assumptions that have been developed or identified for the Total System Performance Assessment to be used in the Viability Assessment. The Panel's goals have been to note weaknesses that can be ameliorated through the use of more appropriate models and data, to seek clarification of the bases for certain of the analytical approaches and assumptions that have been used, and to evaluate the sensitivity analyses of alternative models and parameters and their associated uncertainties.

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EXECUTIVE SUMMARY

This second interim report of the Total System Performance Assessment Peer Review Panel (the Panel) reflects the Panel's activities since its first report was issued on June 20, 1997. Since this report was written to extend and expand on the earlier report, comments made at that time are not repeated here, except where the Panel is amplifying, extending, or revising its previous comments. For this reason, this report should be viewed as an extension of the first, not as a revision.

As was the case with the first report, the findings of the Panel are too extensive to be readily summarized in a brief Executive Summary. Nonetheless, two comments included in the Executive Summary of the first report are still relevant. Updated to reflect the content of this report, they are as follows:

- The Total System Performance Assessment (TSPA) supporting the Viability Assessment (VA) has not yet been completed and, thus, the Panel is reviewing a work in progress. The Panel has available to it previous TSPA reports and various technical documents prepared in support of the TSPA. Panel members also attended related project workshops, including several Technical Exchange meetings between the U.S. Department of Energy (DOE) and U.S. Nuclear Regulatory Commission (USNRC) staff. The observations made as a result of these meetings are included in this report.

- The design of the engineering features of the repository has evolved in several respects since the Panel began its review. For example, initially the inner corrosion resistant material for the waste canisters was specified as Alloy 825. During the first phase of our review, this was changed to Alloy 625. Although this is the current material specified in the reference design, an expanded program on waste package materials is underway, and a change in the reference design to the use of a C-22 alloy for the corrosion resistant material appears to be reasonably likely, based on discussions with project staff.

Since the Panel's first report was completed, more data have become available on specific radionuclides, ^{36}Cl in particular, in groundwater at the site. These data and related information have not yet been fully reconciled with the models of water flow in the unsaturated zone. In addition, the transport via groundwater of plutonium-bearing colloids has been identified and measured at the nearby Nevada Test Site. The interpretation of the significance of these measurements by the Project team has not yet been published.

During the past several months, the Panel has been able to review the current status of the Project staff's analyses of several issues not included in our initial report. As an outgrowth of these efforts, we have included in this second report more detailed comments on external events, such as volcanism, seismic events, and human intrusion.

We have also included comments regarding the assessment of the performance of waste glass, a topic not previously addressed.

In our first report, the Panel commented on how the TSPA-VA results could be made more transparent and accessible. In Section II of this report, we have included more extensive comments on the TSPA methodology, and addressed the limitations and uncertainties inherent in such an analysis. The Panel has also provided recommendations for improving the defensability of the TSPA-VA. These include recognizing (1) that the goal of the TSPA is not to predict the performance of the proposed repository, but rather to provide reasonable assurance on which to judge whether the standards and regulations are being met; and (2) that the models being used have significant limitations, including inevitable and inherent uncertainties in the resulting estimates of repository performance. To address these problems, the Panel recommends (1) that experiments be designed and conducted to test the accuracy and applicability of the near- and far-field models; (2) that limitations on the use and applications of expert elicitations be recognized; (3) that the design team recognize that the success of the safety case or “defense-in-depth” strategy depends on the functions and effectiveness of certain key components and/or elements within the system; and (4) that while the absence of an applicable U.S. Environmental Protection Agency standard and associated USNRC regulations does not pose an operational problem, the TSPA team needs to be aware that the performance measure that DOE has adopted includes a number of assumptions that may not prove to be correct.

An overview of this report is included in Section I, which immediately follows. The detailed findings of the Panel are presented in Section IV. Of these findings, two will be cited here. One is a concern on the part of the Panel that the TSPA team is not taking advantage of existing opportunities to test the validity of the models being used. One such opportunity would be to use the existing models to predict the results/data that will be generated through the Drift Scale Tests. Another, and more important concern, is that it may not be possible to analyze the impacts of certain postulated events on the performance of various systems and components within the proposed repository. This concern applies, in particular, to the responses of various systems to potential events, such as volcanism and criticality, and a thermal pulse. This concern includes details such as how a waste package might degrade under impacts of this nature. If the probabilities of the occurrence of volcanic events or the consequences of criticality are so low as to make them unimportant, then the question of analyzability in these two cases may become moot. This, however, may not be the case in terms of how the TSPA team will address the potential impacts of a thermal pulse. This is a difficult and perplexing problem. Careful thought needs to be given to how it is to be addressed.

I. INTRODUCTION

This introductory Section includes a discussion of the nature of the Total System Performance Assessment (TSPA) peer review process and provides a roadmap to the contents of this report.

A. Nature of TSPA Peer Review Process

In the Energy and Water Appropriations Act for fiscal year 1997, Congress specified four components of a viability assessment for a proposed high level radioactive waste repository at Yucca Mountain, Nevada. One of these was to complete:

> ...a total system performance assessment, based upon the design concept and the scientific data and analysis available by September 30, 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards.

The objective of the Total System Performance Assessment Peer Review is to provide a formal, independent evaluation and critique of the Total System Performance Assessment supporting the Viability Assessment (TSPA-VA) for the Civilian Radioactive Waste Management System Management and Operating contractor (CRWMS M&O). The TSPA-VA is being conducted by the CRWMS M&O for the U.S. Department of Energy (DOE) Yucca Mountain Site Characterization Office. The Performance Assessment Peer Review Panel (the Panel) has been asked to conduct a phased review over a two-year period during the development and completion of the TSPA-VA.

This is the second interim report of the Panel; a third report is scheduled to be issued prior to completion of the TSPA-VA. After the TSPA-VA is complete, the Panel will formally review it and prepare a final peer review report. A copy of the Plan for conducting the Performance Assessment Peer Review was presented in Appendix B of our first report (Whipple et al., 1997).

B. Content of Interim Reports

First Report

In its first report, submitted on June 20, 1997, the Panel:

- Provided an overview of the TSPA-VA approach and constraints, including the Panel's understanding of: (1) the use by the project staff of both detailed deterministic models and simplified abstraction models suitable for application in an integrated probabilistic analysis, (2) the repository and how it is intended to isolate wastes, and

(3) the approach taken by the project staff to assess performance in the absence of applicable standards by the U.S. Environmental Protection Agency (EPA) and accompanying regulations by the U.S. Nuclear Regulatory Commission (USNRC).

- Discussed in more detail its understanding of processes and events that would affect the future performance of a repository at Yucca Mountain and how they are being considered in the TSPA.

- Presented a summary of the Panel's major initial findings.

Second Report

Comments made in our first report are not repeated in this second report, except where the Panel is amplifying, extending, or revising its previous comments. For this reason, this second report should be viewed as an extension of the first, not as a revision.

Topics covered in this report fall into two general categories:

- General topics that were not covered in depth in the first report, for example, glass as a waste form and disruptive events other than criticality.

- Specific issues that the Panel has selected because of their potential significance to the results of the TSPA-VA.

This is not to indicate, however, that all significant issues have been covered. In some cases, the Panel was unable to comment because the supporting documentation does not exist. An example is the computational aspects of the TSPA-VA, including how uncertainties are propagated, how the number of runs needed to arrive at targeted confidence intervals was determined, and how the representation of complex models by simplified abstractions has been implemented. Where the Panel report includes comments on issues for which complete documentation is lacking, they are based on presentations by the Project team at various meetings and on conversations Panel members have had with Project staff.

The Panel's review has benefited from the clarity of recent documents issued by the M&O to describe the TSPA-VA. The document "Total System Performance Assessment - Viability Assessment (TSPA-VA) Methods and Assumptions" (CRWMS M&O 1997a) is particularly well written and provides a useful summary of the approaches the TSPA team plans to use. The Panel also continues to benefit from the cooperation and support of members of the CRWMS M&O staff.

In Section I of this report, the Panel provides an overview of the TSPA peer review process and our two initial reports.

In Section II, the Panel discusses its view of the role of the TSPA-VA, the expectations that may reasonably be set for the TSPA-VA, and how results are interpreted and limitations and uncertainties are addressed.

In Section III, the Panel describes in more detail its understanding of how the processes and events that could affect the future performance of a repository at Yucca Mountain are being analyzed in the TSPA. As in the first report, the organization of the discussion follows the major elements examined in the TSPA analysis: (1) initial conditions of the site; (2) conditions as affected by the repository; (3) isolation as provided by the waste form and the engineered barrier system; (4) disruptive events and criticality; (5) transport of radionuclides from the repository; and (6) the biosphere, doses, and health risks. (See Figure I-1)

In Section IV, the Panel presents a summary of the major findings that have been discussed in Sections II and III.

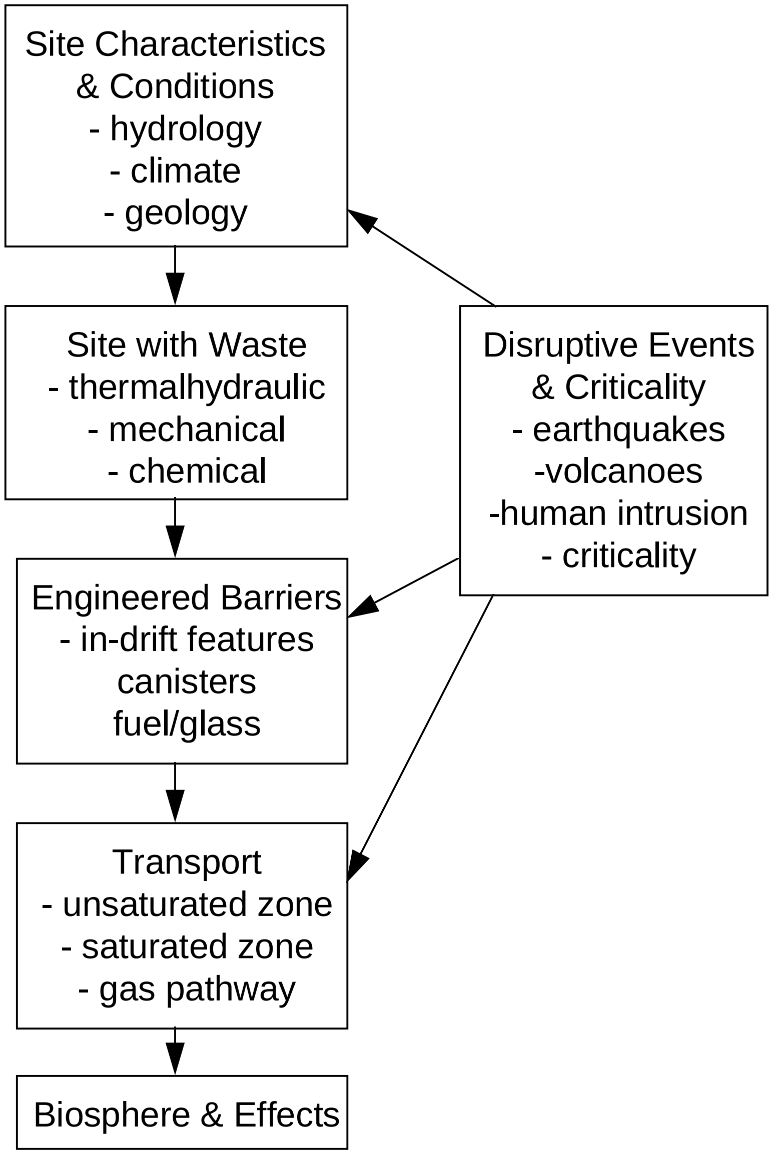

Figure I-1 -- Organization of TSPA-VA Peer Review

II. TSPA Methodology

The TSPA Peer Review Panel's first report included a section entitled "Communicating the Repository Concept and How It Is Intended to Work." In this second report, the Panel expresses its views on the major objectives of the TSPA-VA; describes what it considers to be reasonable expectations for the outcomes of the TSPA; and suggests measures that can be taken to address the limitations of the TSPA process.

A. Objectives

The Panel considers that there are three major objectives for the TSPA-VA:

- To help DOE with its decision about whether to proceed with a license application;
- To identify the major sources of uncertainty and deficiencies in the understanding of how the repository will perform over the extended time periods anticipated to be required by EPA standard, so that the TSPA process can be improved; and
- To provide DOE and its contractors with an integrated tool for evaluating alternative designs and materials.

The first of these three objectives, the use of the TSPA-VA in making a decision to proceed with a license application, is an objective to which the Panel can contribute only indirectly at this time. The results that are currently available are not sufficiently defined for the Panel to focus its review on regulatory compliance. In addition, regulations do not yet exist against which the analyses can be compared. However, the Panel does note in this report those factors, components, and/or systems where the support for particular analyses and assumptions appears to be insufficient.

The second objective is the major focus of the Panel's review. As noted in the Preface, the Panel has directed its primary attention to the methods, data, and assumptions that have been developed or identified for the conduct of the TSPA-VA. The Panel’s goals have been to note weaknesses that can be ameliorated through the use of more appropriate models and data, to seek clarification of the bases for certain of the analytical approaches and assumptions that have been used, and to evaluate the sensitivity analyses of alternative models and parameters and their associated uncertainties.

The third objective for the performance assessment is to assist in establishing a design that is both safe (from the perspective of exceeding regulatory goals) and analyzable. In this regard, the Panel notes that the current TSPA-VA review plan calls for analysis of many options associated with the reference design for the repository. This subject is discussed in more detail under “Design Options” in Section II. D.

B. Reasonable Expectations for the Outcomes of the TSPA

Projections of repository performance over the required extensive periods of time are highly uncertain. There are several factors that inherently limit the outcomes of such estimates.

- The time periods of the TSPA-VA extend to 10,000 or more years, with unknown changes occurring over that time (e.g., climate, locations of people and their sources of food and water). The time period is also long compared to that available for testing the corrosion rates of materials, thus making the extrapolation of materials performance uncertain.

- The site is heterogeneous, and movement of radionuclides occurs as a result both of water flow through fractures and its interactions with the rock matrix. The site cannot be characterized at a scale fine enough to define precisely the flow paths or material interactions.

- The system is complex and coupled. The interactions between heat, moisture, and the chemical environment, and the responses of the proposed repository to the associated mechanical stresses, are complicated and cannot be modeled with precision. Material performance will depend on the thermal, chemical, and hydrological environment as they evolve over time, yet material performance can also alter these conditions, e.g., corrosion byproducts from steel may affect temperature, water flow, colloid formation, and water chemistry.

Predictive Versus Descriptive Analysis

When the standard for the geologic disposal of radioactive wastes was being developed, EPA recognized the uncertainties associated with performance assessments over long time scales. For this reason, in its standard for spent nuclear fuel and high-level and transuranic radioactive wastes (which now applies to the Waste Isolation Pilot Plant (WIPP), but not to the proposed repository at Yucca Mountain), the EPA included in 40 CFR Part 191.13(a) the following statement regarding the degree of confidence that one must have that the containment requirements are met:

> Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13(a) will be achieved. (U.S. EPA, 1985)

In contrast, the Executive Summary of the “Methods and Assumptions” document (CRWMS M&O 1997a) includes a statement that the TSPA-VA will result in a description of “the probable behavior of the repository in the Yucca Mountain geologic setting . . .” and that the TSPA-VA team plans to “Conduct total system analyses that will predict performance.” The Panel believes not only that such claims are unnecessary but also that they cannot be fulfilled. Even though the EPA standard no longer applies to the proposed repository, the Panel believes that the call for “reasonable expectation” that the containment requirements be met can serve as an indication that “... unequivocal numerical proof of compliance is neither necessary nor likely to be obtained.” The Panel recommends that the TSPA-VA team recognize these more modest expectations for what the TSPA can be expected to achieve.

Although the TSPA will provide a basis for an analysis of the probable behavior of the repository over an extended period of time, this goal can be achieved only through the identification of the relevant scenarios and the probabilities assigned to contemplated events. This will involve the characterization of the site, the identification of radionuclide release scenarios, the selection and application of relevant conceptual models, and the acquisition of the required input data. Each of these steps will have associated uncertainties. As such, any “prediction” of repository behavior need not be the purpose or necessary goal of the total system performance assessment.

The philosophical basis for such criticisms has been succinctly summarized by Oreskes et al. in a paper entitled, “Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences” (Oreskes et al. 1994). In their conclusion, the authors make a rather simple but compelling point:

> In areas where public policy and public safety are at stake, the burden is on the modeler to demonstrate the degree of correspondence between the model and the material world it seeks to represent and to delineate the limits of that correspondence.

If the TSPA is described by its authors as “predictive," then it will be taken to be a realistic representation, not an abstraction based on highly simplified models. In such a case, there may be insufficient consideration of the degree to which the model does not correspond to reality. Without consideration of any lack of correspondence, the value or utility of the TSPA may not be realized.

Beyond question, the models used in the TSPA will be reviewed critically by geoscientists, many of whom will have had extensive experience in modeling geologic systems, both modern and ancient. This experience will lead to skepticism if the claim is made that the behavior of the hydrogeologic or geochemical system can or will be predicted over long time scales. This skepticism is likely to be heightened by what appears to be the unwarranted application of the expert elicitation process. This skepticism may, in fact, be independent of the actual methods, content, and findings of the TSPA. It will arise simply because of the perception by geoscientists, true in some instances, that the TSPA team is insufficiently aware of the limitations of their tools.

Examples of the perspective described above have been provided in the Forum discussion in *GSA Today* (vol. 6, no. 5, May 1996), entitled, “Modeling Geology -- The Ideal World *vs.* the Real World”. Only two months ago (October, 1997), the Geological Society of America sponsored a special symposium entitled, “Predictive Modeling in the Earth Sciences: Application and Misapplication to Environmental Problems.”

Limitations of the Models

Significant errors in performance assessment may occur due to the selection of the wrong deterministic model for specific phenomena, to an incorrect analytical solution for the model, to an incomplete description of the system to be modeled, or to the fact that an “abstraction “ may not capture the behavior of the system. Additionally, there always remains the possibility of non-linear behavior in complexly coupled systems. These points are readily illustrated by consideration of two important disciplines in the performance assessment of a repository -- hydrology and geochemistry.

Post-audits of hydrologic models used to assess changes in groundwater salinity (Konikow and Person, 1985) and groundwater level changes (Konikow, 1986), over periods as short as ten years, revealed large discrepancies between modeled and measured values. These discrepancies were due to conceptual errors in the model and/or a failure to anticipate stresses on the hydrologic system (Konikow and Patten, 1985).

Geochemical models have been no more successful in describing water-rock interactions. The evolution of groundwater compositions over time is difficult to predict, as are the phase assemblages formed during the alteration and weathering of even common minerals; particularly difficult to model are groundwater trace element compositions and their host phases (McKinley and Alexander, 1992). Further, geochemical models of even simple systems (e.g., O_2 fugacity set by sulfide equilibria) may not have unique solutions (Bethke, 1992); and despite impressive progress in quantitative analysis of the time-space transport of solutes and their reaction with minerals (Lichtner, 1993), the limiting conditions of such calculations make them difficult to apply with confidence (e.g., the models presume that the host rock is homogeneous and infinite). Other geochemical issues aside (see Nordstrom, 1992, for a summary), the compilation of thermodynamic data for the relevant actinide-bearing phases, e.g. uranium (Grenthe et al., 1992), has proven to be an enormous undertaking and many gaps and inconsistencies in the data remain. These inadequacies in the conceptual models or the associated data bases cannot be entirely overcome by the use of elicited expert opinion, because the expert opinion ultimately relies on some knowledge and appreciation of the conceptual models and the relevant data base.

These philosophical and practical limitations are compounded by the fact that the analytical process involves the use and coupling of complex models to assess conditions over extended periods of time. The TSPA team needs not only to ensure transparency and traceability of the analysis, but also to address the issues of analyzability and the extent to which the outcomes of the TSPA are convincing and/or believable. Given the complexity of the system and the models used in its evaluation, transparency and traceability are difficult to achieve. In the absence of a carefully established basis for the submodels used in the TSPA, one may reasonably expect that the results of the projections provided by fully-coupled models will be questioned.

In summary, the challenging features of the present TSPA-VA are that: (1) the already complex models are coupled; (2) the models are being extrapolated into temporal and spatial scales that are well beyond experimental data bases or human experience; and (3) there is very little testing of the component submodels. Compounding the problem, there can be no test of the fully-coupled and extrapolated models used in the TSPA. Thus, the Panel recommends that attention be given to the suggestions that follow.

C. Interpretation of TSPA Results

Once the assessments have been made, interpretation of the TSPA results is difficult, in view of the inconsistent degree of realism versus conservatism that the TSPA contains. In the first interim report, the Panel discussed the importance of viewing sensitivity analyses from multiple perspectives and over differing time periods. At that stage, the Panel noted that an aspect of performance may not seem important when viewed from one perspective, but may be important on the basis of other performance measures or perspectives. For example, in the TSPA published in 1995 (TSPA-95) (CRWMS M&O, 1995), waste package performance was found to be unimportant in terms of peak dose based on a million years performance measure, but important based on a 10,000 year perspective.

A related point is that sensitivity analyses, conducted to identify which aspects of repository performance are most important from the perspective of selected performance measures, may be unable to provide sufficient information for analysts to distinguish those features that are truly important from those that are unimportant. While it may be possible to analyze some components and systems in a realistic manner, the analysis of others may, of necessity because of data limitations, have to be based on bounding and therefore unrealistic assumptions. This can lead to several problems:

- It will be difficult to assess the relative importance of components and systems analyzed under the two approaches;

- As in the case of sensitivity analyses, an unrealistic bounding analysis may, in some cases, indicate incorrectly that a particular feature of the site or design is unimportant to performance, while, in fact, it is important; and

- An analysis that is unrealistically optimistic may mask the actual sensitivities in some aspects of the performance of that system and/or component.

Where the required documentation has not been provided, the Panel is not in a position to support the use of a particular analytical model for that component and/or system. The identification of areas where the basis for model selection and improved documentation is needed will undoubtedly be expanded as a result of the ongoing technical exchanges between the Project team and USNRC staff. One document that does attempt to analysis the contribution to performance of the various components of the repository system is the *Waste Isolation Study* (CRWMS M&O, 1997d). The Panels comments on this report are provided in Appendix B.

As part of the iterative performance assessment cycle, the Project team has undertaken work where it judged that the conservative nature of the analysis should be corrected. The objective is to make the analysis more realistic, both where it will indicate that a particular concern is not as important as initial analyses implied, for example, volcanism, and where the unrealistic analysis failed to provide appropriate credit for some aspect of performance, for example, the TSPA-95 (CRWMS M&O, 1995) assumption that a waste package failed completely with the first pinhole leak.

The point of noting that the TSPA-VA will inevitably be an uneven mixture of bounding analyses and of more realistic assessments is two-fold. The first is to caution against overconfidence in the validity of the results of sensitivity analysis. The results of the TSPA and the associated sensitivity analyses need to be interpreted with judgment, and recognized as being conditional on many assumptions of varying validity.

The second is to comment, as in our first report, on the issue of analyzability. The Panel’s message is that for a repository to be licensable, it must be analyzable. The issue of analyzability which was briefly discussed in Section II, Part A, above, is addressed in more detail in Section III in connection with several issues, notably with analysis of the thermal pulse and in Design Options, below, in connection with analysis of the effect of backfill.

In the Panel’s view, there has been a tendency by the Project team to judge the benefits of selected components of the engineered barrier system (EBS) and waste package with insufficient technical review of whether the assumed contributions can actually be achieved. In the absence of sufficient supporting analysis or documentation, potentially misleading conclusions can be reached about the sensitivity of the performance of the repository due to failures of various EBS components. The treatment of drip shields, galvanic protection and cement linings provide examples. Drip shields are presumed to remain in place for extended periods and, hence, they are able to extend the life of the waste packages by preventing water access to them. Galvanic protection is presumed to extend the life of the waste packages by delaying the onset of localized corrosion of the inner barrier. Cement is presumed to remain in place for extended periods of time during which it will modify the composition of waters entering and leaving the drift. It is recognized that these issues are works-in-progress and further analysis is underway. The Panel will continue to monitor progress on these issues.

D. Addressing Limitations and Uncertainties

The project can be complimented for adopting two strategies to help with the TSPA analysis: (1) the use of time plots for particular realizations (Whipple et al., 1997); and (2) the use of subsystem measures, such as those utilized in the report "Description of Performance Allocation" (CRWMS M&O, 1996d). Both of these approaches can not only make the TSPA more understandable, but can also provide considerable insight into how the repository systems will operate (e.g., some systems, mainly in the near-field, contain or prevent radionuclide release and dispersion, while others, mainly in the far-field, result in dilution of radionuclide concentrations).

Additional steps that can be taken to address the limitations and uncertainties in the TSPA are discussed below.

Model Testing

The Panel recommends that the Project team investigate methods by which subsystem models can be explicitly tested. These might include:

1. Design of experiments to test specific results of the near-field models. As an example, one could ask if the stable phases actually form in laboratory experiments that are predicted by the geochemical codes?

2. Testing far-field models using the larger scale experiments in the Exploratory Studies Facility (ESF). As an example, has the ability of the computer codes to simulate the thermohydrologic response been critically tested? This can be done by making *a priori* predictions of the temperature, flow rate, and the spatial and temporal variation in the saturation in the three thermal tests: the Single Heater Test, the Large Block Test (both of which are currently underway) and the Drift Scale Test (which is scheduled to begin in early December, 1997). It would be particularly useful to: (1) identify the sets of parameters or variables that exert the largest influence on the response, based on modeling; (2) identify the sets of parameters or variables that exert the smallest influence on the response, based on modeling; and (3) define what constitutes an acceptable match between prediction and observation. The Panel notes that this last point, defining an acceptable match between predicted and actual performance, could be established through the use of a data quality objectives (DQO) approach.

3. Blind-testing of geochemical and hydrologic models in different geologic systems or localities. As an example, the European Community Project to study the Oklo natural reactors in Gabon has conducted a blind prediction modeling exercise in which five geochemical codes and 4 geochemical data bases were used to predict actual, measured groundwater compositions (which are not revealed to the modelers at the beginning of the exercise) (Duro and Bruno, personal communication). Of course, the geologic conditions around the Oklo reactors are different from the conditions at

Yucca Mountain, but one expects that the geochemical codes and thermodynamic data bases used to describe the geochemical behavior of trace element migration will generally be applicable in both cases.

4. Determination of whether the methodology used in the TSPA provides results that are consistent with natural systems. Natural systems are useful analogues because of their large scale, extreme complexity, and age. To the extent that the TSPA models provide results that are consistent with observations in natural systems, their use in the TSPA is more convincing. In some cases, the site itself can be used to test models.

Regarding the fourth point above, the Panel was impressed by the thorough analysis of the flow and transport models for Yucca Mountain as developed from ^{36}Cl studies and the effort to integrate these results with other data sets, such as tritium, ^{14}C, ^{137}Cs, plutonium and ^{99}Tc (J. Fabryka-Martin et al., 1997). In particular, we applaud the effort to predict the distribution of fast paths containing bomb-pulse ^{36}Cl in the planned East-West Drift. Successful predictions based on careful analysis can provide substantial confidence in the TSPA analyses.

Use of Expert Elicitation

A number of important expert elicitations have taken place within the project over the past year, and the Panel has had the opportunity to review some of them, including the elicitations on the probabilistic volcanic hazard, on waste-package degradation, on saturated-zone-flow issues, and on near field/altered zone coupled effects. The documentation package for each of these elicitations is extensive; as a consequence, the Panel has reviewed only parts of the extensive reports, even for the areas in which Panel members have an active interest.

Overall, the Panel is impressed with the use of an advanced methodology for these elicitations. The approach being used incorporates extensive interactions among the experts at all stages, and the process stimulates the participants to strive for, but not force, consensus. The Panel also finds merit with the aggregation process and with the way these elicitations have been documented, including the care with which the interpretations of the individual experts, along with the overall "results," were presented.

However, the Panel continues to be concerned about the possibility that expert elicitation could be misused or abused by the Project team. Given the success of some of the recent expert-elicitation exercises, there could be the temptation to use this approach in situations where the benefits are not large, or even where it is wrong.

Specifically, there are only a limited number of circumstances for which using expert elicitation is appropriate. These circumstances usually involve a technical field where there is considerable scientific work already in existence (either some useful scientific data, some attempts to develop models of the relevant phenomena, or both). Often the issue is that the data or models may have unclear relevance to the problem at hand, and the cognizant experts in the particular field do not have a strong consensus about what the data mean or which modeling approach is correct.

While sometimes the lack of consensus has degenerated into a "dispute," often the situation is that there has not been any need within the community of experts to systematically evaluate the available evidence. The value of a properly executed expert elicitation under these circumstances is that it provides the Project team with the full, and fully documented, range of interpretations of the data or models currently considered valid or respectable. Such a process can also, if properly applied, direct the thinking of the experts toward the specific question(s) facing the project, including where the data or model(s) need to be applied and how. Through the process of being forced to interact on the subject(s) at hand, the experts can often resolve the conflicting interpretations and provide a more unified view than the Project team could reach on its own.

When there is no consensus among experts as to the validity or meaning of the data sets or models, the more typical approach is for a project team, such as that performing the TSPA for the proposed Yucca Mountain repository, to review all of the literature, to interact with all of the key experts individually (by correspondence, telephone, meetings), and then to resolve the situation themselves. This is the normal way of deciphering what's what. The value of expert elicitation is that, in some situations, the elicitation process, involving interactions among the experts themselves, can accomplish a much better job of resolving the lack-of-consensus situation than could be accomplished in any other way.

Thus, the Panel suggests that, when the circumstances are appropriate, there is significant value to be gained by a structured expert-elicitation process. It can provide the best up-to-date thinking of the experts, and that thinking can be directed toward the specific problem(s) that the TSPA team is facing.

The most important results from this process are the identification of the factual basis which the experts deem to be relevant to the issue and the definition it provides of the conclusions that can justifiably be reached on the basis of existing evidence. What an elicitation process cannot accomplish is equally important: (1) it cannot develop "data" or a substitute for data where none exist; (2) while it can enable the existing data to be evaluated, it often cannot permit them to be successfully "assembled" into a useful data set; and (3) if the issue is to select from competing models to explain the relevant phenomena, rather than to understand differences among data sets of varying relevance, the interactions among the experts may not be able to resolve which among the several models is "best."

What a well-executed expert elicitation can do, even if other goals are not met, is to provide the best up-to-date thinking of the various experts on the subject at hand. That is often of significant value.

The Safety Case

The viability of Yucca Mountain as a nuclear waste repository finally must rest on the evaluation of safety (expressed as some measure of radiation exposure to individuals or a critical population). The outcome of the TSPA provides the means for this evaluation; however, the inevitable complexity of the TSPA may obscure or even confound the safety analysis. As the Panel presently understands the fundamental safety case for the proposed repository at Yucca Mountain, it is one of "defense-in-depth", that is, a series of barriers operating to different levels of effectiveness and over different time scales, intended to limit the concentrations of released radionuclides and subsequent radiation exposures to below a prescribed regulatory limit.

The "defense-in-depth" strategy, however, is unproductive when the "depth" consists of a large number of barriers of questionable value. At present, the repository design features the TSPA team is analyzing include a number of barriers whose effect may be substantial, but for which the effect is speculative and the uncertainty is large. The Panel has observed that the contribution to performance such barriers are expected to make fluctuates as the Project team struggles with fundamental design issues (e.g., canister material, galvanic protection, drip shields, fuel cladding as a barrier, length of the dry period, etc.). Minor contributions from each of these additional barriers can lead to a positive result for compliance with a regulation. However, such an approach adds complexity to the analysis, and this complexity may obscure a clear statement of the fundamental basis of the safety case. The issue is whether these additional elements of the repository system design are necessary to the case for safety, or whether they represent minor, but useful, redundancies in the system design.

Given the complexity of the TSPA, the Panel notes that the analysis indicates that the performance of the repository depends primarily on the functions and efficiencies of the major elements of the system. These are the:

- Durability of waste form;
- Canister lifetime;
- Delays and limitations in the contact of water with the waste; and
- Travel times to repository boundaries of radionuclides, as either dissolved or colloidal species.

These are the inherent four elements of the repository system that control the radionuclide concentrations that reach the accessible boundaries. These system elements can be grouped into two spatial and functional groups:

- Near-field: delay in the release and mobilization of radionuclides; and
- Far-field: transport of radionuclides, with associated delay and dilution.

The passive, undisturbed performance of these barriers provides the most solid basis for arguing that the system is sufficiently understood to provide confidence in assessments of its long term behavior. Such discussions should be presented in parallel with the more complex analysis carried forward within the TSPA-VA to ensure that there is a clear and useful understanding of the behavior of the repository system over time.

Additionally, the TSPA team should consider which type of abstraction (e.g., domain-based, process-based, dimensionality and response surface) is most appropriate for the type of phenomenon being modeled. As an example, the description of waste form degradation and dissolution should be based on the chemistry and physics of the corrosion of a solid in the presence of aqueous solutions. The abstraction should be process-based because, in this case, it is possible to test it by comparison of the calculated results with those derived from short term laboratory experiments, empirical field observations, and known principles of physics and chemistry. In contrast, a response-surface may be appropriate when little can be known about the phenomenon (e.g., the actual distribution of fractures in the unsaturated zone). The TSPA team should be organized to match the particular phenomena being modeled with the relevant, possible or testable abstraction methodology.

In the Panel’s view, the confidence that the public can have in the TSPA results will, to a large degree, depend on how the analyses of the major elements of the repository system are conducted and presented. The four major elements listed above can be presented in a framework that includes the supporting models and their underlying physical and chemical principles, conformance with available laboratory and field data, experiences with similar models in comparable systems, and sensitivity analyses based on alternative plausible models. If this is done effectively, the strategy of "defense-in-depth" will have been applied successfully to the design and analysis of the proposed repository.

Design Options

There are currently a large number of basic design features of the repository system that remain as options or are undetermined. This situation can add significantly to the range of analysis to be covered and may compromise the relevance of the Reference Case for the TSPA-VA.

Some engineering design alternatives can be considered in the TSPA through a comparatively simple change in model parameters. For example, the choice of waste package materials can be evaluated through the use of different corrosion rates that are dependent on temperature and humidity. Other design alternatives, however, cannot be so readily incorporated into the TSPA analysis. Backfill as a component of the Engineered Barrier System is one example. The use or exclusion of backfill is a major design feature that has multiple and coupled effects on the design of other components and the response of the repository. Backfill significantly affects the thermal behavior. Radiation of heat from the packages pertains with no backfill, while conduction pertains with backfill.

Waste package temperature is affected. Water composition**,** distribution of water to the waste package, and radionuclide release to the surroundings can be affected. Rockfall effects also vary over a wide range depending on whether backfill is used.

As the backfill example illustrates, alternative engineering designs can lead to the need to analyze fundamentally different processes (e.g., thermal radiation versus conduction). As was previously discussed (Part C), care is needed to ensure that various options are considered on an equal basis, so that one does not incorrectly conclude that Option A offers better performance than Option B, when in fact the differences in projected performance are mostly due to the use of comparatively optimistic analytical methods and assumptions for Option A in comparison to those for Option B.

Use of Data and Models From Outside the Yucca Mountain Project

Although the Yucca Mountain site and the proposed repository have many features unique to the U.S. program (the mixture of defense and commercial wastes; oxidizing conditions for spent fuel disposal; repository in an unsaturated flow regime, etc.), much could be gained from reviews of, and participation in, the programs of other countries and in interchanges with experts in the scientific disciplines relevant to the issues requiring resolution. The evident decision (partly based on limitations in time and resources) to restrict such interactions may prove costly in the long run in that the Project team will unnecessarily duplicate studies that have already been completed and published. Additionally, the general scientific credibility of the project requires participation and publication in the appropriate scientific forums and journals.

As examples:

1. The data base used to develop the response surfaces to describe spent fuel corrosion is restricted to data developed at U.S. national laboratories. There is an extensive literature on the corrosion of uranium oxides in a variety of chemical and geochemical environments. Even if these data are not used explicitly in the response surface abstraction, they can be used to test the general applicability of the response surface approach.

2. Although we were presented with several white papers on the durability of fuel cladding, the Panel notes that there is an extensive, recent literature on the properties of cladding that was not included. Although the white papers focused on the properties of cladding in the disposal environment (for which little is known), there is a substantial literature on the formation of hydrides and resulting embrittlement as a function of the fuel history (irradiation and thermal). This literature will be available to, and reviewed by, critics of the project; the TSPA should endeavor to incorporate as much as is known or published on this issue into its own analysis.

3. As discussed above in Section B, “Limitations of the Models,” one important issue will be the question of whether, and to what extent, coupled processes can be modeled

satisfactorily. In Europe, the FEBEX Project (a collaboration between Switzerland and Spain at the Grimsel test site) has the purpose of developing and testing ". . . conceptual and numerical models for the thermal, hydrodynamic and geochemical (THG) processes expected to take place at the engineered clay barrier of the HLW repository as a consequence of the induced thermal field and water flow." In a recent presentation (J. Samper et al., Materials Research Society symposium on "Scientific Basis for Nuclear Waste Management," 1997), the authors noted, "The current state-of-art on coupled THG modeling does not allow a fully detailed and reliable numerical prediction of the FEBEX *in situ* experiment mainly due to: (1) the lack of a sound conceptual model for the hydrochemical interactions taking place at the water-clay interface for compacted bentonites and (2) the inability of current THG codes to cope with *the simultaneous flow of water and gas through highly reactive and complex porous media under highly non-isothermal conditions*." [italics added]. Although the present design for the proposed repository at Yucca Mountain does not include backfill, the project must be interested in the simultaneous flow of water and gas through highly reactive and complex porous media under highly non-isothermal conditions.

4. As discussed in Section IV, Biosphere, Doses, and Health Risks, one of the radionuclides for which dose assessments are being made is ^{129}I. In some cases it is estimated to represent one of the major contributors to dose for members of the public who may live near the proposed repository. Although such assessments may be mandatory under terms of the anticipated EPA standard, the TSPA team appears to be pursuing this task with little consideration of how organizations, such as the National Council on Radiation Protection and Measurements (NCRP), view the health impacts of this radionuclide. On the basis of its reviews, the NCRP has concluded that "^{129}I does not pose a meaningful threat of thyroid carcinogenesis in people." In a similar manner, the TSPA team does not appear to have considered the range and magnitude of the uncertainties incorporated into the dose conversion factors that they will be using in developing their "Biosphere Dose Conversion Factors." The National Research Council Committees on the Biological Effects of Ionizing Radiation and on an Assessment of CDC Radiation Studies have been careful to point out that these factors were developed for purposes of radiation protection, not dose assessment. As such, they contain large degrees of conservatism. Also contributing to conservatism is the use of the concept of committed dose in estimating the lifetime doses to members of exposed population groups. According to the NCRP, 50% or more of the doses estimated on the basis of this concept will never occur. These represent additional examples where there appears to be a need for the TSPA team to become more familiar with information and data from other groups who are addressing topics relevant to the performance assessment process.

E. TSPA Performance Measure

The EPA standard for Yucca Mountain is not yet available, nor is it clear what the USNRC will do regarding revisions of its regulations. In place of defined standards and regulations, the DOE has established an interim post-closure performance measure as a placeholder until the actual standards exist. The assumption implicit in the DOE interim performance measure is that the eventual EPA standard will include a limit on the dose rate to an individual of specified habits (i.e., the consumption rates of food and water and whether they are produced locally or imported) at a specified distance from the repository for a specified interval of time. In the interim performance measure provided by DOE, the dose rate limit is 25 millirem (mrem) per year to the average individual in Armagosa Valley, measured 20 km down-gradient from the repository, for 10,000 years after closure.

The absence of an EPA standard does not appear to the Panel to pose an operational problem to the Project or TSPA teams, as long as the above assumptions about the nature of the EPA standard prove to be correct. Based on other EPA standards, e.g., 40 CFR 191, the final standard may also include a groundwater protection provision in addition to an individual dose rate limit. Because the TSPA analysis of dose rates is based on estimates of groundwater concentrations, a groundwater protection requirement would not increase the analytical requirements of the TSPA. Whether such a requirement would increase the stringency of the standard depends on the actual limits imposed and on the methods specified for compliance analysis.

The EPA standards for WIPP (10 CFR 191 and 194) contain requirements on retrievability that may reveal the likely thinking of EPA on this subject for the proposed repository at Yucca Mountain. As the Panel reads the WIPP requirement, it is not necessary that waste emplaced deep underground be retrievable forever, or relatively inexpensively, or relatively easily -- only that retrievability of the waste not be essentially precluded by the emplacement scheme in the "early" period after emplacement. In the Panel’s view, the likely retrievability requirement, if it is included and interpreted as in the past, will allow substantial leeway to the Project team in both design and analysis. For example, various backfill options can be considered.

The fact that the USNRC regulations will be revised poses a more complex analytical issue for the TSPA team. The current USNRC requirements, 10 CFR Part 60, include subsystem performance requirements. Depending on whether or how such subsystem requirements are retained, additional analyses may be required.

F. Enhancing the Utility of the TSPA-VA

There are a number of actions that can be taken to enhance the utility of the TSPA-VA. Those discussed in this section include the recognition of:

- Multiple objectives of the analysis (to inform a decision regarding whether to proceed to licensing, to identify data and analyses to improve future analyses and reduce their uncertainties, and to assist with design choices).

- Reasonable expectations for, and limitations in, what the TSPA-VA can do, given the complex, coupled processes and long time periods of interest.

- The availability of tools to address the analytical limitations, for example, model testing, the appropriate use of expert elicitation, and the proper selection and evaluation of various barriers selected as part of the "defense-in-depth" safety case. This includes taking advantage of any and all opportunities to test and evaluated the models being applied as part of the TSPA process, and recognizing the value of, and limitations on, the use and application of the expert elicitation process.

- Relevant studies and data that have been, and are being, generated by other groups throughout the world that have direct applicability to the TSPA for the proposed Yucca Mountain repository.

III. TECHNICAL ISSUES

A. Initial Conditions

Characterization of Yucca Mountain Site and Chlorine-36 Results

Introduction

The analysis of the environmental effects caused by emplacing radioactive waste in the proposed repository at Yucca Mountain requires an understanding of initial conditions of the site. Because the proposed repository at Yucca Mountain would be located in the unsaturated zone (UZ) in a sequence of volcanic tuffs, a major effort has been expended in investigations of the vadose zone. This has required the development of a suite of computer models to investigate different conditions in the UZ which must be coupled in an appropriate manner to the saturated zone (SZ) and validated, where possible, by comparing model predictions to observations and test results.

UZ Site-Scale Flow Model

The outgrowth of this need for a suite of models is a project at the Lawrence Berkeley National Laboratory (LBNL) to develop a three-dimensional conceptual model of the UZ in cooperation with the United States Geological Survey (USGS). Work on this project was initiated several years ago, and there have been a number of modifications. A detailed description of the status of results as of 1997 is given by Bodvarsson et al. (1997a). The UZ Site-Scale Flow Model is a central component of this project, and Figure III-1 illustrates the relationships between this model and the various process models that are being developed for the unsaturated as well as the saturated zones.

Bodvarsson et al. (1997b) state that the primary objectives of the UZ model development are to: (1) integrate the available data from the UZ into a single comprehensive three-dimensional model; (2) quantify the flow of moisture, heat, and gas through the UZ; (3) evaluate the effects of repository loading on moisture, gas, and heat flow within the mountain; and (4) provide Performance Assessment and Repository Design teams with a defensible and credible model of all relevant UZ processes. According to Bodvarsson et al. (1997b), the UZ model provides estimates for important parameters and processes such as, the spatial and temporal values of percolation flux at the repository horizon; the components of fracture and matrix flow in and below the repository horizon; and the probable flow paths from the repository to the water table.

The modeling studies summarized in the LBNL report (Bodvarsson et al., 1997a) are based on the extensive data available from more than 15 years of investigations at Yucca

Mountain. These data include saturation, *in situ* and core-sample water potentials, saturated conductivities and desaturation curves, core-sample bulk-property measurements, pneumatic monitoring, temperature data, air permeability test results, geochemical analyses, and perched water body testing. The Exploratory Studies Facility (ESF) information includes data on fracture mapping, the movement of key radionuclides present in the environment, hydrochemical processes, fracture coatings, and bulk properties from *in situ* and core sample measurements.

The incorporation of all these data into modeling studies has provided a comprehensive and complex UZ model that Bodvarsson et al. (1997b) state is representative of the important UZ flow processes such as moisture flow, capillary pressure effects, gas flow, convective and conductive heat transfer, evaporation and condensation, moisture and gas flow travel times, and transport of conservative and reactive species in the mountain. The model grid is based upon the best available geologic data, and captures the complex structural features which have been characterized by data obtained through nearly 60 boreholes that penetrate a significant portion of the mountain, in addition to data from the ESF and pavement, trench, and section studies. The model has been calibrated by comparing model predictions to observations of saturations, water potentials, temperatures, and pneumatic pressures in newly drilled boreholes, as well as gas flow changes due to the construction of the ESF. In the opinion of the LBNL investigators, the validation process and extensive data set have helped to develop confidence in the model's ability to simulate ambient conditions as well as perform predictive studies.

Chlorine-36 Studies

The LBNL report (Bodvarsson, 1997a) was published in June 1997. In September 1997, Fabryka-Martin et al. (1997) published a comprehensive report on the chlorine-36 (^{36}Cl) studies that have been conducted at Yucca Mountain. The objective of this work is to acquire geochemical data and information on the movement of radionuclides already present in the environment that are relevant to the development and testing of conceptual flow and transport models of the unsaturated zone. More than 600 samples have been analyzed for ^{36}Cl from deep and shallow boreholes, soil profiles, groundwater, and the ESF. According to Fabryka-Martin et al., these data have been used to establish lower bounds on infiltration rates, estimate groundwater ages, establish bounding values for hydrologic flow parameters governing fracture transport, and develop a conceptual model for the distribution of fast flow paths.

The most extensive set of ^{36}Cl data for Yucca Mountain is from the ESF. The quantities in the northern part of the ESF are highly variable and elevated above present background levels. At several locations, the measured signals are high enough that the authors consider them to be unambiguous indicators of at least a small component of bomb-pulse ^{36}Cl, implying that some fraction of the water at the ESF level arrived there during the past 50 years. In the southern part of the ESF, indications of the presence of ^{36}Cl are less variable and at levels equal to or slightly below present-day background.

Detailed characterization of the structural settings of the ^{36}Cl sample locations and of their relationships to structural features and infiltration rates has generally supported a proposed conceptual model for fast pathways at Yucca Mountain. In order to transmit bomb-pulse ^{36}Cl to the sampled depth within 50 years, the modeling assumptions require: (1) the presence of faults that cut the PTn unit and increase its fracture conductivity; (2) sufficiently high infiltration to initiate and sustain fracture flow through the PTn layer; and (3) less than 3 meters of soil cover. The model was used to predict the distribution of bomb-pulse ^{36}Cl for the study area, including the planned East-West drift. A case-by-case evaluation by Fabryka-Martin et al. (1997) demonstrated that the model successfully predicted the presence of bomb-pulse ^{36}Cl in most cases, but did not adequately account for the apparent lack of bomb-pulse ^{36}Cl in the southern part of the ESF.

Cl concentrations measured in porewater from the PTn in the North Ramp range from 15 to 45 mg/L and, based on their low Br/Cl ratios, have not been influenced by ESF construction water. These low Cl concentrations are consistent with the Flint et al. (1996) infiltration model. Their uniformity suggests that the flux through the PTn matrix is on the order of 5 mm/year at this location. Also, because the lower values approach those measured in perched water at Yucca Mountain, Fabryka-Martin et al. (1997) state that these results support a conceptual model that does not need to invoke fracture flow through the PTn to explain the perched water chemistry.

The ^{36}Cl data are consistent with ^{14}C data and, with the results that solute-transport simulations suggest that groundwater travel times are less than 10,000 years everywhere in the unsaturated zone at Yucca Mountain. Low ^{36}Cl ratios measured for some samples from the southern part of the ESF require further evaluation in order to assess whether these ratios provide evidence for longer groundwater travel times.

Implications of Environmental Tracers Studies on Results from Flow and Transport Models

Fabryka-Martin et al. (1997) state that some discrepancies exist between the ^{36}Cl data, the conceptual model for flow and transport, and the numerical solute transport simulations. They indicate that actions needed to resolve these discrepancies include a re-assessment of PTn hydrologic properties, the incorporation of porewater Cl concentrations into the flow-model calibration process, independent evidence to confirm the infiltration model, corroborating evidence to confirm the bomb-pulse ^{36}Cl results, and an expanded data base of porewater Cl measurements.

To calibrate the UZ model, Bodvarsson et al., (1997a) used data on radionuclides present in the environment including bomb-pulse ^{36}Cl data. They concluded that the bomb-pulse ^{36}Cl found in the repository horizon represents only a small fraction of the water migrating through fractures and is therefore not helpful in estimating average percolation fluxes. However, these data can be used to infer localized “fast path” water flow. They also concluded that some of the bomb-pulse ^{36}Cl may be masked by variations in the total chloride concentration used to calculate the ^{36}Cl/Cl ratios and therefore cannot be relied on to identify all of the fast paths.

Bodvarsson et al (1997a) also used other geochemical data in their model calibration activities including total Cl, Sr, ^{87}Sr/^{86}Sr, and ^{14}C. As pointed out by Fabryka-Martin et al. (1997), these data are limited, but Bodvarsson et al. (1997a) state that they yield important information about fluid flow patterns, evaporative and condensation processes, rock/water interaction, percolation flux, and groundwater ages. They believe that these data are also useful in identifying fast paths and constraining flux estimates.

Conclusions

In preparing their report on the Site-Scale Unsaturated Zone Model, Bodvarsson et al. (1997a) did not have the comprehensive report on the ^{36}Cl studies (Fabryka-Martin et al., 1997) available for their review. However, the implications from the use of the environmental tracers suggest that the discrepancies mentioned above between the ^{36}Cl data and conceptual models need further attention. This is a problem of considerable complexity and one that is beyond the scope of the review assigned to the Panel. Its importance is indicated by the fact that the UZ flow model is a key process model for the Yucca Mountain Project team's strategy as it approaches the license application phase.

Proposed East-West Cross Drift in Repository Block

In March 1997, a comprehensive planning activity was undertaken to perform an Enhanced Characterization of the Repository Block (ECRB) using a new East-West cross drift. The purpose was to determine what data would most strengthen the licensing basis while complying with the limitations and constraints imposed on characterization activities. Two of the basic problems under investigation in demonstrating suitability are: (1) the collection of sufficient data to provide a reliable and defensible description of the geologic system and its behavior under present ambient as well as potential future repository conditions, and (2) the selection of a repository site that can take advantage of the best conditions for construction activities while preserving certain options in case of any unexpected developments.

To carry out the ECRB, an integrated (DOE and M&O) team was utilized to develop a plan for an exploratory drift passing through the repository block. A consolidated list of 50 criteria was developed for a crosswalk analysis. As shown in Figure III-2., several options for the location of the cross drift were considered from which a final location was selected. There were two general perspectives that influenced the cross drift configurations: one from testing and one from design/construction. Site attributes that were of interest in testing included zones of potentially higher infiltration on the western side of the block, including evidence of fast paths. A cross section through the block illustrates that the contemplated repository development would be in the middle nonlithophysal, the lower lithophysal, and the lower nonlithophysal zones of the

Topopah Spring welded tuff layer (TSw). A primary reason for testing is to examine this vertical section with respect to fracture mapping, geomechanical, and hydrologic properties.

Repository exposures to the lower nonlithophysal strata generally start in the southern part of the block. The middle nonlithophysal is seen in the East Main drift (Figure III-2) and the bulk of the repository is in the lower lithophysal. During the mapping in the existing ESF, a zone of unexpected fracturing was encountered at station 43+00. A testing perspective was that predictive modeling could be done and compared to conditions encountered in this area. Also, in the southern part of the block, the Solitario Canyon fault has a reasonable amount of displacement, and the splay on the Solitario Canyon is clearly present. A recommendation for testing was to conduct drifting along the repository alignment within the repository block near station 43+00.

The design perspective was more focused on the northern part of the ECRB, which is the preferred zone for potential expansion. The design team was concerned about an excavation in the repository horizon, because if the cross drift orientation is not coincident with the eventual repository alignment, there is a potential to lose repository area. The current planned repository horizon is about as high in the section as it can go. One argument about the presence of drifting below the repository horizon was that it could constrain the ability to move the repository horizon downward. Accordingly, the design group recommended developing a drift above the repository horizon that could also be used as a performance confirmation drift. The design and testing groups reached the consensus location shown on Figure III-2.

The Panel is impressed by the thoroughness with which the ECRB work was accomplished and applauds this type of activity.

B. Site Conditions With Waste Present

Effects of Thermal Pulse on Analyzability of Repository Behavior

Introduction

In assessing the viability of the proposed repository at Yucca Mountain, it has become clear that the effects produced by the thermal field are a key problem in developing a creditable basis for moving forward with the TSPA. The central issue is to understand and predict, with reasonable accuracy, the impact of the thermal field on both the near field and the far field. The far field consists of the total rock mass extending from the surface of the land downward about 300 m below the surface where the proposed repository is to be constructed. The near field is the rock mass that is in the vicinity of, and includes, the repository's engineered barrier system. This system will be constructed with a massive array of tunnels and drifts in which canisters, with their various waste forms, will be emplaced. Predicting the thermal disturbance created by the emplaced waste on both the near and far fields is a formidable challenge and leads to a basic question: "Under these circumstances, how thoroughly and accurately can the effects of a thermal pulse on the behavior of the repository be analyzed?"

In addressing this question, a comprehensive program of analysis has been underway for some time, and a large number of reports on the results are now available (see below). A number of models that can simulate the physics and chemistry of the governing processes have been developed. In particular, the response of the proposed repository under: (1) the current ambient conditions, and (2) the impact of the thermal perturbation, has been analyzed at length. This has been an effort without precedent, and is complicated by the fact that sufficient empirical evidence on the thermohydrologic, thermochemical, and thermomechanical behavior in systems of this kind is not available. Under these circumstances, it is understandable that there will be uncertainties in the results. Those uncertainties must be explicitly recognized by the TSPA team and evaluated to the degree possible.

Uncertainty in Percolation Rate and Flux

The percolation flux at the level of the proposed repository in the middle of the non-lithophysal portion of the Topopah Spring welded tuff (TSw) is one of the most critical parameters both in interpreting the current site conditions and in assessing its suitability as a potential repository. Presumably, this flux has led to the present distribution of water saturations in the matrix of the TSw, which range from 50% to 70% in the top half, up to 90% to 95% in the bottom half, of this layer. This is where most of the proposed repository will be located (Bodvarsson and Bandurraga, 1996).

In analyzing the problem of predicting the percolation flux in the UZ, Wu et al. (1997) state that there exists a large number of uncertainties, key among which are: (1) sizable ranges for the estimated current, past and future net infiltration rates over the mountain; (2) large variances in the measured and calibrated tuff property sets; (3) spatially varying property distributions within the mountain representing lateral heterogeneities, especially for fracture/matrix parameters in the TSw unit; and (4) lack of confirmation of the mechanisms and a numerical scheme for fracture/matrix interactions in the welded units. Given that *in situ* percolation values in the mountain are difficult to measure directly, these investigators concluded that it will be difficult to calibrate or verify accurate values for these parameters.

A large amount of effort, primarily by workers at the USGS, has been devoted to the problem of infiltration from rainfall. The current conceptual model for infiltration is based on numerous measurements of water content profiles in shallow boreholes. Flint et al. (in preparation) have also developed a numerical model to help in these investigations. Rainfall, which currently averages 150 mm/year, is spatially heterogeneous due to variations in soil cover and topography, and it is also variable with time due to storm events (Hevesi et al., 1994). A significant thickness of alluvium can store infiltration and attenuate an infiltration pulse. Thus, infiltration is high on sideslopes and ridgetops, where outcrops are exposed and flow into the fractured volcanics can take place (Flint and Flint, 1994). Modeling studies in the 1996 UZ Model report (Bodvarsson and Bandurraga, 1996) revealed significant differences in the effects of the thermal field on the hydraulic behavior of the repository system as the input value for the infiltration rate was varied from the previous estimate of 0.1 mm/year to the current estimate of 4.4 mm/yr. The magnitude of this critical factor must be well established, if its effects on repository behavior are to be accurately evaluated.

In predicting the percolation fluxes at the repository, an adequate account of the hydrologic properties of the mountain, in particular the fracture/matrix interaction, is necessary (see also discussion below). To match the recently revised estimates for the infiltration flux (currently at 4 mm/year), Wu et al. (1997) were forced to introduce the concept of a fracture/matrix reduction factor that significantly reduces fracture/matrix interactions in the welded tuff layers. This effectively leads to a smaller lateral diversion of water in the model, and allows for physically acceptable estimates of hydrologic parameters consistent with field measurements.

Based on field data, the higher infiltration zones are located along Yucca Crest from north to south. High percolation fluxes at the repository horizon, however, are predicted to be located several hundreds of meters east of the high net surface infiltration area. If higher interactions between the matrix and fractures are assumed, the lateral diversion is significantly increased with important consequences on the distribution of the percolation flux at the repository horizon. Wu et al. (1997) established an upper limit for the average infiltration rates at Yucca Mountain as being no more than 15 mm/year, based on these studies.

Uncertainty from Treatment of Fracture/Matrix Interactions

As noted above, a major obstacle in model development has been the problem of characterizing and modeling the fracture/matrix interactions. Otherwise, the factors controlling the flow of fluids in these two components, with very different hydraulic parameters, cannot be handled correctly. In many cases, this interaction takes the form of a competition between advection in the fracture network and diffusion (mass, heat, capillarity) in the matrix. In particular, the partition of flow between fracture and matrix is dictated by parameters such as the capillary diffusivity (imbibition), the area of interaction and the maximum amount of trapped saturation of the non-wetting phase (air) in the grid block volume.

In the current coarse grid simulation (for example, using the dual permeability model (DKM), where both the fracture and matrix are modeled as distinct parts of the system), the representation of these interactions is through effective parameters, such as the area between fracture and matrix. As noted above, this is currently expressed through a reduction factor to reflect the limited contact resulting from channelized fracture flow. Reduction factors as low as 10^{-3} have been postulated to match field data. This is a drastic departure from the simulation practice only a year ago, where this concept was not used. Although the concept of a limited contact area correctly reflects the physics at the fracture/matrix interface, this factor is currently being used as a fitting parameter in an *ad hoc* fashion. Additional uncertainty, particularly for two-phase flow processes (imbibition, drainage and heat pipes), is introduced due to the volume averaging over a number of fracture-matrix areas, included in coarse grid blocks. In such cases, the set of hydrologic parameters used will not correspond either to that of individual fractures or matrix blocks.

With or without a reduction factor, the use of the DKM has only been partially successful in capturing the fracture/matrix interaction in thermohydrologic applications. It has not been possible to conduct investigations over long enough periods of time to reveal the complete picture of the impact of the thermal perturbation on the repository under an assumed heating load. Currently, this is done using the equivalent continuum model (ECM) in which it is assumed that thermodynamic equilibrium exists between fracture and matrix. On this basis, an appropriate averaging of coefficients can be used to obtain an effective continuum.

Based on an analysis of the fracture/matrix interaction in Appendix A, one can show that reaching conditions of fracture/matrix equilibrium is controlled by the magnitudes of the diffusivity, fracture spacing and flow rate. For typical conditions in Yucca Mountain, fracture/matrix equilibrium is likely for thermal energy and for the imbibition of a high-permeability matrix, but not necessarily for mass diffusion and the imbibition of a low-permeability tuff. The latter is common to many rocks at Yucca Mountain, and in such cases, the assumption of equilibrium will fail. ECM cannot also account for a fracture/matrix reduction factor; thus, it is inherently unable to match the revised percolation flux (unless a non-zero value for the trapped air saturation is introduced, which is not currently done). Nevertheless, the ECM model has been used extensively in investigations of the thermohydrologic behavior of the repository over very long periods of time.

A more detailed analysis of the fracture/matrix interaction is given in the report "The Fracture Matrix Interaction: Reduction of Uncertainty." This report, prepared by Y.C. Yortsos, who is a consultant to the Panel, is given in Appendix A. As noted, he raises a number of questions about the manner in which this subject is being analyzed. The Panel shares these concerns and makes the following recommendations to improve the state of the art in this subject area:

1. <u>Revisit the concept of reduction factor.</u> Use the experiments reported in Glass et al. (1997) and earlier publications, which give a wealth of information on the displacement patterns at various conditions, to estimate reliably the effective area (and the corresponding reduction factor). Then, account for a possible increase of this factor due to the stabilization of the displacement exerted by imbibition in the matrix. Modify the fracture hydrological parameters, particularly the relative permeabilities, to account for the fingered displacement, where appropriate, by considering rate and

gravity effects. Allow for anisotropy in permeability, displacement and reduction factor in the fracture continuum in the horizontal and vertical directions. In this context, reassess the effect of mineral precipitation at areas of geochemical interaction that are expected to occur in the near field (see related comments below).

2. Allow for the possibility of non-zero trapped (residual) air saturation. Account for non-zero trapped saturation in the various lithological units, by considering the direction and rate of invasion (imbibition). Consider the effect of large-scale trapping, due to large-scale heterogeneity in the grid block, in increasing the effective residual gas saturation. Non-zero values may lead to lower, and thus more defensible, reduction factors,

3. Improve the estimation procedure for matching field hydrologic data. Analyze the limitations of the one-dimensional model (only vertical flow) currently used to match field data and estimate parameters. Allow for the possibility of lateral flow, due to capillary and flow barriers, anisotropy, etc. Study the consequences of non-uniqueness inherent to the inversion process.

4. Improve the large-scale description of two-phase flow processes. Revisit the formalism for representing unsaturated now in a grid block, by accounting for effective large-scale permeabilities, relative permeabilities, capillary pressures, large-scale trapped saturations and the fracture-matrix interaction. In this context, particular attention needs to be given to the heat pipe description. Consider the extension of the particle-tracking algorithm to three-dimensional and other diffusive processes.

5. Justify the use of ECM for Thermal predictions. Carefully delineate the validity of capillary equilibrium in ECM applications. Revisit the ECM formalism and validity in light of 1 and 2 above, and also revisit the heat pipe representation (see below).

Uncertainties in Coupled Processes Driven by Thermal Disturbance

The thermal disturbance is expected to affect the hydrology, chemistry and mechanical response of the mountain, particularly in the near field. Thermohydrological coupling occurs mostly in the form of heat pipes; thermochemical coupling is manifested in the chemical alteration of the near field; and thermomechanical coupling produces rock displacements with the notable possibility of altering hydraulic properties, such as fracture permeabilities. Considerable uncertainties currently exist in the understanding and modeling of all these processes. In recognizing the need for the reduction of these uncertainties, a series of *in situ* thermal tests has been proposed.

The first underground thermal test conducted in the ESF is the single-heater test. The preliminary findings have some interesting implications with regard to the anticipated thermal response of the rock system in which the proposed repository may be constructed. A description of the test design, plans and layout area has been prepared (CRWMS M&O, 1996). The heating period for the Single Heater Test started August 26, 1996 using an electrical heater with an active length of 5 m and power input of ~3800 w. Rock temperatures in the near vicinity of the heater exceeded 100° C after about 20 days and were at about 160° C at the end of the 9-month heating period. During this experiment water collected in one instrument hole, and about 17 liters were saved for analysis.

Thermohydrological results

A preliminary analysis of the Single Heater Test results from the thermohydrological standpoint has been reported by Tsang (1997). Before proceeding with her findings, it should be recalled that as temperatures in the repository reach the boiling point, a heat pipe mechanism will set in (shown schematically in Figure III-3). For a fracture/matrix system, the conceptual model is that water vapor (steam) will reside mostly in the fracture, while condensed water reflux will occur mostly in the matrix due to imbibition, although the possibility of liquid counterflow in the form of films along fracture walls can not be discounted. Boiling and condensation processes above the heat source are not necessarily the same as those below (Figure III-3). Above the heat source, the extent of the heat pipe is larger as gravity aids in the return flow. Below the heat source, the return of condensate is only by capillary action, because gravity acts to move the liquid away from the source. In either case, the possibility exists that under the influence of gravity, flow in the fractures can lead to a loss of mass away from the source. This is another indication of the critical importance of properly understanding the nature of the fracture/matrix interaction. It is also evidence that the loss of mass can lead to difficulties in developing an appropriate numerical model of the system behavior.

In analyzing the Single Heater Test, Tsang (1997) states that good agreement was found between field data and simulations and suggests that the thermohydrologic processes of the heating phase are well understood. As others have reported for similar experiments, heat conduction is the main mode of heat transfer below the boiling point. However, an appropriate account for the effects of convection (and the fracture/matrix interaction) is necessary to predict the flow rates and locations of fluid mobilized by boiling (as evidenced by the water collected in one instrument hole). There was disagreement between model predictions and the measured temperature field (almost 30º C at places). Tsang attributes this to spatial heterogeneities which apparently were not detected in the pretest characterization work. She also indicated a problem of uncertainty in the hydrological properties being used, particularly the matrix and fracture characteristic curves. The Panel expects that the effect of this uncertainty will be amplified at later times in the test, now that cooling is taking place and re-wetting will occur. In analyzing the moisture redistribution, Tsang used both ECM and DKM models and reports that a better agreement was obtained using the DKM model for the asymmetry of the condensation zone surrounding the heater horizon. However, she did not make use of the fracture/matrix reduction factor, mentioned as an essential component of the work of Wu et al. (1997).

Being the first thermal experiment at the level of the proposed repository, it was of considerable interest to determine whether it might be possible to see some evidence of the effects of the ambient percolation rate. The thermally induced fluxes are orders of magnitude larger than the ambient flux, thus precluding the detection of the effect of ambient percolation (Tsang, 1997).

Thermochemical results

A preliminary analysis of the Single Heater Test results from the thermochemical standpoint has been reported by Glassley et al. (1997). They have analyzed the water samples above and found pH values ranging from 6.2 to 6.9. These values contrast with pH values of 7.1 to 8.1 for waters collected from matrix, saturated zone, and fracture samples. They attribute these lower pH values to a condensate-fracture-matrix interaction that results from the CO_2 concentration, which is elevated relative to normal atmospheric concentrations.

Glassley et al. (1997) are primarily interested in investigating the hydrothermal processes that drive mineral alteration. Key parameters for defining mineral alteration are: (1) dissolution and precipitation kinetics, (2) thermodynamics of homogeneous and heterogeneous equilibria, (3) flow pathways, and (4) flow rates. As temperatures in the rock walls of the repository drifts exceed the boiling point, the matrix water migrates to nearby fractures where vaporization and heat pipes develop. Figure III-3 illustrates the nature of the fluid movement. Water vaporization will lead to mineral precipitation at the fracture/matrix interface. Away from the heat source, in cooler regions, condensation occurs, and the condensate formation leads to chemical conditions that are not in equilibrium with the surrounding rock. Either of these geochemical interactions contains the possibility of altering the effective fracture aperture. The extent and location of these effects are dependent on the design and operation of the repository.

Glassley et al. (1997) have concentrated on developing an understanding of the nature and magnitudes of these processes. From modeling studies, they find that volume changes are possible as a result of dissolution in the condensation zone, formation of secondary minerals, and the involvement of the fracture and matrix in the chemical evolution. Carbonate, feldspar, and SiO_2 polymorphs can dissolve in the condensation zone, and clays and zeolites can precipitate along the flow paths. However, the extent to which these reactions can lead to significant changes in the porosity and permeability of the rock system is a major uncertainty at this point. Lin et al. (1997) have conducted laboratory investigations that indicate that the permeability of the fractured tuff could be reduced significantly. This may have significant implications on repository performance.

Thermomechanical results

Results from the Single Heater Test from the thermomechanical standpoint have been reported by Costin (1997). Although he has not yet been able to comprehensively analyze a very large data base, his preliminary evaluation of spatial and temporal variations of rock temperatures and rock deformations reveals the complications of analyzing the thermomechanical behavior of fractured rock in the TSw. As others have found (Witherspoon and Cook, 1979), one cannot assume that the system behaves like intact rock. Because of its heterogeneous nature, fractured rock creates a complex medium that cannot be analyzed using the theory of linear thermoelasticity. Much more work on this problem is needed in order to reduce the level of uncertainty in one's ability to predict: (1) thermomechanical behavior of the system, and (2) whether or not the permeability of the TSw rock mass will be adversely affected by changes in fracture apertures. Results from the Single Heater Test will be of great importance in carrying out the investigations planned as part of the Drift Scale Test that was started in December 1997.

As discussed below in connection with the drift scale test Blair et al. (1997) have developed a new method to estimate changes in permeability due to thermomechanical effects. Their results indicate that these effects may cause a significant enhancement in permeability.

Implications for Analyzability of Repository Behavior

This discussion has not touched on problems concerned with the engineered barrier. Nevertheless, it is the Panel's view that uncertainties in the thermal behavior of the repository, revealed by the difficulties discussed above, could lead to questions on alternative designs for the repository. For example, if the thermal pulse were eliminated, as would be the case if the waste were cooled for an appropriate period of time, the effects of waste heat could be reduced or eliminated. Presumably, the uncertainties in the projections of repository behavior would also be reduced. It is well known that the concept of cooling spent fuel through surface storage has been adopted in Europe. The Panel suggests that it would be prudent for DOE to be prepared for questions concerning the analyzability of the thermal behavior of the repository as presently designed.

Drift Scale Test

Introduction

The Drift Scale Test is an important experiment that will provide the first large scale underground investigation on the critical problem of the behavior of the TSw under the impact of the thermal field. The Draft Scale Test will simulate the thermal conditions that will be created by heat released from the waste and investigate the range and magnitude of the different effects in the fractured rock mass.

The Drift Scale Test was first described as an "Emplacement Drift Thermal Test" and is one part of an *in situ* thermal testing program (DOE, 1995) for Yucca Mountain. The Drift Scale Test is located at Station CS 28+27 just off the ESF main drift, at the elevation of the proposed repository in the middle of a non-lithophysal zone in the TSw. The thermal load will be created using electrical heaters placed in a 5 meter drift, 47.5 meters in length and supplemented by wing heaters on both sides along the total length of the drift (CRWMS M&O, 1996).

Objectives

The objectives (DOE, 1995) of this test are to:

- Examine the near-field thermal-hydrologic environment that may impact the waste package (i.e., liquid saturation in rock and backfill, room humidity, propagation of “dry” conditions, liquid drainage in fractures, chemical evolution of liquid flux, and changes in permeability);

- Provide a conceptual model and hypothesis test-bed for which thermal and coupled T-M-H-C models can be used to examine issues of heat transfer, fluid flow, and gas flow that will place realistic bounds on the expected nature of the near-field environment;

- Evaluate the effect of ground support interactions with the heated rock mass, including the effect of materials used for ground support on the near-field water chemistry;

- Measure corrosion rates on typical waste package materials under *in situ* conditions;

- Provide detailed measurements of the response of the rock mass to the construction and heating of an emplacement-drift-scale opening; and

- Provide bounding measurements on the thermal-hydrologic behavior of backfill materials.

Pretest Analyses

Birkholzer and Tsang (1997) have performed an interesting pretest analysis of the thermohydrological conditions for the Drift Scale Test. As part of this exercise, they assumed that the optimum heating schedule will apply almost full heater power in the first year to bring about a fast response in the Drift Scale Test, followed by a three-year period of reduced power output during which the rock temperatures are to be maintained at levels that do not exceed 200° C. It was assumed that the four-year heating period will be followed by a four-year cooling period.

Under these constraints, Birkholzer and Tsang (1997) have used two dimensional models to analyze the temporal evolution and spatial variation of the thermohydrological conditions in the rock mass and to evaluate the impact of different input parameters such as heating rates and schedules, and different percolation fluxes at the test horizon. They have also investigated the problem of the fracture/matrix interaction using ECM and DKM models, but as indicated above, the Panel is not convinced that the fracture/matrix problem is being properly handled in this work.

Another pretest analysis of the Drift Scale Test has been completed by Blair et al. (1997). This relates to the thermomechanical effects in the rock mass. The basic problem is the extent to which the rock permeability will change. Increasing stress across fractures causes a reduction in fracture aperture and a consequent decrease in flow through the fractures (Raven and Gale, 1985). The aperture is generally reduced as compressive stress across the fracture is increased. Thus, as the stress level in the potential repository horizon increases due to thermomechanical effects, the apertures of some fractures may be reduced with a consequent reduction in permeability of the rock mass. However, changes in the stress field may also increase shear stresses on favorably oriented fractures, leading to shear displacements and an increase in permeability (Olsson and Brown, 1994).

Blair et al. (1997) have developed a new method to estimate changes in permeability due to thermomechanical effects, and they present the results of a preliminary analysis of these effects in connection with the Drift Scale Test. Their results show that thermomechanical effects may cause a factor of 2-4 enhancement of the permeability over major regions of the heated rock. This enhancement occurs in the first few months of heating and may accompany the thermal pulse as it travels outward from the heat source.

A critical issue in the methodology linking the thermomechanical analysis to permeability is that permeability enhancement occurs as the result of shear offset due to Mohr-Coulomb slip on pre-existing fracture sets. In this study, Blair et al., (1997) used only two fracture sets in estimating changes in permeability, but the method can easily be adapted to three dimensions. This concept can be tested by comparing displacement measurements made during the Drift Scale Test with those predicted by their model. Unfortunately, the geometry of the wing heaters used in the Drift Scale Test introduces thermomechanical effects that may be much different from those that will be developed in the proposed repository where the heat sources will be located only in parallel drifts.

Conclusion

The Panel believes that the Drift Scale Test will constitute a major step forward in the process of understanding the complex behavior of the proposed repository under the impact of the thermal field. Despite the surprises that are bound to occur, a wealth of data and information will be gathered. An analysis of the results will provide a basis for determining the applicability of our present understanding of the controlling features of the thermal perturbation, as well as much needed data for model calibration. The Panel recommends that an open schedule be adopted for the length of time that the Drift Scale Test will be kept in operation. Underground testing in fractured tuff on this scale has never been done before, and a reduction of uncertainties is anticipated that will be important as DOE approaches the license application phase.

C. Engineered Barriers and Waste Package Performance

Introduction

An effective Engineered Barrier System (EBS) and a robust Waste Package (WP) are essential to the overall performance of the repository. The goal is to design the EBS and the WP for:

- A long isolation period to permit essentially complete decay of many of the radionuclides in the waste, and

- Controlled slow release of the remaining radionuclides to the adjacent geologic formation.

There continues to be significant progress by the TSPA team on the analysis of the EBS/WP performance; however, there remain major areas of concern that can have negative impact upon the TSPA-VA.

In this section, the Panel presents comments first on waste package issues and then on engineered barrier system and waste form/radionuclide release issues**.** This is not a comprehensive treatment, but rather it is intended to provide input to the TSPA team while work is in progress.

Waste Package Issues

Effects of water seepage

Depending on the extent of the thermal pulse and the response of the geologic system, seepage is likely to result in water/moisture coming into contact with some of the waste packages at some time. Since the amount and distribution of such contacts will have spatial and temporal variations, it is prudent to design the waste packages with the expectation that they will be contacted by repository waters. To the extent that the packages remain dry, the benefit can be considered defense-in-depth. Although steel barriers will sustain progressive and cumulative damage from each period of wetness, corrosion resistant metal barriers that remain passive will exhibit essentially no attack (0.1 to 1 micron/year) during wet periods.

Crevice corrosion of the corrosion resistant metal (CRM) barrier is the primary degradation mode to be avoided. Alloy C-22 and titanium are resistant to localized corrosion in the nominal repository environment as well as in many environments beyond this range. The determination of a realistic range of environments that can contact the CRM barrier is the critical requirement for understanding the performance of the waste packages.

The determination of water seepage into the drifts is a matter of large uncertainty. The treatment of water seepage onto waste packages in the TSPA-VA is based on the determination of distribution functions for seepage over the population of packages and additional distribution functions of seepage over individual packages. Those members of the TSPA team responsible for developing the seepage functions must deal with spatial and temporal variability. The combined functions are used to turn-on and turn-off the wet corrosion of packages. The more resistant the packages are to damage from water seepage, the less impact the uncertainty of water seepage will have on the analysis of overall repository performance and reliability**.**

Metal selection for inner barrier

The reliability of the TSPA-VA is increased and uncertainty is reduced by the selection of highly corrosion resistant metals for the waste packages**.** As the Project team has progressed in the design of the proposed repository, the use of more corrosion resistant materials, i.e. Alloy 825 to 625 to C-22 and titanium, has been proposed. Alloy C-22 (a high nickel-chromium-molybdenum alloy) and titanium represent two of the most corrosion resistant classes of metals in oxidizing-chloride solutions (the most prevalent wet environment anticipated in the repository). Such a proposal is prudent for several reasons: (1) resistance to localized corrosion is required for long term containment; (2) there is considerable uncertainty in the prediction of the range and chemical composition of the localized waters in contact with the waste package; and (3) water contacting the waste package should be assumed for this portion of the design. For these reasons, the Panel supports these actions.

In the opinion of the Panel, the designation of the alloy for the corrosion resistant inner barrier of the waste package should be considered a “place holder” that represents an alloy of a given class of metals, e.g. highly corrosion resistant, nickel-chromium-molybdenum alloy. Other specific alloy designations with equivalent or better properties can be expected to provide comparable service.

Effects of crevice corrosion

The Panel concurs with the conclusion of the Waste Package Expert Elicitation (“Waste Package Degradation Expert Elicitation Project Final Report, ” August 15, 1997) that crevice corrosion is the most important degradation mode to be considered in the TSPA-VA**.** Such corrosion of the corrosion resistant metal results from the localized breakdown of the protective (passive) film on the metal. Crevice corrosion is more aggressive than pitting, and a material selection based on crevice corrosion resistance is both more realistic and more conservative. Crevices will always occur and cannot be completely avoided anytime there is contact involving metal/metal, metal/EBS material, metal/rock, metal/corrosion product or deposits. The corrosion control approach is to: (1) determine the range of corrosive environments that pertain; and (2) select materials that are resistant to crevice corrosion in those environments.

The nominal environment in the repository, i.e. neutral to mildly alkaline carbonate waters with low levels of chloride, is not aggressive to corrosion resistant metals at temperatures up to the boiling point. The concern is with modifications to the nominal conditions that arise from the thermal pulse in the rock, interaction with EBS materials, corrosion products, and later on with materials within the packages.

Microbial activity in the drifts is another process that can affect the water composition in contact with the metals; however, it is unlikely that microbial activity will extend the corrosive conditions beyond the range already being considered. Furthermore, the highly corrosion resistant metals being considered are not affected by microbially induced corrosion (MIC).

Environments in contact with the waste package

There is a paucity of experimental data to support either the selection of materials for the waste package or to test and validate the models for assessing their performance. Experimental approaches and methods to determine crevice corrosion environments are well established and do not require long test times. The Project and TSPA teams should exploit these opportunities.

Corrosion resistance of metals

Experimental approaches and methods to determine crevice corrosion resistance are well established and do not require long test times. The Panel recommends that tests be run to determine the behavior of C-22, Ti, 625, and 825 in a range of environments not only to cover the expected repository conditions, but also to extend well beyond these conditions. The inclusion of the less corrosion resistant metals and the more corrosive environments will provide a measure of the margin provided for unexpected conditions.

There is clear agreement among corrosion science and engineering specialists as to the effect of environmental conditions on the occurrence of crevice corrosion, and there is agreement on the relative effectiveness of the metal alloys in providing resistance to crevice corrosion. Unfortunately, there is a lack of experimental data from the project on the behavior of the alloys of interest under realistic repository environments. Notional information is available; realistic data are needed.

The current status can be summarized by a notional figure presented in material prepared for the Waste Package Expert Elicitation Panel and presented at the NWTRB Meeting Oct. 23, 1997. This figure (see Figure III-4) below) presents the relative resistance to crevice corrosion for steel, Alloy 625, Alloy C-276, and Alloy C-22. The last three are nickel-chromium-molybdenum alloys with increasing corrosion resistance in the order presented. For purposes of presentation, the notional crevice corrosion resistance is plotted versus the corrosive environment. On the lower horizontal axis, increasing oxidizing power of the environment is shown as more positive electrochemical potential. The upper horizontal axis shows the notional positions of an oxygen containing environment (O_2), an environment with active microbial activity, and a highly oxidizing environment containing ferric ions (Fe^{+3}). The S-curves show the boundary between no corrosion (to the left) and the initiation of crevice corrosion (to the right). The dashed lines are the notional representation of uncertainty for corrosion behavior. Data generated by experiments are required to support materials selection and assessment of realistic performance.

Useful data are available from the published literature. These data demonstrate the high level of crevice corrosion resistance of C-22 and titanium. For example, the critical crevice corrosion temperature for C-22 is given as 102° C in an oxidizing acid with high concentrations of chloride (pH 2, 4.3% NaCl) (Gdowski. 1991). This is a highly aggressive environment far from the nominal conditions of repository waters.

Dual CRM packages vs. Steel/CRM packages

The reference case for TSPA-VA is likely to specify a dual-canister waste package comprised of a steel outer layer (corrosion allowance metal) and a nickel-chromium-molybdenum alloy inner layer (corrosion resistant metal). The attributes of this design have been well defined by the Project team. A steel outer barrier has several desirable features that would be useful, particularly during a long, dry period. When wetted, however, a steel canister will corrode rapidly. Because of the complex interactions of iron corrosion products on the chemical and mechanical processes within the drifts, this will increase the uncertainty regarding the response of the inner barrier. Dual packages comprised of a double layer of corrosion resistant metals, e.g. C-22/titanium or titanium/C-22 have been proposed and are worthy of further consideration and evaluation in the performance assessment

The temperature limit within the waste package

In order to protect the zircaloy fuel cladding from rapid deterioration, the Design team has specified 320° C as the upper temperature limit with in the waste package. Above this temperature, zircaloy is subject to creep rupture. There are likely other sound reasons to maintain this as an upper temperature limit. These include the fact that there is a wide range of heat output from the spent nuclear fuel (SNF) and a variety of placement configurations within waste packages. Is 350° C the upper limit (e.g. 99th percentile) of the waste packages? Is 350° C the hottest area within a waste package, and what is the average temperature over the waste package?

It is also not clear to the Panel how this limit will be treated conceptually. The heat source has major impacts on many processes within the repository. High heat output increases the duration and extent of the dry out period. A beneficial result is that the longer duration of dry conditions will forestall the onset of wet corrosive conditions. Conversely, the elevated magnitude of the thermal pulse will increase the effects of the geological site on overall repository performance and increases the uncertainty regarding the thermal-hydrological response.

Corrosion data and service experience

The durability of the canisters of the waste package and their likely times-to-penetration have been shown to have a significant effect upon the TSPA results. A long-lived canister has an important and positive effect. All of the available information from the literature and service experience regarding the corrosion behavior of the corrosion resistant metals should be gathered to support materials selection for performance assessment.

The Panel recommends that a comprehensive compilation and critical review of the corrosion behavior of the two primary candidates for the corrosion resistant metal (CRM). These efforts should be directed to the two classes of alloys, namely, nickel-chromium-molybdenum alloys and titanium alloys, and not to a specific metal designation. Earlier efforts (e.g., Gdowski, 1991) should be updated and expanded. The scope of the review should include laboratory data and service experience, as well as information on metallurgical stability and the effect of welds (microstructure and composition). These compilations provide guidance and focus to project experimental needs to validate materials selection and performance, but they do not relax the need for project specific data**.**

Corrosion rates relevant to passive metals

The time-to-penetration of canisters of the waste package is an important factor in the TSPA analysis, and it has a major impact on the calculated repository performance. The corrosion rate that is used when the corrosion resistant metal canister is wet is a fundamental parameter in the TSPA. The values determined for the corrosion rates and the level of confidence in these values being realistic will have a critical effect on the evaluation of the TSPA-VA.

Penetration rates as low as 0.1 to 1 micron/year are not unrealistic for corrosion resistant metals in the passive state. Such penetration will be fairly uniform and projected penetration rates of 10,000 to 100,000 years/cm of CRM result. When crevice corrosion is active, the metal penetration rates are high and rapid penetration can be observed (1 to 10 mm/year). Clearly, confidence in the long term performance of the corrosion resistant barrier depends on the selection of metals which, under the anticipated environmental conditions, will provide high resistance to crevice corrosion.

In short, the need is to select materials that will realistically remain passive in the repository for long periods of time. First, it is necessary to document that the corrosion resistant metals have a high resistance to the initiation of crevice corrosion. Furthermore, it is necessary to document that should crevice corrosion initiate there is a high propensity for arrest of the corrosion and a return to the passive state. A structured experimental program and modeling effort to address both issues above are required. In addition to determining the metal/environment behavior regarding crevice corrosion, It will be necessary to develop a rationale for the behavior with respect to chemical and electrochemical processes.

Although the Project team appears to be moving in this direction, the current plans do not fully address these issues. The work in Canada on titanium corrosion for waste storage (as presented to the Waste Package Expert Elicitation Panel) provides a useful guide and approach.

Stress corrosion cracking

No mechanistic models for stress corrosion cracking (SCC) are available for TSPA-VA, and it is not recommended that project resources be allocated for stress corrosion modeling. Rather, an engineering approach is recommended to select metals that are resistant to SCC and to specify design and manufacturing procedures that avoid SCC.

Stress corrosion cracking is a threat to the adequacy of waste package performance. Full penetrations result in short times if SCC occurs . For a given metal, the environmental conditions and magnitude of tensile stresses control SCC. The required approach is to select materials that are resistant to SCC in the anticipated repository environments and to avoid tensile stresses to the extent possible. It is not practical to design for arresting stress corrosion cracks once they have begun, because the crack growth rates are too rapid compared with the long life desired for the waste package. This leads initially to the selection of materials that are highly resistant to crevice corrosion. Once these materials have been identified, consideration needs to be directed to how they will resist conditions that could lead to SCC. The previously cited concerns regarding the uncertainties and lack of experimental data for environments anticipated to be in contact with the waste package also pertain here.

Control of tensile stresses to avoid stress corrosion cracking is a fundamental part of the required design strategy. Tensile stresses cannot be completely avoided; however, the manufacturing, handling, and service conditions can be reviewed and evaluated to select material and maintain conditions so as to minimize stresses. Residual stresses from cold work, differential thermal expansion and welding are the most important. Rock falls can also be a source of residual stresses to the packages after emplacement. From the perspective of undesirable tensile stresses, the proposed shrink-fit operation and welds without subsequent stress relief are of most concern.

Effects of corrosion products

Gaps will exist between the CRM inner barrier and the proposed steel outer waste canister barrier. Once the integrity of the outer barrier has been lost, water can penetrate these gaps along and around the waste packages and this can lead to the growth of corrosion products in these gaps. The corrosion products of steel will occupy more space than the parent metal. As corrosion progresses, the gap will be filled. Further expansion will apply loads to the canisters that can be sufficiently high to deform the metal. Two practical cases of this phenomena are “pack out” damage to bolted steel structures and “denting” in PWR steam generators.

Shrink fit of inner and outer waste package canisters

The shrink fit process involves heating the outer barrier so that it expands, and then lowering it over the inner barrier where it contracts on cooling to give a tight fit between the two canisters. While this is desirable from some perspectives, the potential effects and implications of this process introduce additional uncertainties. First, the residual stresses resulting from the process need to be considered with respect to stress corrosion cracking. Secondly, a thick iron oxide coating will form on the steel surface after it has been heated. This oxide layer will remain in the crevice between the two barriers after the shrink fit assembly is completed. The potential effects of the oxide coating on waste package performance must be considered.

Galvanic protection

As discussed in the report on the Waste Package Expert Elicitation, the extent to which galvanic protection to the corrosion resistant barrier is provided by the steel outer barrier will be limited to the order of millimeters. The beneficial effect is realized from the shift of the electrical potential of the CRM to more active potentials below that which is critical for crevice corrosion. When the corrosion potential of the CRM is more negative than the critical potential for crevice corrosion, no galvanic protection occurs. The need for and extent of the required galvanic protection will depend on the geometry of the galvanic couple, the degree to which the outer barrier has been penetrated, the resulting exposed area of inner barrier, the presence or absence of corrosion products and deposits and the chemical composition of the waters present. The basis for any credit/benefits for this type of protection in the TSPA-VA must be explicitly presented and documented.

Engineered Barrier System and Waste Form/Radionuclide Release Issues

Conceptual drawings of EBS/WP over time

The development of schematic drawings and notional figures of the appearance of the EBS and waste package at various times are extremely helpful in understanding the various design configurations being considered. These are especially useful in conveying the expected results. The Panel encourages further development and refinement of these approaches.

The long dryout period

An extended dryout period resulting from the heat output from the waste packages is a basic feature of the current design. The extent of the dryout period is determined by the heat output from individual packages, the placement of packages along the drift and the spacing between drifts. As previously noted, the thermal pulse will not be uniform due to variations in packages, package placement, unused or unusable areas within the repository, and edge effects around the repository. This will affect the movement of water to and away from the drifts. The Panel recommends that increased effort be made to develop the conceptual description of the response to this large and nonuniform thermal pulse.

Chemistry of waters entering the drifts

The nominal water chemistry in the unperturbed repository is a mildly alkaline (pH 9), dilute (10^{-3} molar) bicarbonate solution with low concentrations of chloride, sulfate and silicates. The gas in the repository is essentially air with modest increases in carbon dioxide. The rock and waters will be heated by the waste packages, and the thermal pulse can extend into the rock for distances up to tens of meters from the drifts, depending upon the density of thermal loading. As the water is heated above boiling, a water vapor plume will extend from the area of the waste emplacement out into the rock. Many of the thermal, hydrological and geochemical processes have been identified. However, as mentioned above, the conceptual description of the thermal pulse effects is poorly developed and more effort needs to be directed to an evaluation of its impacts.

Large volumes of water are mobilized by the thermal pulse. The flow paths and amounts of water transported along various paths are not well defined. This leads to large uncertainties regarding the amounts and distribution of seepage flowing back into the drifts. The spatial and temporal flows are uncertain. From the perspective of reducing the uncertainties in rate of waste package corrosion, the Panel notes that essentially no damage will occur during dry periods for steel or the corrosion resistant metal barriers. Steel corrodes rapidly when wet, and cumulative damage will occur during intermittent wet periods. The corrosion resistant metal should be selected to remain passive when wet, so that extremely low corrosion rates can be obtained.

The water chemistry of heated water has been modeled by Glassley and others, and there are limited experimental data to serve as input to these models. Current models do not correlate well with experimental observations. More experimental data (laboratory and field) are needed to determine the water chemistry under realistic conditions and to refine and validate the water chemistry models. Early results from one of the heater tests indicate that water flowing due to heating were more dilute and less alkaline (pH 6-7) than cooler waters. Carbon dioxide in the gas phase was increased from the unperturbed conditions.

None of these waters (perturbed or unperturbed) is corrosive to the CRM inner barrier. Conditions conducive to corrosion require the presence of either highly acidic, high chloride solutions or highly alkaline solutions. No realistic conditions to generate these corrosive waters have been demonstrated for the proposed repository; however, the realistic range of water compositions in contact with waste package metals is yet to be determined.

Modification of water chemistry by concrete

The pH of solutions in contact with concrete will become alkaline due to reaction of water with concrete structures in the drifts and this process may affect water chemistry in the drifts. As the concrete degrades by carbonation, it loses its ability to release alkaline species. The condition and distribution of concrete during the period when water enters the drift and the water pathways are uncertain. The amount of water that enters the drifts will affect the extent of this affect and the duration over which it operates. Some clarification of this issue is needed.

Modification of water chemistry

The potential for modification of water chemistry, while in and on egress from the waste packages, remains an area of major uncertainty. The current project strategy and activities are unlikely to determine a realistic set of water chemistries for water entering the drifts. The determination of water chemistries once a package has been penetrated is more uncertain**.** Once waters have entered the waste package through penetrations in the corrosion resistant metal barrier, they will encounter a wide range of spent fuel, cladding and internal assembly materials. It is unlikely that any current model will reliably predict realistic water chemistries. Relevant experiments could be done to determine the water chemistries under a range of realistic conditions. Experimental work and models focused on the critical species are required.

Transport from the Engineered Barrier System

The conceptual description of transport from the EBS is poorly developed. The many processes that can occur have been identified by the Project team, but a realistic description has not been presented of the alternative transport modes and how they are distributed over a given waste package, over the population of packages, or over time. A critical factor is the form and amount of water transported into and from perforated packages. Water is the medium of advective and diffusive transport for radionuclides as soluble species and colloids.

There are major uncertainties regarding: (1) the number and distribution of penetrations through the packages; (2) the morphology of penetrations; (3) the presence or absence of corrosion products or deposits in the penetrations; (4) the form and composition of corrosion products/deposits outside of the penetration; and (5) the form and composition of waste form, transformation products and other materials within the package. In addition, the radionuclide forms, amounts and distributions are uncertain. These uncertainties have led to a treatment in the TSPA analysis that is unrealistic and likely to be overly conservative. For example, past TSPA analysts have assumed that all of the waste form is instantly wetted when the first penetration occurs.

Treatment of Spent Fuel Cladding

The long term performance of the cladding on spent fuel can have a significant effects on the exposure and release of radionuclides. Zircaloy has excellent corrosion resistance in a wide range of solutions, and its barrier performance is worthy of analysis. However, there are major uncertainties to be considered in the analysis. These include the condition of the cladding on arrival of the spent fuel at the repository site, the condition of the cladding when barrier performance is required (hundreds and thousands of years after emplacement); and the determination of the corrosive environment in contact with cladding after waste package penetrations. Neither Sweden nor Canada, two other counties that have announced plans to dispose of spent fuel, take credit for cladding in the analysis of their repository performance. The Panel recommends that the basis for any credit and treatment of this credit in the TSPA-VA be explicitly presented and documented.

Treatment of Backfill

It is the Panel’s understanding that the base case for the TSPA-VA will be the “no backfill” case. Nevertheless, the Panel recommends that, because backfills of various types are under active consideration by the project, an analysis of the backfill case be included to the extent possible in the TSPA-VA and that a thorough analysis be prepared for the subsequent TSPA for a possible license application. The objectives of performing such a backfill case analysis should be to:

- Determine if there are any phenomena that are qualitatively different from the “no-backfill” case and that may have been overlooked to date; this would be in contrast to learning that the major differences represent small quantitative differences in various parameters such as temperature, saturation, etc.

- Determine which experimental data, not now available, are necessary to perform the analysis of the “backfill case” properly in the longer time frame (over several years beyond the VA).

An initial "backfill case” analysis undertaken over the next few months might reveal the need for either modifying the drift-scale test that is just being initiated, or undertaking another test series that might take a substantially different direction.

To meet the two above objectives, the "backfill case" analysts need over the next several months to focus on identifying the key controlling features of the system with backfill, rather than launching a full-scale multi-year project that would ultimately complete the backfill-case analysis in more detail. In other words, the Panel believes that the proper approach is to "scope out" the issues at this early stage and to provide a sound technical basis to launch a full-scale analysis of the backfill case.

D. Waste Form Degradation and Radionuclide Release

Introduction

The Panel continues to review the models that will be used in the TSPA-VA to describe waste form corrosion and radionuclide migration. In the first interim report, the Panel offered preliminary comments on models to be used for spent fuel corrosion. In this second report, the behavior of the glass waste form is considered.

Although the Panel has continued to meet with principal investigators and DOE contractors (meeting at Argonne National Laboratory on November 14-15) to review waste form degradation models, we note that there is an on-going Expert Elicitation Panel which is addressing this topic; therefore, the following comments should be considered as preliminary until the final report of the Expert Elicitation Panel is available (March, 1998) and the final selection of corrosion/release models has been made for the TSPA.

Grambow (in press) has noted that the alteration mechanisms of high-level radioactive waste (HLRW) glass and spent nuclear fuel (SNF) are quite different. Glass is an aperiodic, thermodynamically metastable, covalent/ionic solid whose degradation depends on ion-exchange, surface complexation and Si-saturation. The UO_2 of spent nuclear fuel is a crystalline, redox-sensitive semiconductor whose dissolution behavior is mainly governed by redox mass balance at the oxide-solution interface. Thus, the corrosion of the spent fuel is very sensitive to radiolytic effects at the solid-liquid interface. For both phases, corrosion is accompanied by the formation of alteration phases (gels and crystalline solids) which may incorporate various radionuclides into their structures by precipitation, coprecipitation and sorption.

Glass Waste Form

Although the vitrified, defense waste will occupy a large volume (approximately 6,000 canisters), it will represent only 4,400 MTHM (equivalent) of the total 70,000 MTHM of the repository capacity. The vitrified waste will account for only five percent of the total activity, and most of this will be associated with short-lived fission products. Still, the total amount of radioactive material in the vitrified waste is substantial (approximately 10^9 curies).

As a result, the impacts of the corrosion of the vitrified waste could represent a significant source for potential releases of radionuclides from the repository This has been discussed in a system-level performance assessment (Strachan et al., 1990) which compares releases from spent nuclear fuel and vitrified waste. This study distinguished between radionuclides of low and high solubilities. For those of low solubility, the release from spent fuel packages exceeded the release from glass waste packages by a factor of two. For radionuclides with high solubilities, matrix dissolution controlled long-term release. In this case, the initial release of radionuclides from the gap and grain boundaries of the spent fuel dominated short-term release by several orders of magnitude, but the long-term release depended on the relative long-term dissolution rates for vitrified waste and the spent fuel (Strachan et al., 1990). Grambow (in press) has also compared the kinetics of the long term rates for these two waste forms and noted that the long term rates depend critically on two different phenomena: (1) for glass, the rate is related mainly to processes associated with silica “saturation” and (2) for spent nuclear fuel, the rate is most directly related to radiolytic, oxidative dissolution. For radionuclides for which concentrations are bounded by solubility limits, both the spent nuclear fuel and the glass will be contributing (at different rates) to the radionuclide inventory of the solution; thus, one must anticipate chemical interactions between these two very different waste forms, and the assemblage of alteration products which control solubilities may depend on this interaction.

The “Methods & Assumptions” Report of the TSPA-VA (CRWMS M&O, 1997a, pages 6-80 to 6-97) describes the approach taken in modeling the degradation of both the SNF and the vitrified HLRW. Expanded descriptions of the models for glass dissolution and radionuclide release are provided in the Waste Form Characteristics Report (Version 1.2, December, 1996) and a Lawrence Livermore National Laboratory (LLNL) Report (O’Connell et al., 1997). The basic approach is to develop a response surface that describes the dissolution rate for which the principal parameters are temperature, pH, and dissolved silica concentration. The input for the model will be experimental data provided by Finn and Bates (Argonne National Laboratory, but no reference given). The model will not consider other aspects of the solution chemistry.

On the basis of its review to date, the Panel makes the following preliminary observations:

1. The decision to use a response surface (based on a limited experimental data set) for the description of glass degradation and radionuclide release fails to take into account a large quantity of published laboratory data, the variety of conceptual models for glass dissolution, and the studies of natural analogues of glass dissolution which have been developed over the past twenty years. Although the response surface approach may be computationally efficient, glass dissolution can certainly be based on a mechanistic model which can provide a stronger basis for long-term extrapolation.

2. Because of the extensive amount of previous work on glass dissolution and the data available in the literature, one must reasonably expect that the TSPA-VA will include rigorous comparison of these data sets to the modeled response surface.

3. It is unclear to the Panel how models, which only have pH and silica concentration as their principal parameters, can be used to calculate solubility limits for phases that form during the alteration of the glass. The phases that form will be a result of groundwater/spent fuel/glass/canister material interactions. This will certainly depend on the evolution of the near field environment, an important issue identified at the Waste Form Degradation and Mobilization Workshop.

4. One of the important issues identified at the Waste Form Degradation and Mobilization Workshop was the time dependent evolution of solution compositions and the structure and composition of the alteration/gel layer on the surface of the corroded glass. This was also identified as an important issue in the workshop entitled, "Glass: Scientific Research for High Performance Containment" sponsored by the French CEA in Mejane-le-Clap in September 1997. The reason that the gel layer is now viewed as important is that it can either be an efficient "sink" for rare earth elements and actinides or a source of colloids with high actinide concentrations. The importance of the leached layer is illustrated in Figure III-5. More than 90% of the actinides may be concentrated in the leached layer. Although proper evaluation of the role of the leached layer and the effects of alteration products will require more information than is presently used in the TSPA, the potential retardation of actinides in this layer may justify a more sophisticated approach that considers the role of the gel layer.

5. Prior to the breach of containers and contact with water, the glass will experience an extended thermal pulse and be subjected to high fluxes of ionizing radiation that will reach saturation values during the first few hundred years of storage (Weber et al., 1997). The TSPA should determine whether there are any deleterious effects on the glass waste form as a result of the combined effects of heat and radiation prior to contact with water.

6. Reaction rates for glass dissolution increase with temperature. Has the TSPA evaluated the effect of reduced temperature (disposal away from the spent fuel assemblies) on the release rate? If not, the Panel recommends that they do so.

7. The present model does not explicitly include vapor phase alteration of the glass. Is this not the most likely form of alteration that will occur? Will the vapor phase alteration increase or decrease the durability of the glass when it comes into contact with aqueous solutions? In later sections of the "Method & Assumptions" document, reference is made to the abstraction of the "DHLW Glass Degradation and Radionuclide Release Model." This will include a consideration of the extent of vapor hydration prior to liquid water content, but it is not clear how this potentially important factor will be incorporated into the model.

8. The corrosion rates and reaction progress for glass are sensitive to glass composition (Ebert presentation, Argonne National Laboratory, November 14, 1997)(Strachan and Croak, in press). Will the use of a single glass composition in the TSPA-VA properly bound radionuclide release for the variety of glass compositions that will finally be disposed of at Yucca Mountain?

9. The model used to describe the dissolution of the glass waste forms does not account for concentrations of chemical species in the corroding solutions which may enhance the leach rates. A principal concern is the role of ferric iron released by corrosion of the steel canister of the waste package. Precipitation of iron silicates can prevent the solution compositions from reaching silica saturation values that result in a decrease in corrosion rate of the glass. The iron can also act as a sink for sorption of actinides on colloids which may either be mobile or immobile. The Panel calls attention to this issue which was raised in the 1995 Audit Review by the Nuclear Regulatory Commission (Baca and Brient, 1996). In the Panel’s view, this issue still requires attention.

In a broader sense, such a comment emphasizes the need to consider the near-field environment as an integrated system in which spent fuel, cladding, glass, and canister materials interact with water that has reacted with near-field rock and concrete. This is a complicated geochemical system.

Closing Commentary

In a recent review of source terms used for spent nuclear fuel and HLRW glass in performance assessments, Grambow (in press) has posed a number of questions that should be addressed to waste form modeling in the TSPA-VA:

1. Is the relation between experimental data and model unambiguous? Are alternative models possible?

2. Is the mechanistic understanding of the corrosion process sufficient to allow for ‘best estimate’ extrapolation?

3. How can short-term (up to years) laboratory data be scaled to long-term processes?

4. Are the important, inherent uncertainties quantifiable?

This Panel echoes these questions.

E. Transport

Colloids

The transport of actinides in natural geologic systems can be either as dissolved species complexed with anions or as colloids. The concentrations of the dissolved species in solution can be estimated or at least bounded by a knowledge of the solubility limits of the expected, dominant solid phases. To the extent that solution concentrations are in equilibrium with the solid phases in the system, these concentrations are expected to remain constant over time, and the total release of radionuclides depends on the volume of water in contact with the waste. In the case of spent nuclear fuel, the solids which limit solubility concentrations are the original UO_2 in the used fuel and resulting uranium-bearing alteration products. These phases are expected to control uranium concentrations in solution. Other elements can be expected to have their concentrations limited either by the solubility limits of phases in which they are important constituents or by phases into which they are incorporated in trace amounts.

In general, the solubility-limited actinide concentrations are expected to have relatively low values; however, colloids provide a demonstrable way of maintaining elevated concentrations of actinides in solution, and colloids provide a demonstrable means of transport, e.g. as aquatic colloids which are ubiquitous in natural systems (Kim, 1991, 1994). In addition to the ability of actinides to form intrinsic colloids or to be sorbed onto mineral surfaces and form aquatic colloids, the dissolution and degradation of the waste form itself may serve as a source of colloids. Bates et al. (1992) have shown that the laboratory "weathering" of a prototype nuclear waste glass leads to the concentration of nearly one hundred percent of the Pu and Am into the colloid-sized particles in the alteration layer of the glass. Additionally, actinides sorbed on colloids may be transported at a faster flow rate than the solute species (Savage, 1994). Thus, the failure to consider colloid transport can lead to a significant underestimation of actinide transport (Ibaraki and Sudicky, 1995).

On the other hand, natural colloids may disassociate as solutions become more dilute or be filtered and trapped during transport through porous media. In his presentation to the Saturated Zone Expert Elicitation Panel, Professor D. Langmuir suggested that the fate of colloids could include:

- They are filtered out by crushed tuff backfill under unsaturated conditions.

- Intrinsic colloids, such as Pu-oxy-hydroxides, will degrade in undersaturated solutions as they move away from the waste and once in solution tend to be adsorbed by rock surfaces in fractures especially in the matrix.

- Actinides on the surface of geocolloids will tend to desorb with groundwater flow and to be re-absorbed by surrounding rock surfaces which have unoccupied sites and orders of magnitude more reactive surface sites.

On the other hand, the Nuclear Regulatory Commission has identified a number of critical technical issues relevant to colloid transport (Manaktala et al., 1995). Principal among these are:

- The identification of geochemical conditions that would inhibit particulate and colloid formation.
- The effects of the degree of saturation on geochemical processes, such as colloid formation and sorption, on the transport of radionuclides.
- The parametric representation of retardation processes.

Thus, there appears to be a rather wide range of views as to the importance of colloid transport on repository performance. Although it is not possible (nor necessary nor appropriate) for the Panel to summarize previous work on colloids, it is perhaps worthwhile to note the challenges inherent in modeling colloid transport. Kim (1994) has commented on the extent to which predictive modeling is now successful in describing colloid transport:

> Various approaches have been tried for formulating predictive modeling for the colloid-facilitated actinide migration and the aquatic colloid migration. Since too many assumptions are incorporated into these models, their applicability to real natural systems is still far from straightforward.

Further, in a summary of the role of colloids in transport, Savage (1995) notes,

> To date, this [colloid transport and dispersal] is poorly understood (although both laboratory and field data regarding colloid and groundwater chemistry are available), and there have been few attempts to incorporate such information into a dynamic colloid migration model able to quantify the impact of colloids on radionuclide breakthrough.

Finally, the fundamental analysis of the role of colloids in actinide transport depends critically on the knowledge of, and assumptions concerning, sorption of actinides onto free and immobile colloids. At present, this behavior is generally captured by the use of bulk K_d data; however, the limitations of such an approach are becoming increasingly evident as more experimental work is completed (Geckeis et al., in press).

Although the TSPA-95 report (CRWMS M&O, 1995) did not include a consideration of possible mobilization and transport of radionuclides by colloids, the report does include a discussion of colloid transport and a brief review of models that could be incorporated into the TSPA. The conceptual representation of models treats sorption of radionuclides onto colloids by the use of a distribution coefficient, K_d. Despite the apparent computational simplicity of the approach, one may anticipate a number of problems:

- Definition of the types and amounts of colloid particles.

- Definition of the number of sorption sites.

- Distinction between reversible and irreversible sorption.

- Definition of mobile vs. immobile colloids.

- Use of experimental data to estimate the above parameters.

- Scale-up of experimental data to field-scale models.

- Confirmation of field-scale models.

The "Methods and Assumptions" report (CRWMS M&O 1997a) discusses colloid formation and transport in two sections: (1) as part of the near-field geochemical environment (6.3); and (2) as part of transport in the unsaturated zone (6.7). In both sections, the focus of the discussion is a description of models that will be used to evaluate the significance and effects of colloid transport; however, little mention is made of the theoretical and experimental basis for these models. It would be useful to address some of the fundamental questions:

1. Will colloids form?

2. What types of colloids will form?

3. Will the colloids be stable during transport?

Without convincing answers to these simple questions, the models will be of limited use. Given the previously cited comments, the Panel is concerned that the TSPA team not be overly optimistic in what can be modeled in a convincing and defensible manner. The Panel notes that there appears to be an extensive data base from work at the Los Alamos National Laboratory (LANL) (Triay et al., numerous cited reports); however, there is only a very limited discussion of how this work (conceptual models and data base) will be used in the TSPA-VA. The TSPA team should anticipate that this subject will be given careful attention and scrutiny.

Recently, colloid (<1 micrometer size particles) transport has assumed increasing importance with the report of evidence for colloid transport of radionuclides through fractured volcanic rock at the Nevada Test Site (Kersting and Thompson, 1997). The Panel received an oral presentation from A. Kersting on this subject on November 10th. The data presented supported the contention that radionuclides (^{60}Co, ^{137}Cs, Eu, Pu) are concentrated in the colloid-sized fraction; more than 90% of the measured radioactive material was detected in the particulate and colloid sized fractions and not in the dissolved fraction. The radionuclides are sorbed onto the surfaces of clay and zeolite particles. Because of the unique 240/239 signatures of the Pu isotopes, it was possible to identify the specific source (underground test sites) of the radionuclides. The cited evidence supports the proposal that transport has occurred over distances of at least 1,300 meters during the past 28 years. In the absence of an alternative interpretation or additional data, this work provides a clear example of rather rapid transport of radionuclides as colloids in volcanic rocks similar to those at Yucca Mountain. Perhaps of even more importance than the observation of colloid transport in volcanic rocks, the Panel was impressed by the possibility of testing transport models at the underground test sites of the Nevada Test Site (NTS) in both saturated and unsaturated volcanic units. As discussed in other parts of this report, such tests are essential to developing useful models for the TSPA and determining the associated uncertainties by comparison to natural systems.

On the basis of its review, the Panel recommends:

- The conduct of a careful analysis of the data of Kersting and Thompson (1997) to determine their applicability to the Yucca Mountain TSPA.

- The use of the data available at other sites at the NTS to perform tests of models used to describe radionuclide transport in the volcanic rocks of the site.

The Panel notes that the Project team has clearly identified colloid transport of actinides as an important issue (presentation by S. Brocum to the NWTRB in October of 1997). Evidently, a substantial amount of work has been completed, but the LANL report which will summarize the occurrences and effects of radionuclide migration via colloids is not scheduled for completion until October of 1998. The proposed work for transport and PA modeling (FY 1998 and beyond) will not be available for the TSPA-VA.

F. Disruptive Events, Criticality, and Climate Change

Disruptive Events

The three principal "disruptive events" that the TSPA-VA project is analyzing are:

- earthquakes;

- volcanism; and

- human intrusion.

Earthquakes

The effects of earthquakes at Yucca Mountain include, in principle, a wide range of phenomena depending on how large the postulated earthquake might be, when it might occur, whether ground shaking/acceleration or ground displacement (or both) might be important, and whether the effects are limited to disruption of the integrity of the waste in its canister or also includes effects during UZ transport or SZ transport of radioactive materials.

An extensive probabilistic seismic hazard analysis (PSHA) has been undertaken to understand the issue of how large the earthquakes might be at Yucca Mountain, when they might occur, and the characteristics of their effects. This PSHA is still in its final stages and will not be available for a few months; the Panel looks forward to reviewing it at that time.

In the meantime, the TSPA-VA team, using preliminary insights from earlier PSHA-type evaluations, has chosen to narrow their analytical effort to study principally only one key issue: the direct effect that a postulated earthquake might have on in-drift rockfalls that could impact an otherwise intact or nearly-intact canister and its contents. Enhanced waste degradation and enhanced mobility of the waste are the undesired endpoints being studied. The analysts will examine whether earthquake-caused rockfalls could make an important contribution in addition to effects in the non-seismic base-case scenario. Issues to be studied include damage to the waste package as a function of rockfall size (which can have larger effects at later times when the waste canister has lost significant integrity), and possible changes in seepage patterns into the drift.

The approach for the TSPA-VA is to perform an exploratory bounding-type analysis, to ascertain whether the effects are important enough to merit significantly deeper study.

Various indirect effects due to earthquake motion, such as changes in groundwater flow and transport patterns in either the unsaturated or saturated zones, will not be studied in detail in this TSPA-VA round. In part, this is due to the fact that the PSHA is not yet available and time is limited.

The Panel recognizes that this effort is still in an early stage, and looks forward to reviewing the work as it progresses. In particular, we expect to review both the direct-effect studies to determine if they require supplementing with more work later, and the indirect-effect issue to ascertain whether it can truly be dismissed.

Volcanism

The Basin and Range Province of the western United States is an active tectonic and volcanic region, and, indeed, there has been volcanic activity not very far from the proposed repository site at Yucca Mountain in quite recent times: within the past few thousand years. To understand both the frequency and the sizes/effects of potential volcanic activities of different types, the Project team commissioned the previously cited PVHA that enlisted the participation of most of the recognized experts in the field who could contribute to understanding the issues for the proposed repository (CRWMS M&O 1996c).

The Panel has studied this PVHA, which is well documented. Since none of the Panel members is an expert on volcanic hazards, there is no basis for the Panel providing a formal peer review of that work. The results of the PVHA suggest that volcanic activity that might affect the repository is quite unlikely; the aggregated results are that return frequencies are in the range of 10^{-7} to 10^{-9} per year, or even smaller, for the intersection of a volcanic event with the repository footprint. While the various experts have different models, and while several different types of volcanism could affect the repository, these PVHA results suggest that volcanism is very unlikely to be an issue for the repository.

Nevertheless, despite this quite low frequency, the TSPA project has undertaken an extensive effort to understand the effects of various volcanic scenarios on the repository. Much of this work was done, or well underway, before the results of the PVHA were available, and the work represents a substantial effort that has covered a large number of issues.

The work is in three parts. First, an exhaustive effort has been made to identify all of the possibly relevant scenarios, using a decision-tree-type or event-tree-type structure to differentiate among the scenarios. This has provided the basis for the second stage, which has been to identify a few scenarios for further analysis, basing the selection on criteria such as being reasonably comprehensive, conservative, and yet with enough breadth of coverage to assure that no key issues remain uncovered. Finally, the consequences of each of the scenarios selected for further analysis are to be analyzed (this stage is still underway, with the results not expected for a few months.)

The Panel's effort so far has been: (1) to review the logic of the approach, which seems reasonable; (2) to review the choice of scenarios for analysis, which choice seems sensible although it has not been possible to review that choice in detail because the full documentation is not yet available; and (3) to discuss the volcanism issues with the analysis team, so as to understand what is being attempted and why.

The analysis plan is ambitious, covering both potential direct effects of volcanic activity that might directly impact the waste in the repository, and indirect effects such as modifications to the geologic and hydrologic setting. A large amount of detail has been included in the models developed to date, and the work planned for the next few months will exploit this work-to-date to determine some reasonably good estimates or bounds on the potential consequences of several volcanic scenarios.

The Panel is looking forward to a review of the volcanism work when it is complete. As explained to the Panel, the TSPA team is attempting at this stage to do an analysis that will be sufficiently comprehensive to demonstrate with high confidence that volcanism is not important for the repository's overall performance. The TSPA team believes that the modeling work already accomplished, and the plans for the next few months, will provide such a demonstration.

Inadvertent Human Intrusion

The approach that the TSPA project will ultimately take in analyzing inadvertent human intrusion into the repository is still in limbo. The analytical approach applied in the License Application will depend on regulatory decisions by the EPA and the USNRC that have not yet been made. Specifically, until the EPA standard and USNRC's regulatory approach to implementing it are promulgated, the Yucca Mountain Project team will not know which human intrusion scenarios to analyze, which regulatory figures-of-merit to use, or the details of any other specific regulatory guidance. The need for regulatory guidance in this area is clear; because there is no way to predict human behavior in the distant future, no analysis can be "realistic" in either selecting its intrusion scenario(s) or assigning them probabilities -- thus the need for regulatory guidance.

Given the uncertainty in what the regulatory bodies will ultimately adopt, the approach that the TSPA-VA team is taking at this time seems eminently sensible. The project is temporarily assuming that the guidance in the report “Technical Bases for Yucca Mountain Standards” (National Research Council, 1995) will become the EPA/USNRC regulatory guidance.

That guidance suggests that the project not be required by regulation to analyze for human intrusion in a full probabilistic sense, because the probability per year of intrusion cannot be known. Instead, the suggestion is that the project be required to analyze the effects on overall repository performance from a single exploratory borehole (or perhaps a very small number -- two or three -- if that small number creates a scenario qualitatively different from the single-borehole scenario). The idea is to determine if such a modest campaign of exploration sometime in the distant future could compromise the performance that the repository would otherwise exhibit in terms of containment.

The guidance further suggests that only inadvertent future human intrusion be considered; that current-day exploration technology be assumed; and that the analysts assume that the exploration team somehow does not detect what it has encountered until the operation is complete. Then the explorers become suspicious and stop their campaign, but do not repair any damage to the repository underground. The analysts should ignore the effects of the intrusion on the exploration team themselves or their immediate environment (for example, from exposure to radioactive cuttings brought to the surface, either direct exposure or exposure due to subsequent dispersion), because such effects cannot differentiate between an excellent repository site/design and a poor one.

Because no regulatory guidance now exists, and because once that guidance is promulgated a full suite of analyses will become necessary, the TSPA-VA team's approach at this stage is to do some exploratory analysis, that is believed to be conservative and simplified. The approach, as described to the Panel, is that the analysts assume that a single exploratory borehole is drilled using typical modern drilling technology, that would pass from the surface directly through a waste package, extend all the way down to the saturated zone, and deposit radioactive waste at the bottom of the borehole directly at the top of the SZ. This waste would then be available to migrate in the SZ and toward the accessible environment. The question will then be asked as to whether such a scenario, that is assumed conservatively to bypass the unsaturated zone entirely, produces important additional radionuclide transport to the accessible environment when compared to the no-human-intrusion base case. The time in the future when such an exploratory hole is assumed to occur will be varied, to assess which future time period might be "worst" in terms of consequences.

While the Panel has not had the opportunity to review the details of this analysis, because it is still underway, the approach makes eminent sense. Insights gained from this preliminary analysis can indicate whether a much more detailed analysis of human intrusion scenarios will be needed, assuming that EPA and USNRC adopt the regulatory approach suggested by the Committee on Technical Bases for Yucca Mountain Standards (National Research Council, 1995). The Panel will await the opportunity, over the next few months, to review the details as the analysis proceeds.

Criticality

The TSPA-VA constitutes the first attempt to address the issue of criticality at Yucca Mountain through performance assessment; it was not addressed systematically in TSPA-95 or earlier TSPAs. The TSPA-VA team will not attempt to integrate the criticality analyses with the larger PA model, but instead will perform a set of side analyses of criticality scenarios as a sensitivity study in parallel with the mainline analysis of future repository performance. That is, criticality scenarios will not be incorporated into the mainline models for TSPA-VA, but will be analyzed separately.

In brief, the criticality problem is that a very large number of critical masses, of either plutonium or uranium-235, will be emplaced in the waste canisters, and many other critical masses of various fissile nuclides will grow into the waste over the eons through radioactive decay of parent nuclides. Although the material as originally emplaced will be in configurations that will be designed to preclude criticality, it is necessary to determine whether a critical mass could be reassembled later in time after the engineered barrier features degrade.

As the Panel pointed out in its first report, the task of TSPA-VA Project team in this area should be some combination of the following: (1) to perform a set of realistic analyses of all of the various potential criticality scenarios, or (2) to analyze only a subset of the potential scenarios and then to argue that this subset bounds the larger set of scenarios that are not analyzed; or, where appropriate, (3) to produce bounding analyses of some scenarios if such would be adequate for the purposes of the overall TSPA-VA project.

The Project team has approached this difficult analysis task in four steps. First, the Project team has identified three physically distinct regions where criticality might occur in the far future: in-package criticality (after degradation of the packages or of their contents); near-field, in-the-drift criticality after material might migrate out of the canisters into the drift space; and far-field criticality, defined as anywhere outside the drift. Secondly, the team has differentiated in a complex decision-tree or event-tree format the full range of potential scenarios, in each of the three regions, that might occur given different postulated future events and processes. Using this complex event-tree structure, the third step has been to choose a small number of potential scenarios for analysis during this round (TSPA-VA). The fourth step, now underway, will be to analyze each of these scenarios in a realistic manner, but using conservative assumptions where appropriate.

It is important to describe the two key explicit assumptions with which the TSPA-VA team is operating that: (1) that it can later be shown that the few analyzed scenarios truly do "bound" all of the others, in the sense that the doses/risks from them exceed the doses/risks from all of the others; and (2) that none of the scenarios analyzed will contribute importantly to the overall doses/risks from the proposed repository when compared to the no-criticality base-case analysis.

If both of these assumptions are correct, the issue of criticality will have been shown to be "unimportant," at least in a regulatory-compliance sense.

In principle, any specific criticality scenario can be screened out if either its likelihood is found to be exceedingly small, or its dose/risk consequences are found to be minor compared to the base-case behavior of the repository, absent that scenario. As the Panel understands the TSPA-VA team's approach, this logic will be used to eliminate many, if not all, scenarios, thereby enabling the analysts to dispense with criticality concerns for the repository. (Of course, care must be taken that one does not screen out a myriad of small scenarios one-by-one while overlooking the possibility that they will add up to an important impact; the likelihood for error inherent in such a "divide-and-conquer" approach is an ever-present danger when choosing to examine only a few scenarios among a much larger set.)

Progress to date has been significant. The TSPA-VA team has completed developing the set of scenarios and has selected a subset for analysis in this round. The team has recently published an account of its work (CRWMS M&O 1997c) and is now embarking on the analysis itself, which will be designed to estimate both the likelihood and the dose/risk consequences of each chosen scenario. The TSPA-VA team has selected for analysis six different in-canister scenarios and one each in the near-field and far-field regions.

Over the past year, in the course of differentiating among the scenarios and choosing the few to analyze, the TSPA-VA team has reached some important conclusions about the various phenomena. They now believe that if any criticality scenarios turn out to be important, they will be the in-canister ones; they believe that it will be possible to show, in this TSPA-VA round, that all scenarios in both the near field and the far field can be dismissed on the basis of either probability or consequences, and perhaps both. In particular, criticality scenarios in the near field (in-the-drift after material migrates out of the canisters into the drift space) seem so far likely to produce only very minor increases in consequences over the no-criticality base-case scenario. Further, these scenarios have at most a rather small likelihood of occurring -- although these likelihoods are difficult to estimate, especially the likelihoods that neutron-absorbing materials might be separated from the fissile materials enough to produce the criticality scenario(s). Similarly, the far-field scenarios appear to be of concern, if at all, only for time periods beyond a million years, because the important processes that might segregate and/or reconcentrate a critical mass and eliminate any neutron-absorbing materials in the far field appear to be very slow, taking place in the millions-of-years range. (These conclusions, if supported by further work now under way, will require careful review by the Panel.)

The in-canister scenarios remain as the most likely concern. Here, the TSPA-VA team is developing details of how canister-failure mechanisms might introduce moderator (water), displace the neutron-absorbing material, assemble the fissile material into a critical configuration, and sustain all of this to produce a fissioning system. In the opinion of the Panel it is unlikely that anybody will ever be able to "predict" the details of how canister failure and the other phenomena might occur, and to assign split-fraction probabilities to the various failure scenarios and the subsequent events. Even though there is a sound scientific understanding of the key phenomena, such as differential chemical-separation effects as a function of conditions (pH, Eh, temperature, etc.) and critical-assembly behavior, it is more likely that the analysis team will be successful because the TSPA-VA team will be able to show, with confidence, that the bounds it can place on consequences and/or probabilities, taken together, are acceptably minor. If not, and the specific details need to be understood, the situation could be beyond the capabilities of current knowledge, especially insofar as it would be necessary to understand the details various future canister-failure scenarios.

The Panel expects to review the details of the criticality work over the next few months, as the Project team completes its analysis of the various scenarios. We will try to be especially attentive to whether the scenarios chosen are a reasonable set; whether any conservative or bounding-type assumptions are well chosen and used properly; and whether the mix of consequence-type arguments and likelihood-type arguments holds together coherently.

To summarize our comments about the criticality work to date, the Panel believes that the two key elements of the approach above -- allowing criticality to be studied through side analyses instead of in the mainline TSPA modeling, and developing a few scenarios for analysis in order to bound the problem -- are both sensible. The project should be commended for the logic adopted in the work being undertaken.

Regulating Against Criticality

Another important issue concerns the relevant standard to be used in evaluating the risks associated with criticality. In its first review report, the Panel observed that the USNRC regulations adopted many years ago for evaluating the possibility of criticality in deep-geological repositories such as that proposed at Yucca Mountain, imply that it is necessary to preclude criticality with high confidence. Unfortunately, in our view, the regulations, as written, do not clearly indicate whether they were intended to apply to the operational phase (pre-closure), the post-closure phase, or both. The Panel urged that the Project team request that the U.S. NCR staff clarify this situation.

During the intervening months, much progress has been made on this issue. The Panel is gratified and will monitor the evolution of the situation over the next year. Our reason for assigning this topic high importance is that, as the Panel stated in its first report, we believe that, depending on the figure-of-merit used in the regulations for the proposed Yucca Mountain repository, it may be determined whether the proposed repository "passes" or "fails" depending on the specific details to a much greater extent than for any other of the important phenomena that may occur in the future. Specifically, if the regulations require that the repository design "preclude" criticality from occurring within Yucca Mountain for all future times, or for any regulatory time period beyond when canister failure begins, the Panel believes that it may be impossible to demonstrate whether the facility complies.

As stated in our first report, the Panel’s judgment on the above is based on the following (preliminary) observation. Despite all of the best efforts that the criticality modelers will bring to bear on the subject, it is our judgment that it likely will not be possible to preclude criticality processes with high confidence over the full future time covered in the TSPA. This is likely the case even if only a 10,000-year regulatory period is to be covered, and all the more true if much longer times, such as a million-year period, require study. This is because the specific details of the ways that the canisters may fail, and the ways that materials may chemically interact and move (both in-canister and in-drift), may not be knowable in enough detail.

Climate Change

The TSPA-VA Project team has not completed sufficient work on how climate change might affect the long term behavior of the proposed Yucca Mountain repository to provide revisable material for the Panel. Therefore, our review of this topic is deferred.

G. Biosphere, Doses, and Health Risks

Since issuance of its initial report, the Panel has been provided with the following reports that contain details on progress in the development of the biosphere components of the TSPA-VA:

- *Total System Performance Assessment - Viability Assessment (TSPA-VA), Methods and Assumptions* (TRW, 1997a); and

- *Biosphere Abstraction/Testing Workshop Results* (TRW, 1997b).

The Panel was also provided a transcript of the meeting of the Panel on Environmental Regulations and Quality Assurance, Nuclear Waste Technical Review Board, that was held on October 21, 1997.

On the basis of our reviews of these reports and related documents, the Panel offers the following comments and recommendations related to the methods and procedures that will be used in assessing the doses/risks to the public.

Assessing Doses and Health Risks

In the case of performance assessments for the proposed Yucca Mountain repository, it is possible that the EPA and the USNRC will provide the TSPA-VA team with specific values for the dose conversion factors and risk coefficients that are to be used.
Even so, the DOE and the TSPA team should seek to develop realistic estimates, with the objective of reaching an understanding of the conservatisms that underlie, and have been incorporated into, the dose conversion factors for each of the critical radionuclides as well as the coefficients for converting these dose estimates into the related risk. At the same time, the Panel wants to make it clear that it is not seeking to imply that the TSPA-VA team should develop new more realistic dose conversion factors and risk coefficients; rather it is to encourage the TSPA-VA team to be aware of the related conservatisms, to quantify them at least in a cursory sense, and to be prepared to discuss and evaluate their implications in terms of the outcome of the TSPA-VA.

Difficulty of the Task

The next comment pertains to the difficulties anticipated by the M&O staff in estimating the doses to population groups who may be exposed. In Section 1.1.2 of the Workshop report (CRWMS M&O, 1997b), the statement is made that:

> In the TSPA computational code it was a simple calculation to convert concentration of each radionuclide in the groundwater to dose. The dose for each radioisotope could be readily generated by simply taking the product of the dose conversion factor (DCF), the concentration of that radionuclide in the groundwater and the quantity of drinking water. The total dose was arrived at by summing this product over all radionuclides.

The Panel does not agree that this process is as “simple” as implied. As discussed below, unless care is exercised many of the errors, uncertainties, and conservatisms associated with making such estimates may not be recognized. Additional conservatisms and uncertainties will be introduced, as noted above, in converting the dose estimates into risk estimates.

Degree of Conservatism Being Sought

Closely associated with these topic is the degree of conservatism that is being sought in developing the dose/risk estimates. Although most of the analyses in the TSPA-VA appear to be directed to the development of "best estimates," Section 1.3 of the Workshop report (CRWMS M&O, 1997b) indicates that:

> Approximations and systematic errors (in the Biosphere 'add-in' model) have to be shown to provide predictions of dose that will be conservative.

Although the Panel agrees that conservatisms need to be incorporated into the standards or regulations, we do not agree that they should be incorporated into the dose/risk assessments. In fact, every effort should be made to make these assessments as realistic as possible. This was one of the points made by Dr. Marsha Sheppard of the Atomic Energy of Canada Whiteshell Laboratories during the Workshop cited above. As noted earlier in this report of the Panel, this was also one of the implications of the wording in the original EPA Standards, 40 CFR 191.13 (a), as cited in Section II (U.S. EPA, 1985). Although now remanded, these Standards clearly stated that "unequivocal proof of compliance is neither expected nor required because of the substantial uncertainties inherent in such long-term projections. Instead, the appropriate test is a reasonable expectation of compliance based upon practically obtainable information and analysis." The regulations of the USNRC (1983) followed a similar pattern in stating that "While these performance objectives and criteria are generally stated in unqualified terms, it is not expected that complete assurance that they will be met can be presented. A reasonable assurance, on the basis of the record before the commission, that the objectives and criteria will be met is the general standard that is required." Neither the EPA standards nor the supporting USNRC regulations imply that the risk/dose assessments should be calculated on a conservative basis.

Magnitudes of Conservatisms and Associated Uncertainties

It is important the TSPA team recognize the magnitudes of the conservatisms that have been incorporated into the existing dose conversion factors and risk coefficients. In this regard, the BEIR-V Committee (National Research Council, 1990) has cautioned that the

> … methodology and values given by International commission on Radiological Protection (ICRP) (for calculating the doses due to the internal deposition of radionuclides) were assembled for radiological protection purposes. Thus, the values chosen for the various parameters are conservative; that is, they can lead to overestimates of risk factors. These values may not be appropriate for estimation of risk when the organ and tissue doses received by exposed individuals are considered. (pages 40-41).

Similar words of caution have been expressed by the Committee on an Assessment of CDC Radiation Studies (National Research Council, 1995), when they stated that

> The largest dose will be to organs that accumulate and retain the radionuclide. However, the variability in absorption of the ingested radionuclides in the gastrointestinal tract is responsible for the greatest uncertainty in the potential dose. Because radiation guidelines are usually conservative, it is likely that the commonly used absorption factors overestimate the amount of the radionuclide that is absorbed and hence the organ dose. (page 43).

The Committee on an Assessment of CDC Radiation Studies also recommended that: (1) "In assessing exposure and absorbed dose, uncertainty should be expressed for physical, biological, and computational methods. The calculations of uncertainty should be propagated throughout all calculations…"; (2) "In obtaining measures of propagated errors, procedures for incorporating methods of assessment of uncertainty for physical and biologic results are required." (page 49); and (3) risk assessors should recognize that "Traditionally, radiation protection guidelines are predicated on a linear dose response, which assumes that the harmful effects of radiation are linearly related to the dose and that there is no threshold dose. Most experts believe this assumption is conservative; that is, it overestimates the effects of ionizing radiation at low doses because it ignores the potentially beneficial effects of the body's repair mechanisms." (page 43).

Still another conservatism is that resulting from the use of the committed dose concept, particularly for radionuclides with long effective half-lives, as is the case with ^{237}Np and ^{239}Pu. According to the National Council on Radiation Protection and Measurements (NCRP) (1993, page 25), the use of this concept "will overestimate by a factor of approximately two, or more, the lifetime equivalent dose or effective dose."

Adding support to these concerns is the recent action by the National Radiological Protection Board, United Kingdom, to develop an independent set of RBE values for use in risk assessments involving exposures from neutrons, as contrasted to applying those that have been developed for purposes of radiation protection (Edwards, 1997).

Acceptability of Health Endpoint

At this stage, it is anticipated that the standards being developed for the proposed repository will be expressed in terms of dose and/or risk limits that are based on the probability of fatal cancers as the health endpoint. Although this was the endpoint commonly used in the past (ICRP, 1977), newer recommendations of organizations such as the NCRP and the ICRP are based on what is called the "total detriment." This includes considerations of both morbidity and mortality, as well as years of life lost (ICRP, 1991).

If fatal cancers are considered to be a surrogate for other health endpoints, the basis for this selection needs to be explained. The issue of what endpoints should be considered, including fatal and nonfatal cancers and other late effects of ionizing radiation, are appropriate topics for discussion between the project staff and the regulators, and should be considered by the regulatory agencies as issues to be raised in the public input processes associated with development of the standard. To the extent that considerations of this type may impact on the acceptability of the TSPA, the Panel encourages the TSPA team to keep these factors in mind and to be prepared to address them.

Identification of Significant Radionuclides

The conservatisms cited above, coupled with other considerations, have led the Panel to question whether the TSPA-VA Team has devoted sufficient effort to the identification of those radionuclides that are most important in assessing the potential impacts of the proposed repository. The current list needs to be shortened and the key radionuclides need to be identified. Included in this process should be a thorough discussion of the scientific basis for each such selection. One radionuclide that serves as a source for these comments is ^{129}I.

According to the NCRP (1985, page 41), "The low specific activity (0.17 µCi/mg) of ^{129}I and the restricted capacity of the normal human thyroid to store iodine, limit the hazard from ^{129}I." Based on these observations and studies of the effects of ^{129}I in animals, the NCRP concluded that "^{129}I does not pose a meaningful threat of thyroid carcinogenesis in people."

For these reasons, the Panel believes that, while ^{129}I will still have to be considered by the TSPA-VA team and appropriate dose estimates made, the team should be aware of the views of the NCRP. Similar reviews should be conducted of the detailed physical, biological, and chemical information on each of the other 39 radionuclides currently on the list of those considered important by the TSPA-VA Team. These types of issues should be analyzed and discussed with the regulators to ensure that there is a scientifically sound basis behind whatever regulations are adopted. The goal should be to define a sound scientific basis for the selection of each radionuclide considered to be important.

Relative Importance of Dose/Risk Uncertainties and Conservatisms

In summary, the Panel believes that it is important for the TSPA team to recognize that the conservatisms enumerated above and to document and quantify the associated uncertainties. Although predictions of future climatic conditions and geologic developments, and the anticipated behavior of population groups, are important, the biosphere dose/risk issues appear to the Panel to offer equal challenges. In certain cases, the magnitude of the uncertainties and potential errors in the pathway, dose and risk estimates may equal those involving assessments of the performance of the natural and engineered barriers .

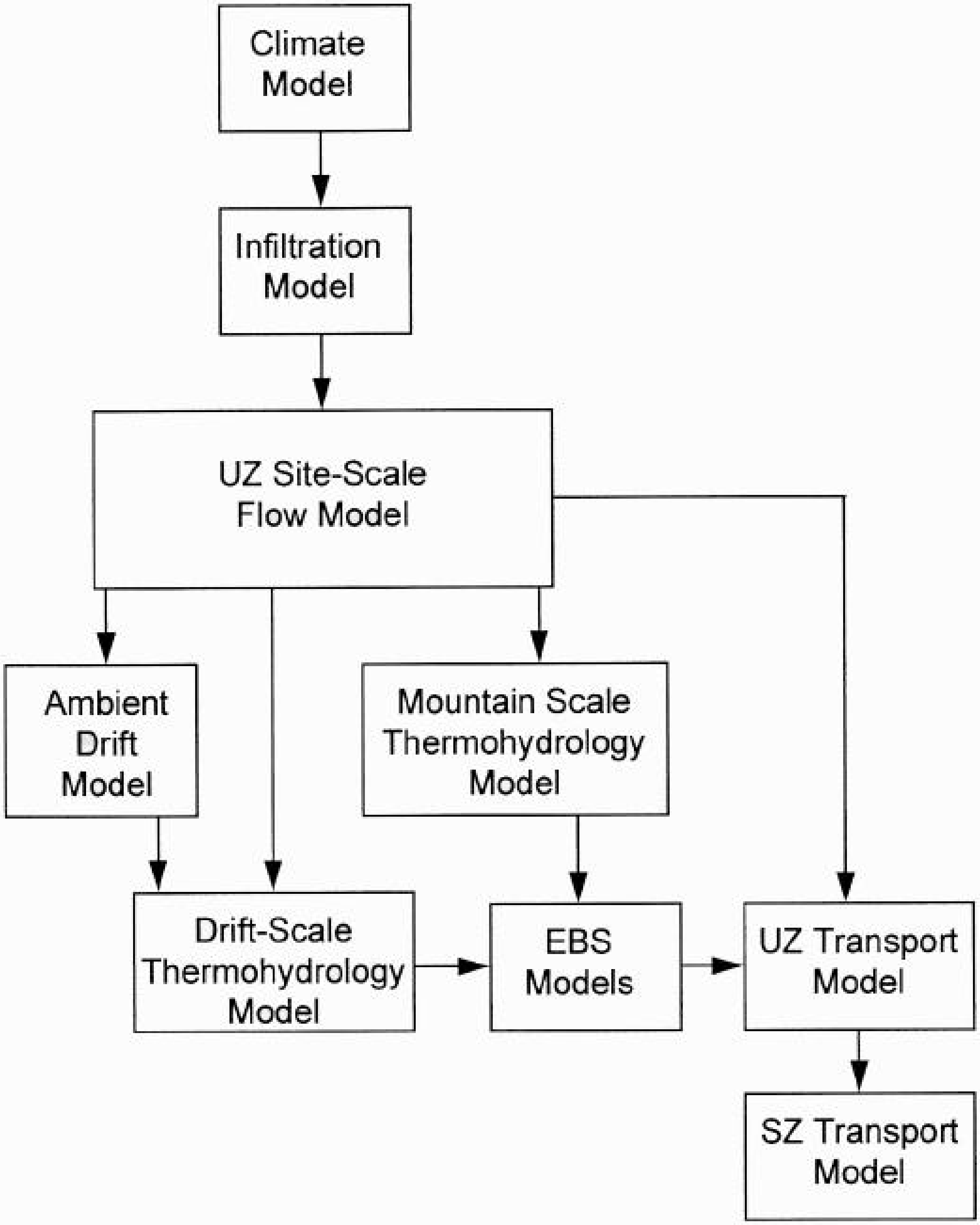

Figure III-1. Relationships between various computer models being used in the analysis of Yucca Mountain (from Bodvarsson et al., 1997b).

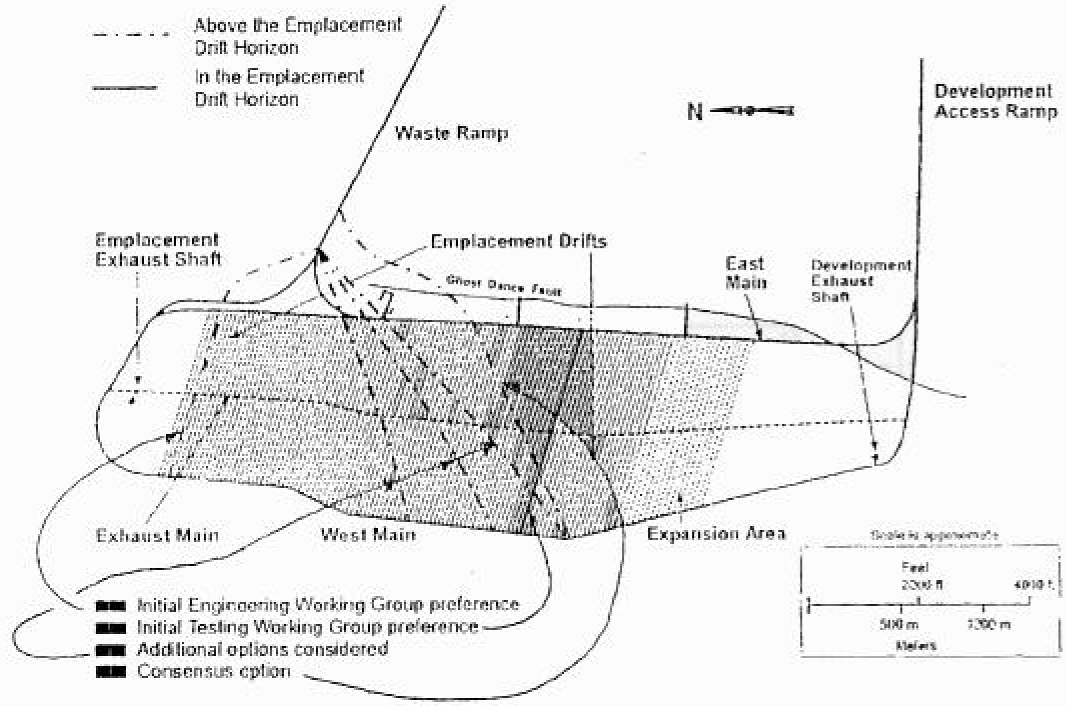

Figure III-2. Location of East-West drift selected from the enhanced characterization of the repository block (ECRB) showing various options considered in the analysis.

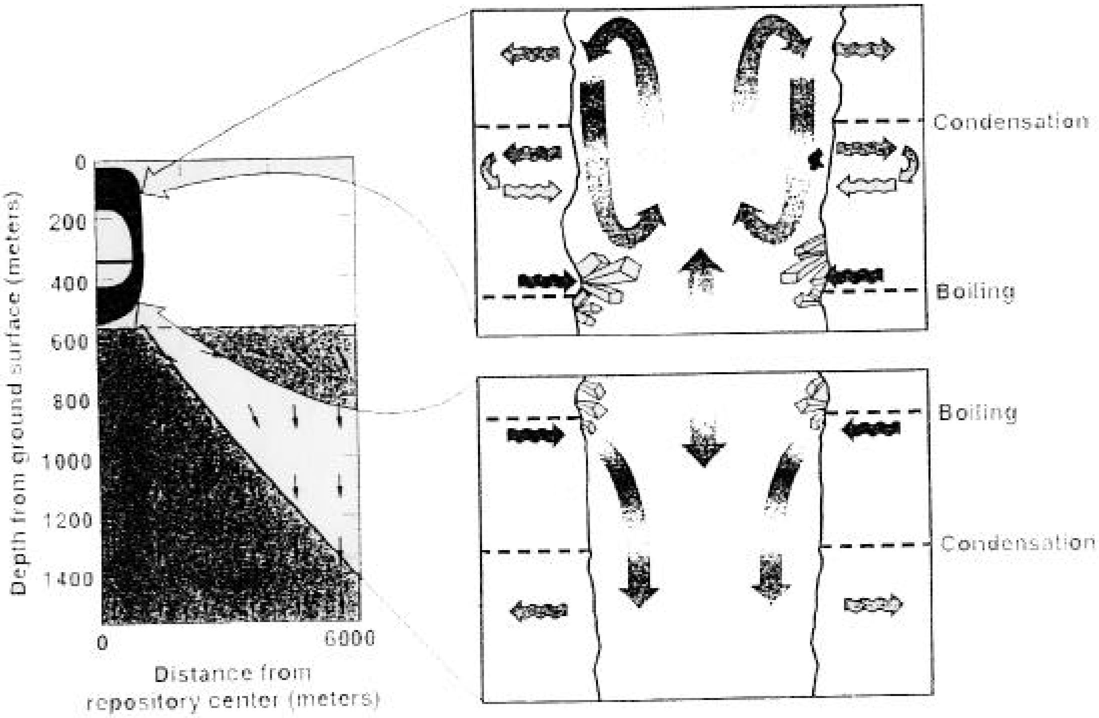

Figure III-3. Schematic drawing of heat pipes and geochemistry regimes at 1000 years post closure (from Glassely et al. 1997).

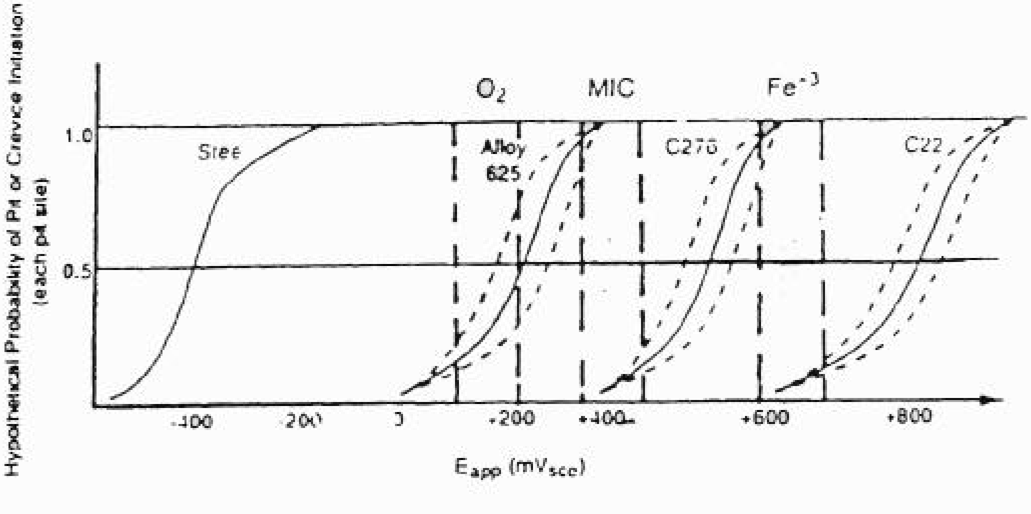

Figure III-4. Crevice corrosion in metals (from J.R. Scully, U.S. Nuclear Waste Technical Review Board Meeting, October 23, 1997).

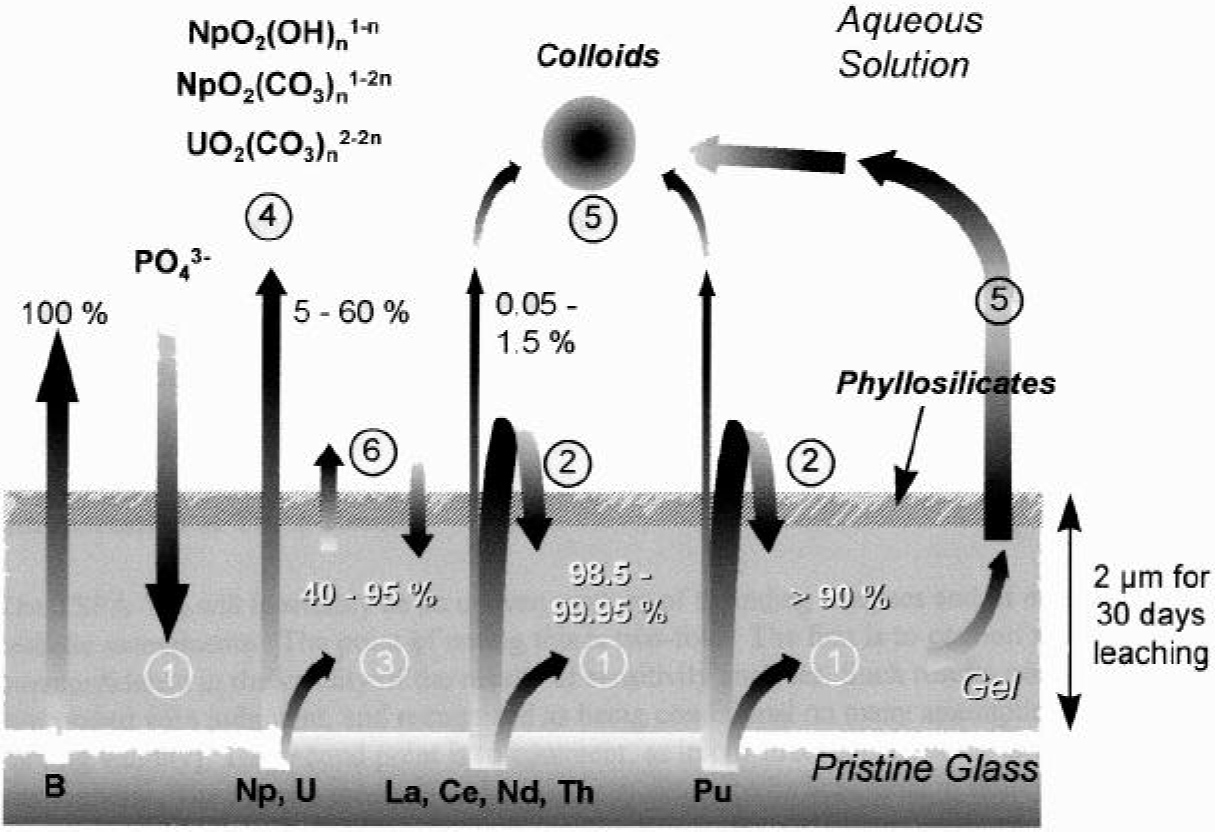

Figure III-5. Principal mechanisms involved in controlling the mobility of the lanthanides and actinides during the leaching of R7T7 nuclear glass under simulated geological disposal conditions: (1) Coprecipitation/Condensation; (2) Chemisorption; (3) Precipitation of phosphate or oxide/hydroxide phases; (4) Complexation; (5) Colloid transport; (6) Ion exchange. Figure courtesy of Thiery Advocat (CEA) (Menard et al. in press).

IV SUMMARY OF FINDINGS

The Panel's goals have been to note weaknesses that can be ameliorated through the use of more appropriate models and data, to seek clarification of the bases for certain of the analytical approaches and assumptions that have been used, and to evaluate the sensitivity analyses of alternative models and parameters.

A. Section II Findings -- TSPA Methodology

The Panel believes that the expectations for what TSPA can accomplish, as expressed in the "Methods and Assumptions" document, will not be achieved. Although the EPA standard (concerning a "reasonable expectation" requirement, quoted in Section II) no longer applies to the proposed Yucca Mountain repository, the explicit goals as expressed in these regulatory requirements are, in the Panel's view, more consistent with what the TSPA can achieve than are the goals that are stated in the "Methods and Assumptions" document.

Interpretation of TSPA Results

The TSPA-VA will inevitably be an uneven mixture of bounding analyses and of more realistic assessments. The point of noting this is two-fold. The first is to caution against overconfidence in the validity of the results of sensitivity analyses. Such results need to be interpreted with judgment, and recognized as being conditional on many assumptions [of varying validity]. The second point is to comment, as in our first report, on the issue of analyzability. The Panel's message is that for a repository to be licensable, it must be analyzable.

In this regard, the TSPA team needs to recognize that it may not be possible to analyze the impacts of certain postulated events on the performance of various systems and components. This applies, in particular, to the responses of various systems to potential events, such as volcanism and criticality, and the thermal pulse. It includes details such as how a waste package might degrade under impacts of this nature. This is a difficult and perplexing problem. Careful thought needs to be given to how it is to be addressed.

Although the Panel supports the "defense-in-depth" philosophy, there has been a tendency on the part of the Project team to judge the benefits of selected EBS/WP components with insufficient technical review of whether their contributions can actually be achieved. Without sufficient analysis or documentation to support the presumed performance, the resulting sensitivity analyses can be misleading. An unrealistic bounding analysis may, in some cases, indicate incorrectly that a particular feature of the site or design is unimportant to performance, while, in fact, it is important; an analysis that is unrealistically optimistic may mask the actual sensitivities in some aspects of the performance of that system and/or component.

Because of the inevitable and inherent uncertainties of the TSPA process, the DOE contractors must be prepared to explain the limitations of their analyses. Other groups who review this work will certainly point out the philosophical and practical limitations of the TSPA-VA.

Model Testing

On the basis of its review, the Panel has concluded that the TSPA team is not taking advantage of existing opportunities to test the validity of the models being used. To assist in correcting this problem, the Panel recommends that the Project team investigate methods by which subsystem models can be explicitly tested. These might include: (1) design of experiments to test specific results of the near-field models; (2) testing far-field models using the larger scale experiments in the Exploratory Studies Facility; (3) blind-testing of geochemical and hydrologic models in different geologic systems or localities; and (4) determination of whether the methodology used in the TSPA provides results that are consistent with natural systems. One such opportunity would be to use the existing models to predict the results/data that will be generated through the Drift Scale Test. Successful assessments based on careful analysis can provide substantial confidence in the TSPA analysis.

Use of Expert Elicitations

Overall, the Panel is impressed with the use of an advanced methodology for the conduct and interpretation of the expert elicitations. The Panel, however, continues to be concerned about the possibility that this process could be misused or abused by the Project team.

The value of expert elicitation is that in some situations, the elicitation process, involving interactions among the experts, can help resolve a lack-of-consensus situation. What an elicitation cannot accomplish is equally important: (1) it cannot develop "data" or a substitute for data where none exist; (2) while it can provide a mechanism for evaluating the existing data, it often cannot provide a means for successfully "assembling" them into a useful data set for the needs at hand; and (3) if the issue is to select from competing models to explain the relevant phenomena, rather than to understand differences among data sets of varying relevance, the interactions among the experts may not be able to resolve which among the several models is "best."

The Safety Case

While the TSPA addresses the likelihood, timing, and consequences of events and processes that could lead to a release of radioactive materials from the repository, a safety case looks at the same information and analyses with the objective of identifying the key features in why a repository could operate safely. Because the performance assessment and safety case share an underlying technical basis, the confidence that one can have in the TSPA results will, to a large degree, depend on how the analyses of the major elements of the defense-in-depth strategy are conducted and presented. These elements include the durability of waste form; canister lifetime; delays and limitations in the contact of water with the waste; and travel times to the repository boundaries, as either dissolved or colloidal species. They can be presented in a framework that includes the supporting models and their underlying physical and chemical principles, conformance with available laboratory and field data, experiences with similar models in comparable systems, and sensitivity analyses based on alternative plausible models. If this is done effectively, the principle of defense-in-depth will have been applied effectively.

Enhancing the Utility of the TSPA-VA

There are a number of actions that can be taken to enhance the utility of the TSPA-VA. Those considered important by the Panel include recognition of: (a) multiple objectives for the analysis (for example, to help DOE with its decision about whether to proceed to licensing, to identify data and analyses to improve future analyses and reduce their uncertainties, and to assist with design choices); (2) expectations for and limitations in what the TSPA-VA can do, (given the complex, coupled processes and long time periods of interest, it may not be possible to analyze the impacts of certain postulated events on the performance of various systems and components); and (3) the availability of tools to address the analytical limitations, for example, model testing, the appropriate use of expert elicitation, and defense-in-depth.

B. Section III Findings -- Technical Issues

Initial Conditions

The studies of radionuclide tracers (for example, ^{36}Cl) suggest that the discrepancies between the data and the conceptual models need further attention. This is a problem of considerable complexity and is beyond the scope of the charge to the Panel. Nonetheless it is extremely important. A prime example is the important role of the UZ flow model in the Yucca Mountain Project team's strategy as it approaches the license application phase.

Site Conditions with Waste Present

A number of models that can simulate the physics and chemistry of the governing processes have been developed. In particular, the response of the proposed repository has been analyzed at length under: (1) the current ambient conditions, and (2) the impact of a thermal perturbation. This has been an effort without precedent, and is complicated by the fact that adequate empirical evidence on the thermohydrologic, thermochemical and thermomechanical behavior in systems of this kind is not available. Under these circumstances, it is understandable that there will be uncertainties in the results that must be recognized and evaluated to the best possible degree.

Modeling studies have revealed significant differences in the potential effects of the thermal field on the hydraulic behavior of the repository system as the input value for the infiltration rate was varied from the previous estimate of 0.1 mm/year to the currently estimated rate of 4.4 mm/yr. It is apparent that the magnitude of this critical factor must be well established, so that the potential effects on repository behavior can be accurately evaluated.

Fracture/matrix interactions play a dominant role on the infiltration rate. In the coarse grid simulation, these interactions are simulated through the use of effective parameters, such as the area between the fractures and matrix. This is currently expressed by a reduction factor to reflect the limited contact resulting from channelized fracture flow. Reduction factors as low as 10^{-3} have been postulated to match field data. This is a drastic departure from the simulation practices previously used. At the present time, the foundation for this factor is weak. Additional uncertainty, particularly for two-phase flow processes (imbibition, drainage and heat pipes), is introduced through the use of volume averaging over a number of fracture-matrix areas. In such cases, the set of hydrologic parameters applied will not correspond to that of either individual fractures or matrix blocks.

The TSPA team is using the equivalent continuum model (ECM) to assess the long term impacts of the thermal perturbation on the proposed repository. Application of this model requires that thermodynamic equilibrium exists between fracture and matrix. Although this may be true for thermal energy and for the imbibition of a high-permeability tuff, it will not necessarily be true for mass diffusion and imbibition of a low-permeability tuff, such as that at Yucca Mountain. ECM also cannot account for a fracture/matrix reduction factor, and this model is therefore inherently unable to match the revised percolation flux. Nonetheless, the ECM is being used extensively in evaluations of the thermohydrologic behavior of the proposed repository. This is of concern to the Panel and it has recommended steps that should be taken to assess uncertainties in and range of validity for how the ECM is being used.

Modeling studies have shown that volume changes are possible as a result of dissolution in the condensation zone, formation of secondary minerals, and the involvement of the fracture and matrix in the chemical evolution. Experimental studies have shown that hydrothermal processes can alter minerals and cause them to precipitate at the fracture/matrix interface. The extent to which such reactions can lead to significant changes in the porosity and permeability of the rock system is a major uncertainty at this point. Laboratory investigations indicate that processes of this nature could significantly reduce the permeability of the fractured tuff. This may have significant implications on repository performance.

Engineered Barriers and Waste Package Performance

Reducing uncertainty

Large volumes of water will be mobilized by the thermal pulse. However, the flow paths and amounts of water transported along various paths are not well defined. This leads to large uncertainties in estimates of the amounts and distribution of seepage that would flow back into the drifts within the proposed repository. The spatial and temporal characteristics of these flows are also uncertain. The impacts of these uncertainties on overall repository performance can be reduced, and the reliability of the TSPA-VA increased, by the selection of highly corrosion resistant metals for the waste packages. For these reasons, the Panel supports a TSPA analysis that is based on the selection of the most corrosion resistant metals for the corrosion resistant metal barrier.

A steel outer barrier has several desirable features that pertain during a long, dry period. When wetted, however, the steel canister corrodes rapidly and adds to uncertainty. Dual packages comprised of a double layer of corrosion resistant metals have been proposed and are worthy of further consideration and evaluation in the performance assessment.

Improving information and data quality

Although notational information is available, there is a paucity of experimental data on the behavior of the alloys of interest in the environments anticipated to be present within the repository. Realistic data are needed to support the selection and evaluation of the performance of such materials. For this reason, the Panel recommends that a comprehensive effort be undertaken to compile and critically review the corrosion behavior of the two primary candidates for the corrosion resistant metal. These reviews should be directed to the class of alloys, not to a specific metal designation.

Analytical approach

The Panel concurs with the conclusion of the Waste Package Expert Elicitation effort, namely that crevice corrosion is the most important degradation mode to be considered in the TSPA-VA. With respect to stress corrosion cracking (SCC), the Panel notes that no mechanistic models are available for the TSPA-VA. Rather than suggest that resources be directed to additional model development, the Panel recommends that an engineering approach be applied, namely, that the Project team select metals that are resistant to SCC and specify design and manufacturing procedures that avoid SCC.

The need for and extent of galvanic protection will depend upon the geometry of the galvanic couple which, in turn, will depend on the nature of the perforation of the outer barrier and exposed area of the inner barrier, the presence or absence of corrosion products and deposits, and the chemical composition of the waters present. The basis for any credit assumed to be provided by galvanic protection, and how this is incorporated into the TSPA-VA, will need to be explicitly presented.

An extended dryout period resulting from the heat output from the waste packages is a basic feature of the current design. The thermal pulse will not be uniform due to variations in the waste packages and their placement, unused or unusable areas within the repository, and edge effects around the repository. As in the findings with respect to other aspects of the proposed repository, the conceptual description of the response of the waste packages to this large and nonuniform thermal pulse is not well developed.

Water chemistry

The chemistry of heated water has been modeled but there are limited experimental data for evaluating the models that have been developed. Unfortunately, the estimates generated using the current models do not correlate well with the experimental observations. As a result, the impacts of various factors on the chemistry of water entering or within the drifts remain an area of major uncertainty. The current project strategy and activities are unlikely to resolve these problems. The determination of water chemistries once a package has been penetrated is even more uncertain**.** More laboratory and field data on water chemistry, gathered under realistic conditions, are required to refine and validate the existing models.

Transport from the Engineered Barrier System

The conceptual description of transport from the EBS is poorly developed. A critical factor is the form and amount of water transport into and from waste packages that are assumed to be perforated. There are major uncertainties regarding: (1) the number and distribution of penetrations through the packages; (2) the morphology of the penetrations; (3) the presence or absence of corrosion products or deposits within the penetrations; (4) the form and composition of corrosion products/deposits outside the penetration; and (5) the form and composition of the waste form, transformation products and other materials within the package.

Treatment of Backfill

It is the understanding of the Panel that the base case for the TSPA-VA will be the "no backfill" case. Nonetheless, the Panel also understands that backfills of various types are under active consideration by the Project team. As a result, the Panel recommends that, so far as possible, an analysis of the backfill case be included in the TSPA-VA.

Glass Waste Form Degradation and Radionuclide Release

The decision to use a response surface for the description of glass degradation and release fails to take into account an enormous amount of relevant published laboratory data, the variety of existing conceptual models for glass dissolution, and studies of natural analogues of glass dissolution that have been developed over the past twenty years. For these reasons, the Panel anticipated that the TSPA-VA team would include a rigorous comparison of these data sets to the modeled response surface. This does not appear to be the case. Although the response surface approach may be computationally efficient, mechanistic models would provide a stronger basis for long-term extrapolations of glass dissolution.

It is not clear to the Panel how models, which only have pH and silica concentration as their principal parameters, can be used to calculate solubility limits for phases that form during the alteration of glass. The model used to describe the dissolution of the glass waste forms also does not account for concentrations of chemical species (for example, the ferric ion) in the corroding solutions which may enhance the leach rates. In addition, the present model does not explicitly include estimates of the vapor phase alteration of glass.

One of the important issues identified over the past few months is the time dependent evolution of solution compositions and the structure and composition of the alteration/gel layer on the surface of corroded glass. The gel layer is now viewed as important because it can either be an efficient “sink” for rare earth elements and actinides or a source of colloids with high actinide concentrations. The potential retardation of actinides in this layer may justify a more sophisticated approach, that is, one that considers the role of the gel layer.

Prior to the breach of containers and contact with water, glass will experience an extended thermal pulse and be subjected to high fluxes of ionizing radiation. The TSPA team should evaluate whether there are any deleterious effects on the glass waste form as a result of the combined effects of these stresses. As in the other studies, the full range of types of glass waste forms anticipated to be placed in the repository need to be considered.

Disruptive Events, Criticality, and Climate Change

Volcanism

If the probabilities of the occurrence of volcanic events are so low as the hazard analyses indicate, the Project team should be able to screen out volcanism from consideration in the performance assessment on input-frequency grounds alone. If this proves to be the case, extensive work on the potential effects of various volcanism scenarios would not be necessary.

Inadvertent Human Intrusion

Given the uncertainty in what the regulatory bodies will ultimately adopt, the approach that the TSPA-VA team is taking at this time appears to be eminently sensible.

Criticality

The Panel believes that the two key elements of the approach of the TSPA team for the analysis of criticality -- allowing criticality to be studied through side analyses instead of in the mainline TSPA modeling, and developing a few scenarios for analysis in order to bound the problem -- are both sensible. The Panel commends the Project team for the logic adopted in the work being undertaken. If the consequences of criticality are so low as to make it unimportant, then the question of its analyzability may become moot.

Transport

Colloids

Evidence has recently been reported of the colloidal transport of radionuclides (^{60}Co, ^{137}Cs, Eu, and Pu) through fractured volcanic rock at the Nevada Test Site (NTS). The Panel recommends that these data be carefully analyzed to determine their applicability to the TSPA. The Panel also recommends that data available at other locations within the NTS be used to evaluate the models that have been developed to describe radionuclide transport within the proposed Yucca Mountain repository.

Biosphere and Dose

It is possible that the U.S. EPA and the USNRC will provide the Project team with specific values for the dose conversion factors and risk coefficients that are to be used in the TSPA-VA. Even so, the DOE and the Project team should seek to gain an understanding of the conservatisms that underlie, and have been incorporated into, these factors. It is also important that the team recognize additional conservatisms that may result from the use of the concept of the committed dose and the assumption of a linear dose response relationship. For these and other reasons, the Panel does not agree that the process of estimating the doses and risks from radionuclide concentrations in groundwater, and other media, is as “simple” as implied by the TSPA team. In making this recommendation, however, the Panel wants to make it clear that it is not seeking to imply that the TSPA-VA team should develop new more realistic dose conversion factors and risk coefficients; rather it is to encourage the TSPA-VA team to be aware of these conservatisms, to quantify them at least in a cursory sense, and to be prepared to discuss and evaluate their implications in terms of the outcome of the TSPA-VA.

Procedures used for identifying the critical radionuclides need to be carefully reviewed. The Panel notes that the NCRP has concluded “that ^{129}I does not pose a meaningful threat of thyroid carcinogenesis in people.” These types of issues should be analyzed and discussed with the regulators to ensure that there is a scientifically sound basis to support whatever regulations are adopted. Similar reviews should be conducted of the detailed physical, biological, and chemical information on each of the other radionuclides considered important by the TSPA-VA team. The goal should be to define a sound scientific basis for the selection of each such radionuclide.

APPENDIX A: The Fracture-Matrix Interaction: Reduction of Uncertainty

The fracture-matrix interaction: Reduction of uncertainty

by Y.C. Yortsos
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Submitted to the Review Panel of TSPA-VA, October 31, 1997

Summary

A good description of the fracture-matrix interaction is necessary to reduce uncertainties in the numerical predictions of the repository performance and in process assessment, in general. In many cases, this interaction takes the simple form of a competition between advection in the fracture network and diffusion (mass, heat, capillarity) in the matrix. The partition of flow between fracture and matrix is dictated by parameters such as the capillary diffusivity (imbibition), the area of interaction and the amount of maximum trapped saturation of the non-wetting phase (air) in the grid block volume. Reaching conditions of fracture-matrix equilibrium is controlled by the magnitude of the diffusivity, the flow rate partition and the time elapsed. In typical applications, fracture-matrix equilibrium is likely for thermal energy and for the imbibition of a high-permeability matrix, but unlikely for mass diffusion and the imbibition of a low-permeability tuff. The latter is common to many rocks of the Yucca mountain. In such cases, the assumption of equilibrium is likely to fail. In the current coarse grid simulation, the representation of this interaction is through effective parameters, notable among which is the effective area of fracture-matrix interaction, expressed through a reduction factor that reflects the limited contact resulting from channelized fracture flow. To match field data, reduction factors as low as 10^{-3} have been postulated. This is a drastic departure from previous simulation practice, where this concept was not used. Additional uncertainty, particularly for two-phase flow processes (imbibition, drainage and heat pipes), is introduced due to the volume-averaging over a number of fracture-matrix areas, inherent to the coarse description.

Main recommendations that may help reducing this uncertainty include:

1. Revisit the concept of reduction factor.

Use the experimental information reported in Glass et al. (1997) and earlier publications, on displacement patterns at various conditions, to estimate reliably the effective area (and the corresponding reduction factor). Then, account for a possible increase of the factor due to the stabilization of the displacement exerted by imbibition in the matrix. Modify the fracture hydrological parameters, particularly the relative permeabilities, to account for channelized displacement, by considering rate and gravity effects where appropriate. Allow for anisotropy in permeability, displacement and reduction factor in the fracture continuum in the horizontal and vertical directions.

2. Allow for the possibility of non-zero trapped (residual) air saturation.

Account for non-zero trapped saturation in the various lithological units, by considering the direction (imbibition) and rate of invasion. Consider the effect of large-scale trapping, due to large-scale heterogeneity in the grid block, in increasing the effective residual gas saturation. Non-zero values may lead to lower, and thus more defensible, reduction factors.

3. Improve the estimation procedure for matching field hydrologic data.

Analyze the limitations of the 1-D model (only vertical flow) currently used to match field data and estimate parameters. Allow for the possibility of lateral flow, due to capillary and flow barriers, anisotropy, etc. Study the consequences of non-uniqueness inherent to the inversion process.

4. Improve the large-scale description of two-phase flow processes.

Revisit the formalism for representing unsaturated flow in a grid block, by accounting for effective large-scale permeabilities, relative permeabilities, capillary pressures, large-scale trapped saturations and the fracture-matrix interaction. In this context, particular attention needs to be payed to the heat pipe description in this context. Consider the extension of the particle-tracking algorithm to 3-D and to other diffusive processes.

5. Justify the use of ECM for TH predictions.

Carefully delineate the validity of capillary equilibrium in ECM applications. Revisit the ECM formalism and validity in light of 1 and 2 above. Revisit the heat pipe representation.

Other recommendations are listed in the text.

The fracture-matrix interaction: Reduction of Uncertainty

The ultimate criteria for the viability assessment of the Yucca Mountain repository are the arrival times and the concentrations of potentialy released radionuclides to the biosphere and the accessible environment. These are determined by two different processes:

- The rates of release of radionuclides from the site- due to the breaching of its integrity by corrosion.
- Their transport from the repository to the accessible environment.

Both processes depend crucially on the distribution of liquid and gas flows in the mountain. The potential for canister corrosion, thus the release rate, is a function of the humidity at the repository, which is dictated by the fluid flow distribution in the mountain, in response to infiltration and the heat released from the spent fuel. In radionuclide transport, advection by flow is the predominant mechanism and controls transport rates, even at the relatively small expected infiltration rates (order of mm/year).

In such a problem, to quantitatively formulate a criterion requires:

- (i) a qualitative (physical) understanding of the factors affecting flow and transport in the subsurface;
- (ii) a characterization of the subsurface (initial conditions) and of the infiltration rates (boundary conditions) with acceptable (or at least bounded) uncertainty; and
- (iii) a mathematical (numerical) model of acceptable (or at least bounded) accuracy.

A major factor that hampers the reduction of uncertainty is the heterogeneity in subsurface properties, a basic component of which in Yucca mountain is its extensive fracturing. In this report, we will focus on this important factor, and specifically on the *fracture-matrix interaction,* in the context of the three issues noted above.

(i). Physics

In connection to the repository performance, the main physical processes of interest are:

- transport of molecular species (e.g. potentially released radionuclides or colloids)
- transport of thermal energy (due to the released heat from the waste), and
- transport of multiphase momentum, the latter being mostly imbibition from rain infiltration (drainage is also discussed below)

In the fractured mountain, these three transport processes occur by essentially similar mechanisms: mostly by advection in the fractures, and mostly by diffusion in the matrix, where fluid flows are relatively slow (see also below). Matrix diffusion includes diffusion of molecular species, heat conduction, or capillary imbibition, in the respective cases. Although different from one another (for example, imbibition is a non-linear process, it is history-dependent, it may involve additional non-diffusive phenomena, etc.) they all share common diffusive aspects. Transport is also influenced by retardation, for example the sorption of molecular species in the matrix (particularly when the formation is zeolitized), of heat in the rock matrix, or by the filtration of colloidal particles mostly in the fractures.

The transverse transport from fracture to matrix originates at the fracture-matrix boundary (see schematic of Figure 1). Thus, its rate will be influenced by the effective area of contact between fracture and matrix. We note in advance that this area is not necessarily the entire geometric fracture-matrix interface, but can be only a fraction of it (for example, when fluid flow in the fracture is channelized). The fracture-matrix interchange will also be affected by the competition between advection and diffusion. These issues are extensively discussed below.

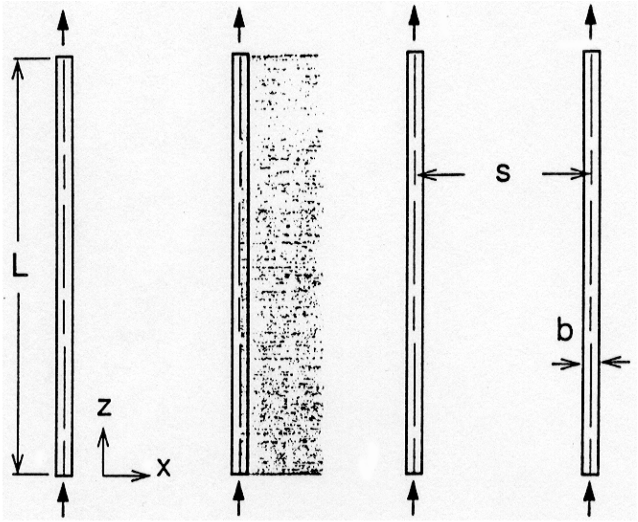

Figure 1. Simplified schematic of the fracture-matrix interface. (From Zyvoloski et al. (1997)).

The fracture-matrix interaction is fundamental to the determination of the flow distribution and transport rates, at conditions of saturated or unsaturated flow. Consider, for example, saturated (single-phase) flow. In the absence of any fracture-matrix interaction, transport will occur either in a well-connected fracture continuum of porosity ϕ_f, or in a well-connected matrix continuum of porosity ϕ_m. Assuming that the same overall amount of fluid flows in each, and that transport is dominated by advection, the ratio of the respective arrival times of an advected quantity (mass, heat, etc.) is simply

$$\frac{t_m}{t_f} = \frac{\phi_m}{\phi_f} \tag{1}$$

For typical values in the Yucca mountain, this is of the order of 100-1000 (see also Figure 2 below). When single-phase flow occurs in parallel in both the matrix and the fracture network, the ratio of fluid velocities in the fracture and the matrix, therefore the ratio of arrival times in the matrix to the fracture (again in the absence of diffusion), is

$$\frac{t_m}{t_f} = \frac{k_f}{k_m} \tag{2}$$

where k is permeability. For typical values in the Yucca mountain this ratio can be of the order of 100,000. On the other hand, in the limit when diffusion in the matrix is very strong (with a criterion to be developed below), such that fronts advance in the matrix and fracture continua at the same rate, the corresponding ratio in arrival times would be of order 1. Parenthetically, the latter is essentially a condition of *equilibrium* between matrix and fracture, and forms the basis of the widely used ECM model (see discussion below).

These simple examples show the great disparity in predicted arrival times depending on the assumed degree of the fracture-matrix interaction and the competition between advection and diffusion. Such disparity has been observed in the particle transport simulations of Robinson et al. (1997), where arrival times can vary in the range 10 years to 10,000 years. Correspondingly, depending on the strength of diffusion (heat conduction, capillarity), an analogous disparity may also apply to temperature and fluid distributions, as discussed below. In reality, arrival times will also be affected by many additional factors, such as the dispersion of flow paths in a single fracture (due to aperture variability and correlation), in the fracture network (due to branching of fractures or fracture termination or other causes of poor fracture connectivity) and in the matrix (due to permeability heterogeneity), by the strength of the diffusive process, by retardation, by conditions of unsaturated flow and by the effective area of contact between fracture and matrix. In this report, the factors pertaining to the fracture-matrix interaction will be emphasized.

Consider, first, the competition between advection and diffusion. For the case of mass and heat transport, this is expressed in terms of the Peclet number

$$Pe_i = \frac{qL}{D_i}; i = M, T \tag{3}$$

where M and T stand for mass and thermal energy respectively, D_i is the respective diffusion coefficient and L is a characteristic linear size. In the absence of restricted diffusion effects, mass diffusivity in the matrix is proportional to the species diffusivity D

$$D_M = \frac{\phi_m D}{\tau} \tag{4}$$

where τ is a tortuosity factor. Estimated typical values of D_M for transport in the liquid phase. are of the order of 10^{-10}-10^{-11} m^2/sec. (However, one must exercise caution in using this expression in very tight porous media, for example the heavily zeolitized tuff of Yucca Mountain, where diffusion will be restricted.) Thermal diffusivity in the matrix is substantially greater than mass diffusivity,

$$D_T = \frac{\lambda_H}{\rho C_p} \tag{5}$$

where λ denotes thermal conductivity and ρC_p, is volumetric heat capacity. For Yucca mountain conditions, a typical estimate of D_T is of the order of 10^{-7}-10^{-6} m^2/sec, which is three to four orders of magnitude greater than mass diffusivity in the liquid.

Diffusion control in the matrix requires that the Peclet number is smaller than unity. This can be accomplished at low velocities. For example, assuming $L = 1$ m (order of magnitude of the matrix block), mass transport in the matrix will be diffusion-controlled for velocities lower than about 3.1 mm/year. Given that this is of the order of magnitude of the currently accepted infiltration estimates and that most of the flow will actually occur in the fracture, diffusion control in the matrix is very likely. A similar dimensionless number can be defined to characterize the interaction between fracture and matrix: Assuming advection control in the fracture and diffusion control in the matrix, the competition between these two mechanisms can be expressed through the Peclet number

$$Pe_{i,f} = \frac{q_f l}{D_i}; i = M, T \tag{6}$$

where l is the matrix block size (of the order of 1 m for Yucca mountain). This number will be used below to assess the validity of the ECM model.

Consider, next, imbibition in an unsaturated matrix of a wetting liquid flowing in a saturated fracture, which is driven by the difference in the capillary pressure in the matrix and the fracture. This problem is more complex, since the flow of water and the water saturations will affect both diffusion (imbibition) in the matrix and advection. Under conditions of countercurrent flow, or if the overall fluid flow rate in the matrix is small, matrix imbibition can be approximated as nonlinear diffusion with a diffusion coefficient

$$D_c = -\frac{\phi_m k_m k_{rw}}{\mu}(dP_c / dS) \tag{7}$$

where S is liquid saturation, dP_c/dS is the slope of the capillary pressure curve at the particular saturation and μ is liquid viscosity. Since the capillary pressure is inversely proportional to the square root of the permeability by the Leverett expression, $P_c \sim \frac{\gamma}{\sqrt{k/\phi}} J(S)$ where γ is the inter-facial tension between gas and water, equation (7) gives an estimate of the magnitude of capillary diffusivity during imbibition

$$D_c \sim \frac{\gamma \phi_m^{3/2} \sqrt{k_m}}{\mu} \tag{8}$$

For example, for $\phi_m = 0.1$ and a TS tuff value of $k_m = 1\ \mu$ d (=10^{-18} m^2/sec), a value of 1.8 x 10^{-9} m^2/sec is predicted, while for a much more permeable rock with k_m = 1 d (=10^{-12} m^2/sec), the diffusivity is about 1000 times larger. Thus, capillary diffusivity depends significantly on permeability and can be of the same order of magnitude as mass diffusivity in a liquid for tight rocks or as thermal diffusivity for very porous rocks. The rather sensitive dependence of imbibition on k underscores the importance of pore-lining minerals at the matrix-fracture interface, which will act to retard matrix imbibition (and essentially restrict the fracture-matrix interaction). Although superficially analogous to mass diffusion, however, it must be also noted that imbibition is a nonlinear process and that diffusivity will change as a function of saturation and of the history of imbibition (namely whether it is primary or secondary), through the variable $k_{rw} dP_c / dS$. For example, near dry conditions (expected during re-wetting of the repository rock at the conclusion of boiling), the latter is the product of a vanishing quantity, k_{rw}, multiplied by a quantity that diverges, dP_c / dS. This shows the importance of as accurate a determination of the hydrologic matrix properties as possible.

Some simple conclusions follow: Transport in the fracture will be mostly by convection, and in the matrix mostly by diffusion (compare with (1) and (2) above). Thermal equilibrium between matrix and fracture will be set in long before mass or capillary (for the case of tight rocks) equilibrium. A thin layer of pore-lining minerals is sufficient to reduce transverse diffusion into the matrix for the case of molecular species (due to low porosity) or imbibition (due to low permeability), but not for the case of thermal energy, the conduction of which occurs mostly over the solid matrix.

Assuming advection control in the fracture and transverse diffusion control in the matrix, a simple model can be used to study the effect of diffusion on arrival times during transport. Figure

2 from Zyvolvoski et al. (1997) shows results using such a simple model for the geometry of Figure 1. (An analogous model for heat conduction was used earlier by Lauwerier, 1955, and by Yortsos and Gavalas, 1982.) In this figure, GWTT ($= L / q_f$) is the convective time in the fracture, where L is the extent of the fracture while S is the fracture spacing (equal to l above). The figure shows the retardation in the arrival times as a result of transverse diffusion in the matrix and can also be used to infer the conditions for fracture-matrix equilibrium (as discussed below). Note that the upper limit in the vertical axis is ϕ_m / ϕ_f . Using our notation, the horizontal and vertical axes in the figure are $\left[\frac{Pe_{i,f}\,l}{L}\right]^{-1/2}$ and $\frac{Pe_{i,f}\,l}{L}\frac{TD}{l^2}$, respectively.

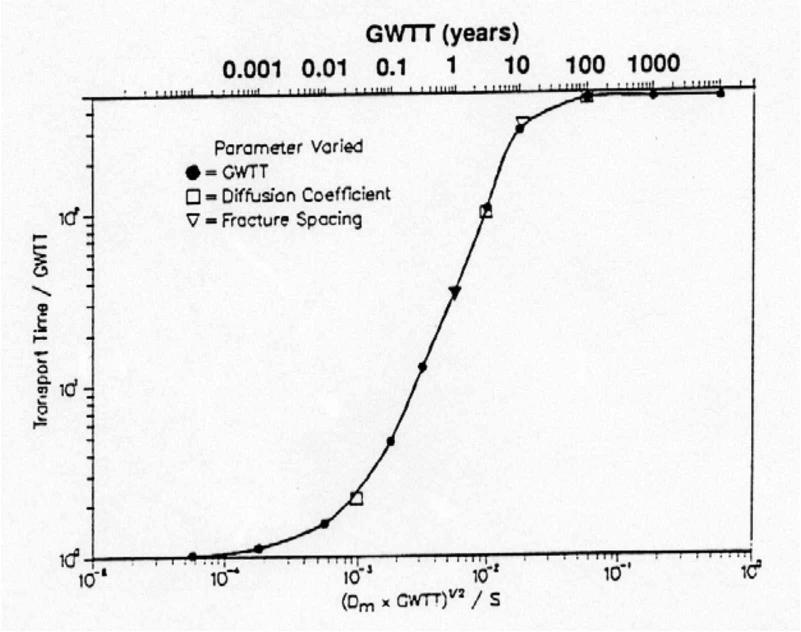

Figure 2. Arrival time for the transport of a tracer advected in the fracture and diffusing in the matrix. (From Zyvoloski et al., 1997.)

Conditions of saturated flow in the fracture (and in the matrix for that matter) will exist in the SZ far below the repository. However, in the UZ, all processes will be controlled by two-phase flow. Here, the direction of displacement is important and one needs to distinguish between drainage (in which the vapor phase, in the present context, displaces liquid), imbibition (which is the inverse process), and countercurrent flow (which will be present in heat pipes), as well as between primary and secondary drainage/imbibition. In the majority of instances in the Yucca mountain, the process of interest is secondary imbibition, resulting from water infiltration or from the condensation of vaporized liquid. However, drainage will also occur, specifically during the vaporization of liquid water near the emplaced waste. In addition, if completely dry conditions develop in the heated rock near the repository, the re-wetting of rock at the conclusion of the heating cycle will be primary imbibition, with much slower rates of matrix penetration. Finally, countercurrent flow will occur in heat pipes near the emplaced waste. The fracture-matrix interaction is a key factor dictating the distribution of fluids (hence the transport) under all these conditions.

During drainage, the non-wetting phase (e.g. the vapor) will remain in the fracture if its flow rate is not sufficiently high. Matrix penetration requires that the capillary entry pressure of the matrix (which scales as $\gamma / \sqrt{k_m}$) be exceeded. Such pressure difference can be provided by viscous (or gravity) forces in the matrix (see Haghighi et al., 1994). Under the conditions of Yucca mountain rates, however, this is rather unlikely. Thus, during drainage (e.g. boiling) the vapor phase will be present in the matrix only as a direct result of vaporization of the liquid in the matrix (and not by invasion from the fracture side). One should also recall in the present context, that vaporization of a liquid in a tight matrix requires an elevated boiling point, due to the porespace curvature (Kelvin effect). The roles of vapor phase diffusion as well as vapor flow, in this context, could also be important, but they will not be discussed here.

Whether at conditions of drainage, imbibition or countercurrent flow, the fracture-matrix interaction will also be affected by viscous and gravity forces, which play an important role in setting displacement patterns in the fracture. Consider the downwards displacement of gas by liquid in a single fracture isolated from (non-communicating with) the porous matrix. This displacement will be subject to the destabilizing effect of gravity, the stabilizing effect of viscous contrast and capillarity and the channeling in the fracture, if the aperture of the latter is spatially correlated (as it appears to be in many natural systems). The combination of these three factors will result in a fingered displacement in the fracture (see, for example, the work of Glass et al. summarized in Glass et al., 1996, 1997). Likewise, a fingering pattern will emerge in the upwards displacement of liquid by gas (for example during boiling), where now viscous instability will further promote the fingering pattern.

Fingering or channeling in the fracture will restrict the *effective area* between the fingered phase in the fracture and the matrix, therefore it is a key parameter of the fracture-matrix interaction. Depending on the extent of the correlation length, the capillary number, $Ca = \frac{q\mu}{\gamma}$, and the Bond number, $B = \frac{\Delta\rho g_x k_f}{\gamma}$, such fingering will not be amenable to the standard continuum description, e.g. using van Genuchten or Corey-Brooks parameters. Instead, rate and gravity effects (through *Ca* and *B)* and the correlation structure, must be included in its description. This problem has not yet been solved. However, we expect that the conventional approach currently used will start losing validity when *Ca* or *B* become larger than about 10^{-5}. This is likely for typical flow parameters (for example for water-air in a fracture of permeability 10^{-10} m^2, $B \sim 10^{-4}$). In addition, when infiltration is episodic, the flow may not necessarily occur continuously, but rather in the form of individual blobs of a finite extent. Fingering and channeling may also occur in the adjacent matrix. However, due to the relatively small amount of flow rate partitioned in the matrix, and the small matrix permeability, *Ca* and *B* will be sufficiently small, so that the continuum theory is expected to be applicable there.

We must note that if communication between matrix and fracture is allowed, imbibition of wetting liquid in the matrix block will act to reduce the severity of fingering. This problem is analogous to the stabilizing effect that heat losses to the adjacent formations have on the stability of a steam front during steam injection in a porous medium (Yortsos, 1982). The competition is essentially the same to that of advection vs. diffusion discussed above, and will depend on the flow rate in the fracture and the capillary characteristics of the matrix (or, essentially, on an equivalent Peclet number). To our knowledge, this problem has not been studied yet. (A different version of the same problem, but in a 2-D geometry, in which the fracture is essentially a line and fingering is not an issue, was studied by Nitao (1992), who showed the existence of a critical flow rate, q^*, above which the propagation of an advancing front in the fracture is faster than in the matrix. Essentially, Nitao 's criterion is equivalent to requesting that the process operates at the rightmost part of Figure 2 (see also discussion below regarding ECM). Pore-network simulations by Haghighi, 1994, have confirmed the existence of such transition).

When the unsaturated flow involves saturated steam (for example during boiling), steady-state heat pipes will be possible, in which there is countercurrent flow of vapor and liquid. Above the repository, vapor will move upwards, cool and condense, condensed liquid will move downwards, become heated and evaporate. Below the repository, the direction of flow is reversed. The mechanics of 1-D heat pipes are well understood, even though the precise mechanism for countercurrent relative permeabilities is not. However, in the Yucca mountain this process takes place in a fractured system. In such a system it is very likely that the vapor flow will be restricted only in the fractures, for the reasons described above. However, the return flow of liquid can be either in the matrix or in the fracture. Identifying the appropriate mechanisms and the effective fracture-matrix interaction will affect the calculation of the heat pipe extent, hence that of the dryout region.

It should be pointed out that a reduction of the effective interfacial area between fracture and matrix is possible even under conditions of saturated flow, provided that the fracture aperture distribution is heterogeneous and spatially correlated. In such cases, most of the fluid flow will take place over a backbone consisting of the largest connected apertures (e.g. see Katz and Thompson, 1986, Moreno and Tsang, 1994, Shah and Yortsos, 1996 for the corresponding porous media problem), thus diffusion into the matrix will, at least initially, occur from a substantially smaller area. This area will increase as a function of time, however, as transverse diffusion in the fracture will eventually spread the diffusing species over the entire fracture area.

(ii). Characterization

From the above it follows that the accurate characterization of the fracture-matrix interaction requires information on:

1. The hydrological characteristics of single fractures, including aperture statistics and its spatial correlation.
2. The hydrological characteristics of the adjacent matrix for drainage and imbibition cycles.
3. The effective fracture-matrix area for the various transport processes.
4. The characteristics of the network of fractures, particularly its spacing, connectivity, and the distribution of fracture permeabilities.

In present models of repository behavior, the practice currently followed for items (1) and (2) involves assigning van Genuchten parameters to match available field data or (rather sparse) laboratory data on saturation and capillary pressures (Bodvarsson et al., 1997). This approach allows for a convenient parametric representation, but is not justified from first principles (van Genuchten models were developed for drainage in soils, and may not necessarily apply to tuff or fractures or to imbibition processes). In fact, a Brooks and Corey representation, which is computationally simpler, can be used with equal justification. To our knowledge, the fracture hydrologic parameters have not been measured, but are assigned from matching field data (Bodvarsson et al., 1997; see also discussion on parameter identification below). Sonnenthal et al. (in Bodvarsson et al., 1997) proposed an indirect method, in which the variability of permeability values from pneumatic testing field data is mapped to that of mean fracture aperture, which is subsequently used to infer a van Genuchten parameter. Although based on a number of assumptions, this indirect approach can be useful and needs to be pursued further. Identifying the spatial correlation structure of fracture apertures is also important and needs to be pursued as well. In this direction, the work of Glass et al. (1996, 1997) should be useful.

Measurements of the hydrologic properties of the matrix, particularly of capillary pressure, have been conducted. It is obvious, however, that additional data are needed, particularly for relative permeabilities in imbibition and drainage, to minimize the number of parameters indirectly estimated from matching field data. Finally, an effort needs to be launched to study what effect pore-lining minerals at the fracture-matrix interface, resulting from precipitation, or their removal, resulting from dissolution reactions, will have on imbibition and diffusion into the matrix.

The effective fracture-matrix area (item (3) above) has not been independently measured or characterized. In fact, previous site-scale models (Bodvarsson and Bandurraga, 1996) did not account for such correction, even though early experimental evidence (e.g. Nicholl et al., 1992) was suggestive of a reduced area of contact. The need for a (large) reduction factor has been necessitated from the recent revised estimates of higher infiltration, which apparently can only be reconciled by an increased flow in the fracture network. Bodvarsson et al. (1997), Robinson et al. (1997) and Ho (1997) have proceeded with incorporating such a reduction factor in their studies. In current practice, the fingering pattern in the fracture (which is the origin of the reduction factor) is essentially ignored, in that standard continuum equations are used for the displacement in the fracture (using the same van Genuchten formulation for relative permeabilities and capillary pressure, regardless of flow rates, fracture orientation, etc). It should be apparent from the previous discussion that if at all, the latter would be applicable only for conventional, capillary-controlled displacement in random media, and certainly not when Ca and B are relatively large, or in cases where the fracture aperture is spatially correlated over large scales, either of which will create a channelized displacement. Despite this inconsistency, the reduction factor is used in conjuction with the standard formalism. Three different options have been considered, where the reduction factor is: (i) constant, (ii) proportional to a power of the liquid saturation in the fracture, (iii) equal to the relative permeability of the liquid in the fracture. The current consensus is that the latter option actually leads to a better match of the hydrologic field data. It must be noted that such a reduction factor will lead to an effective fracture-matrix area of interaction which can be 1000 times smaller than the geometric.

The importance of a small effective fracture-matrix area reflects the need to increase *substantially* the flow partitioned in the fracture. In essence, this is another admission of the existence of *fast paths*. Although only recently acknowledged, a reduced fracture-matrix area has a well-based physical justification, as discussed. The currently used option, based on relative permeability, however, is ad hoc and not readily justifiable. In fact, a reduction factor based on saturation is more consistent with the actual physics (although in a displacement in a prewet fracture wetting films will cover the fracture surface and may further increase the area of interaction). A recommendation for a more consistent approach is given in a later section. In defense of the approach taken, it must be pointed out that the reduction factor in coarse-grid numerical models, typically used in Yucca Mountain site-scale models, is actually an overall factor that incorporates in one parameter the combined uncertainty about the overall matrix-fracture geometry over the grid block volume, which contains several fractures. This point will be further discussed below.

With respect to item (4) above, little is known about the properties of the fracture network. Overall fracture permeabilities have been inferred from pneumatic tests, while outcrop fracture maps have also been traced (for a recent application, see Eaton et al., 1996). Current simulation practice, however, is based on the assumption of a well-connected, isotropic continuum with uniform permeabilities. In reality, one expects that due to orientation, the fracture network will actually be anisotropic, that the relative permeabilities and the flow pattern in horizontal fractures will be different than in vertical, and specifically, that patterns along horizontal fractures will be less or not at all channeled or fingered, hence the effective fracture-matrix area will also be different in different directions. An improvement of the simulation to account for these differences should be considered. Distributing permeabilities in the fracture network will result in enhanced dispersion of flow paths and should also be attempted. We note the effort to use geostatistics in the distribution of zeolite abundance, in the recent work of Robinson et al. (1997), and we believe that this approach should also be extended to the permeabilities of matrix and fracture networks.

(iii). Numerical Simulation

Currently, the simulation of the fracture-matrix interaction is handled differently, depending on the application: For the thermal-hydrologic response, due to excessively large computational requirements, use is made of the Effective Continuum Model (ECM), which proceeds with the assumption of capillary, thermal and chemical (namely mass diffusion) equilibrium between matrix and fracture, and considers the system as an equivalent continuum (for a recent thermal-hydrologic application, see Birkholzer and Tsang, 1997). For the case of species mass transport under isothermal conditions, a dual permeability (DK) model is used, in which two effective continua (the matrix and the fracture) coexist at each grid point.

Due to computational restrictions and the large-scale nature of the problem, computational grids are necessarily coarse, the typical grid block containing a multitude of fractures (see, for example, the schematics of Figure 3 reprinted from Glass et al., 1996). Advances in computational capabilities (parallel processing, for example) will lead to further reduction in grid block size. For instance, 3-D site transport models with grid block size of 50 m are now possible (Zyvoloski et al., 1997). Nonetheless, existing computer models are effectively *volume-averaging* processes oocuring over a large number of fractures, inherently containing a number of fracture-matrix interactions. For linear diffusion processes (such as molecular species and thermal energy at conditions of saturated flow) volume-averaging is relatively straightforward, and would result (for the case of the DK model) into defensible effective transport coefficients between fracture and matrix. Then, the arguments used above (and Figure 2, for example) will carry over, with appropriate geometric modifications, to the larger scale as well. However, this is not the case for two-phase flow, such as imbibition, drainage or counter-current flow, which are non-linear processes, and the averaging of which is not straightforward (particularly when capillary-end effects and capillary barriers are involved, see also Yortsos et al., 1993). In current practice, the large-scale interaction between fracture and matrix continua for unsaturated flow (for instance, in the DK model) is approximated by an effective transport coefficient, which lumps all underlying interactions, including unstable flow, the matrix-fracture effective area, capillary discontinuities, etc., into effective transport parameters coupling fracture and matrix continua. At present, this averaging process is, at best, empirical, and efforts should be made to improve its state. The same applies to the heat-pipe problem, where flows are counter-current.

The shortcomings of ECM have been addressed in previous studies (e.g. Witherspoon et al., 1996). Using the above formulation, we can delineate its applicability as follows. For equilibrium to be reached within a matrix block of linear size l, requires a characteristic time of the order of

$$t_{char} \sim l^2 / D \tag{9}$$

where D is the diffusivity appropriate to the quantity being transported (molecular species, thermal energy or capillarity) and we have assumed no reduction in the fracture-matrix area. For $l = 1$ m, this time may range between 10^6 sec (~ 10 days) to 10^{10} sec (~ 300 years), for heat conduction to mass diffusion, respectively (and where we used the previous values for diffusivities). Capillary diffusion-imbibition will fall in-between these two extremes. Now, for equilibrium between matrix and fracture to be valid, the advective flux in the fracture must be sufficiently small, so that the advected quantity has not been transported over distances larger than the matrix linear size over the same time. Otherwise stated, this implies that the Peclet number, $Pe_{i,f}$, is of order 1. (The same can also be deduced from Figure 2, where fracture-matrix equilibrium requires reaching the plateau on the rightmost part of the curve. In fact, Nitao's (1992) condition, $q^* \sim D_c$, is also equivalent to the same condition and to $Pe_{c,f} \sim 1$, if one notes that in his definition, q^* is actually

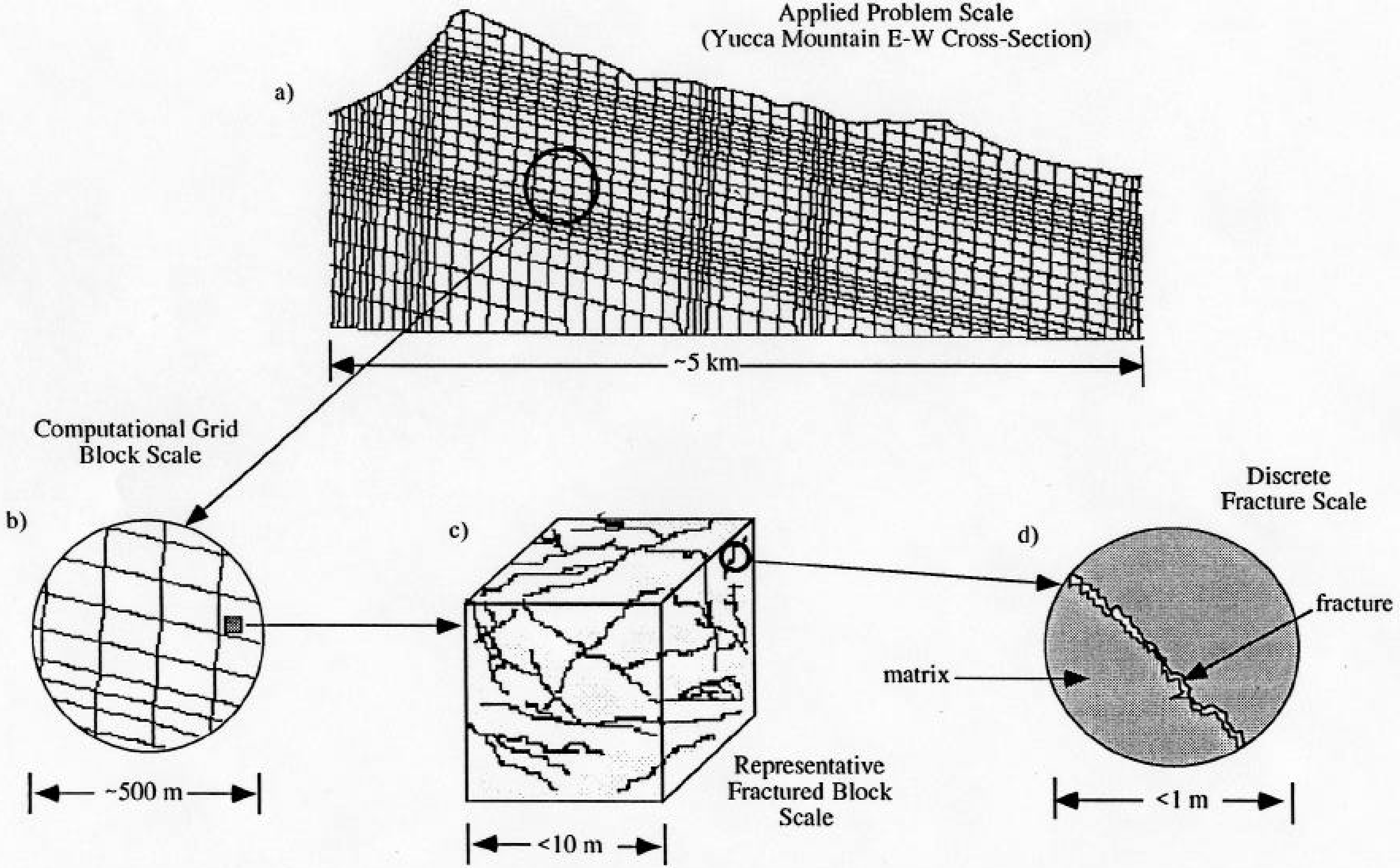

Figure 3: Averaging inherent in the use of equivalent continua models: It is neither possible nor desirable to model large field problems (a) at the scale of individual fractures (d). It is however, essential that numerical models be formulated in a manner that is consistent with the behavior of individual fractures (d) and fracture networks (c). Several discrete scales of averaging for both material properties and physical processes may be required to move from the scale of a single fracture (d) to that of a computational grid block (b).

01_fracture to grid

the product *ql.)* This leads to estimates for the maximum flow velocity in the fracture of the order of 10^{-4} cm/sec (~ 3.3x 10^{3} cm/year) to 10^{-8} cm/sec (~ 0.33 cm/year), in the respective cases, for conditions of fracture-matrix equilibrium. Current infiltration estimates are of the order of mm/year. Given, however, that flow is significantly partitioned in the fractures, and the effect of the reduced fracture-matrix interface, these limits are likely to be exceeded, at least for the case of slow diffusive transport (namely for mass diffusion or for imbibition in a tuff of small permeabilities). On the other hand, fracture-matrix equilibrium should be possible for thermal energy or for the imbibition of a high permeability matrix. The inadequacy of ECM to capture transient events of high infiltration rates was recently documented in the Fran Ridge field test (Eaton et al., 1996).

In an effort to salvage ECM, a modification was recently proposed (Ho, 1997) that effectively forces more fluid in the fracture than allowed from the original model. In this approach, the maximum water saturation in the matrix, termed the “satiated water saturation”, S_{sm}, is not set equal to one (as currently used), but becomes instead an adjustable parameter. By reducing this parameter, more flow is effectively allocated to the fracture, thus mimicking the effect of an area reduction factor. Physically, S_{sm} can be related to the trapped non-wetting phase (air in the present case) saturation, S_{nwr}, during an imbibition process, through

$$S_{sm} = 1 - S_{nwr} \tag{10}$$

In quasi-static imbibition, the trapped saturation $Snwr$ is well-defined and can be related to the pore-structural parameters of the porous medium. In fact, in the analogous problem of waterflooding a water-wet oil reservoir, S_{nwr} is the residual oil saturation, typically of the order of 0.3, which is the target of many enhanced recovery methods. In the present context, the situation may not be entirely analogous, in that trapped air may slowly dissolve in water, if the latter is not saturated, and another diffusion process may need to be considered. Nonetheless, we believe that the concept is worth studying, and, in fact, it should not be restricted to the ECM formalism alone.

In their current van Genuchten version, all site-scale models assume $S_{nwr} = 0$. In general, we expect that S_{nwr} would be a function of *Ca* (as well as *B,* in the case of gravity instabilities). High-rate imbibition in the absence of gravity instability would result in a more uniform displacement, with accordingly lower $S_{nwr.}$ Gravity instabilities would lead to effectively higher trapped non-wetting phase saturation. In addition, large-scale averaging, implicit to the coarse grids of the Yucca mountain project, leads to *large-scale trapping* (Yortsos et al., 1993), namely to macroscopically trapped saturations due to bypassing of macroscopic regions. In the context of a naturally fractured medium, this could be due to either trapped fractures or partially saturated matrix blocks. This trapping would also result in a non-zero effective $S_{nwr.}$ It follows that non-vanishing S_{nwr} should be considered in the relative permeability and capillary pressure formalisms for imbibition in the various models (TOUGH and FEHM), regardless of the mode by which they operate (ECM or DK). Such a modification can conceivably lead to more reasonable and defensible (e.g. based on fracture saturation) reduction factors. Whether, however, it would also lead to an improvement of the performance of the ECM model remains to be seen, since in comparing ECM with DK, the effect of a reduced S_{sm} should be about the same in both models.

The transport problem in the unsaturated zone below the repository and further into the water aquifer, has less severe computational demands and can be modeled by the dual permeability (DK) model. To account for the great disparity in travel times in the fracture and matrix (see equation (2)), Robinson et al. (1997) proposed a particle tracking approach, which appears to improve dramatically the computational requirements. At present, this approach is best suited for 1-D computations, however, and efforts should be made to modify it for the more challenging 3-D site-scale problem. A variant of the same method could also be considered for the imbibition problem, which shares common diffusive aspects with molecular diffusion (assuming, of course, that all other pertinent aspects of imbibition are kept under consideration).

We conclude with a comment on parameter estimation. The existing computer models have been used in an "inverse" mode to estimate parameter values by matching field data using an optimization algorithm. Bodvarsson et al. (1997) describe this approach in considerable detail. Geothermal temperature data have also been used for an indirect estimate of the percolation flux. Work along these directions is needed and these efforts should continue. At the same time, it must be pointed out that the inverse algorithm is inherently non-unique, limiting the confidence on the estimates so obtained. Furthermore, the estimation is usually done by matching field data to predictions from a model run in an 1-D mode. This effectively diregards lateral flow or transport and adds uncertainty to the relevance of the estimates so obtained. It is somewhat disconcerting, in this context, that in order to reconcile, using the present methodology, available hydrologic data with the new rain infiltration estimate, a *structural* change in the model (namely the introduction of the effective fracture-matrix interaction), was necessary. As pointed out above, in many instances this required a reduction factor of the order of 1000. In retrospect, this reduction (although not of this magnitude) being physically justifiable, should have been used before. In fact, a consideration of the effect of instabilities in the flow in fractures (although not an explicit reduction of the fracture-matrix area) was clearly pointed out in the work of Glass et al. (1996) and recommended in recommendation No. 15c of Witherspoon et al. (1996).

Conclusions and Recommendations

A good description of the fracture-matrix interaction is necessary to reduce uncertainties in the numerical predictions of the repository performance and in process assessment, in general. In many cases, this interaction takes the simple form of a competition between advection in the fracture network and diffusion (mass, heat, capillarity) in the matrix. The partition of flow between fracture and matrix is dictated by parameters such as the capillary diffusivity (imbibition), the area of interaction and the amount of maximum trapped saturation of the non-wetting phase (air) in the grid block volume. Reaching conditions of fracture-matrix equilibrium is controlled by the magnitude of the diffusivity, the flow rate partition and the time elapsed. In typical applications, fracture-matrix equilibrium is likely for thermal energy and for the imbibition of a high-permeability matrix, but unlikely for mass diffusion and the imbibition of a low-permeability tuff. The latter is common to many rocks of the Yucca mountain. In such cases, the assumption of equilibrium is likely to fail. In the current coarse grid simulation, the representation of this interaction is through effective parameters, notable among which is the effective area of fracture-matrix interaction, expressed through a reduction factor that reflects the limited contact resulting from channelized fracture flow. To match field data, reduction factors as low as 10^{-3} have been postulated. This is a drastic departure from previous simulation practice, where this concept was not used. Additional uncertainty, particularly for two-phase flow processes (imbibition, drainage and heat pipes), is introduced due to the volume-averaging over a number of fracture-matrix areas, inherent to the coarse description.

Main recommendations that may help reducing this uncertainty include:

1. <u>Revisit the concept of reduction factor</u>.

Use the experimental information reported in Glass et al. (1997) and earlier publications, on displacement patterns at various conditions, to estimate reliably the effective area (and the corresponding reduction factor). Then, account for a possible increase of the factor due to the stabilization of the displacement exerted by imbibition in the matrix. Modify the fracture hydrological parameters, particularly the relative permeabilities, to account for channelized displacement, by considering rate and gravity effects where appropriate. Allow for anisotropy in permeability, displacement and reduction factor in the fracture continuum in the horizontal and vertical directions.

2. Allow for the possibility of non-zero trapped (residual) air saturation.

Account for non-zero trapped saturation in the various lithological units, by considering the direction (imbibition) and rate of invasion. Consider the effect of large-scale trapping, due to large-scale heterogeneity in the grid block, in increasing the effective residual gas saturation. Non-zero values may lead to lower, and thus more defensible, reduction factors.

3. Improve the estimation procedure for matching field hydrologic data.

Analyze the limitations of the 1-D model (only vertical flow) currently used to match field data and estimate parameters. Allow for the possibility of lateral flow, due to capillary and flow barriers, anisotropy, etc. Study the consequences of non-uniqueness inherent to the inversion process.

4. Improve the large-scale description of two-phase flow processes.

Revisit the formalism for representing unsaturated flow in a grid block, by accounting for effective large-scale permeabilities, relative permeabilities, capillary pressures, large-scale trapped saturations and the fracture-matrix interaction. In this context, particular attention needs to be payed to the heat pipe description in this context. Consider the extension of the particle-tracking algorithm to 3-D and to other diffusive processes.

5. Justify the use of ECM for TH predictions.

Carefully delineate the validity of capillary equilibrium in ECM applications. Revisit the ECM formalism and validity in light of 1 and 2 above. Revisit the heat pipe representation.

Other recommendations are listed in the text.

References

1. Zyvoloski, G., Robinson, B.A., Birdsell, K.H., Gable, C.W., Czarnecki, J., Bower, K.M., and Faunt, C., Milestone SP25CM3A (1997).
2. Robinson ,B.A., Wolfsberg, A.V., Viswanathan, H.S., Bussod, G.Y., Gable, C.W., and Meier, A., Milestone SP25BM3 (1997).
3. Lauwerier, A.H., Appl. Sci. Res. 5,145 (1955).
4. Yortsos, Y.C. and Gavalas, G.R., Int. J. Heat Mass Trans. 25, 305 (1982).
5. Haghighi, M. Xu,'B., and Yortsos, Y.C., J. Colloid Interface Sci., 166, 168 (1994).
6. Glass, R.J., Nicholl, M.J., and Tidwell, V.C., SAND95-1824 (1996).
7. Glass, R.J., Nicholl, M.J., and Yarrington, L., SAND96-2820 (1997).
8. Yortsos, Y.C., AIChEJ 28, 480 (1982).
9. Nitao, .J.J, Proc. 2nd Annual International Conference on High Level Radioactive Waste Management, Las Vegas, NV, April 28- May 3, vol. 2, 845 (1992).
10. Haghighi, M., PhD Thesis, University of Southern California (1994).

11. Katz, A.J., and Thompson, A.H., Phys. Rev. B 34, 8175 (1987).

12. Moreno, L., and Tsang, C.-F., Water Res. Res. 30, 1421 (1994).

13. Shah, C.B., and Yortsos, Y.C., Phys. Fluids 8, 280 (1996).

14. Bodvarsson, G.S., Bandurraga, T.M., and Wu, Y.S., LBNL-40376 (1997).

15. Nicholl, M.J., Glass, R.J., and Nguyen, H.A., Proc. 3rd Annual International Conference on High Level Radioactive Waste Management, Las Vegas, NV, April 28- May 3, vol. 2, 861 (1992).

16. Eaton, R.E., Ho, C.K, Glass, R.J., Nicholl, M.J., and Arnold, B.W., SAND95-1896 (1996).

17. Birkholzer, J.T., and Tsang, Y.W., Milestone SP9322M4 (1997).

18. Witherspoon, P.A., Freeze, R.A., Kulacki, F.A., Moore, J.N., Schwartz, F.W. and Yortsos, Y.C., Peer Review Memorandum (1996).

19. Ho, C., personal communication (1997).

20. Yortsos, Y.C., Satik, C., Bacri, J.-C., and Salin, D., Transp. Porous Media 10, 171 (1993).

APPENDIX B: COMMENTS ON WASTE ISOLATION STUDY

In the course of its review of the development of the TSPA-VA, the PAPR Panel reviewed the *Waste Isolation Study*, B00000000-01717-5705-00062 REV 2 (May 13, 1997).

Although this report is in a draft stage, the Panel was concerned about some of the statements made and the approaches used. The more significant comments and observations of the Panel are summarized below.

1. During the meeting of the NWTRB Panel on Environmental Regulations (October 21, 1997), the DOE representative was careful to point out that what some people refer to as the DOE "interim standard" is not correct. He emphasized that DOE does not set standards, that what they have proposed for use is more properly referred to as an "interim post-closure performance measure," and that it was developed solely to help guide the DOE technical program. The PAPR Panel agrees that this is an important distinction. Yet, the performance measure is referred to as a "standard" throughout the Waste Isolation Study. The same error is made in the TSPA-VA "Methods and Assumptions" document (B00000000-01717-2200-00193, August 13, 1997).

2. In making decisions on which additional engineered barriers may be justified, the analysts state that (1) they will consider only those that fall within a specific cost limitation; and that (2) this approach is in accordance with the ALARA criterion. The PAPR Panel questions these statements for the following reasons:

   a) Normally an ALARA cost limitation (see, for example, 10 CFR Part 50, Appendix I, USNRC, 1976) is based on how much the collective dose to the neighboring population can be reduced as a result of a given additional expenditure to implement more effective control measures; it is not based on a percentage of the total cost of a project;

   b) Under the standard guidance on radiation protection (ICRP, 1991), the first objective is to assure that the dose rate limits are met. The ALARA criterion is applied only after this goal has been met, the purpose being to determine if dose reductions below the limits are economically justified.

The Panel believes that this portion of the Waste Isolation Study needs to be re-evaluated.

3. At the time the report was prepared, DOE had included the EPA Standards for Ground Water Protection (U.S. EPA, 1996) as a part of its interim performance measure. Although the Panel now understands that this is no longer the case, the need to protect groundwater may still be included in the standards for the proposed high-level waste repository at Yucca Mountain. Although the existing EPS Ground Water

Standards specify a limit of 5 pCi/l for ^{226}Ra and ^{228}Ra, the limit for other alpha emitting radionuclides is 15 pCi/l. For this reason, and to enable DOE to be in a position to comment on whatever regulatory requirements may be imposed, the Panel recommends that the DOE staff review the EPA Ground Water Standards in detail and:

a) Estimate the dose rate limits the Standards would impose for the key radionuclides that may be released from the proposed repository;

b) Determine whether the dose rate limit on multiple pathways, or the limits on individual radionuclides, will govern and under what conditions; and

c) Identify those cases for which the 4 mrem/y dose rate limit from man-made beta and gamma emitting radionuclides will prevail.

4. One of the radionuclides cited (page 3-13) as being a "primary contributor to dose" is ^{129}I. The NCRP (Report No. 80, 1985, page 41) has concluded that the published information suggests "that ^{129}I does not pose a meaningful threat of thyroid carcinogenesis in people." It would appear useful to review similar background information on the detailed physical, biological, and chemical information on each of the other radionuclides currently on the list of those considered important by the TSPA-VA team.

5. The comparative evaluations of the various cases and barriers are helpful. Nonetheless, the presentation of the results in several cases could be made more clear. For example:

   a) The meaning of the negative numbers in the third column of Table 3-4 needs to be explained;

   b) The information on BDCFs presented just below Table 3-5 would be improved if a column were added to indicate the BDCF for drinking the water;

   c) The title of Table 3-6 fails to mention that the quoted values are for "drinking water" and that they are expressed as "dose rates," not "doses"; and

   d) Table 4-1 could be improved through the addition of a column indicating the "APF" for each barrier.

References:

ICRP, "1990 Recommendations of the International Commission on Radiological Protection," Publication 60, International Commission on Radiological Protection, Annals of the ICRP, Vol. 21, No. 1-3 (1991).

NCRP, “Induction of Thyroid Cancer by Ionizing Radiation,” National Council on Radiation Protection and Measurements,” Report No. 80, Bethesda, MD (1985).

U.S. EPA, “Drinking Water Regulations and Health Advisories,” Report EPA 822-B-96-002, U.S. Environmental Protection Agency, Washington, DC (October, 1996).

USNRC, “Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion ‘As Low As Reasonably Achievable’ for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents,” Title 10, Code of Federal Regulations, Appendix I, U.S. Nuclear Regulatory Commission, Washington, DC (1976).

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ACRONYMS AND ABBREVIATIONS

CFR	Code of Federal Regulations
CRM	corrosion resistant metal
CRWMS	Civilian Radioactive Waste Management System
DCF	Dose Conversion Factor
DHLW	Defense High Level (radioactive) Waste
DOE	U.S. Department of Energy
DKM	dual permeability model
DQO	data quality objective
EBS	Engineered Barrier System
ECM	equivalent continuum model
ECRB	Enhanced Characterization of the Repository Block
Eh	oxidizing potential
EPA	U.S. Environmental Protection Agency
ESF	Exploratory Studies Facility
HLRW	high-level radioactive waste
ICRP	International Commission on Radiological Protection
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
M&O	Management and Operating Contractor
MIC	microbially induced corrosion
MTHM	metric tons heavy metal
NCRP	National Council on Radiation Protection and Measurements
NWTRB	Nuclear Waste Technical Review Board
pH	measure of the hydrogen ion concentration or level of acidity
PSHA	probabilistic seismic hazard analysis
PTn	Paintbrush nonwelded tuff layer
PVHA	probabilistic volcanic hazard analysis
RBE	(first use, page 58, need spelling here and there)
SCC	stress corrosion cracking
SNF	spent nuclear fuel
SZ	saturated zone
THCM	thermo-hydro-chemical-mecanical
TSPA	Total System Performance Assessment
TSPA-95	TSPA completed in 1995
TSPA-VA	TSPA supporting the Viability Assessment
TSw	Topopah Spring welded tuff layer
USGS	U.S. Geologic Survey
USNRC	U.S. Nuclear Regulatory Commission
UZ	unsaturated zone
VA	Viability Assessment
WF	waste form
WIPP	Waste Isolation Pilot Plant
WP	waste package

REFERENCES

Baca, R.G. and R.D. Brient. 1996. Total System Performance Assessment 1995 Audit Review. Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas (September, 1996).

Bair, William J., 1997. "Radionuclides in the Body: Meeting the Challenge," Lauriston Taylor Lecture, *Health Physics*, Vol. 73, No. 3, pages 423 - 432 (September, 1997).

Bates, J.K., J.P. Bradley, A. Teetsov, C.R. Bradly, M. Buchholtz ten Brink. 1992 Colloid formation during waste form reaction: Implications for nuclear waste disposal. *Science*, vol. 256, 649-651.

Bethke, C.M., *Geochimica et Cosmochimica Acta*, 56, 4315, 1992.

Birkholzer, J.T. and Y.W. Tsang. 1997. Pretest Analysis of the Thermal-Hydrological Conditions of the ESF Drift Scale Test. Ernest Orlando Lawrence Berkeley National Laboratory, Level 4 Milestone SP9322M4, June 1997.

Blair, S.C., P.A. Berge, and H.F. Wang. 1997. Bounding Models for Estimating Changes in Fracture Permeability due to Thermo-Mechanical Stresses in Host Rock Surrounding the Repository, I: Permeability Changes Estimated for the Heated Drift Test. YMSCP Deliverable SPLF3M4, Aug. 15, 1997.

Bodvarsson, G.S. and T.M. Bandurraga, eds. 1996. Development and Calibration of the Three-Dimensional Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, Ernest Orlando Lawrence Berkeley National Laboratory Report., LBNL-39315, 563 pages.

Bodvarsson, G.S., T.M. Bandurraga, and Y.S. Wu, eds. 1997. The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment. Ernest Orlando Lawrence Berkeley National Laboratory Report, LBNL-40376.

Bodvarsson, G.S., T.M. Bandurraga, and Y.S. Wu, eds. 1997a. The Site-Scale Unsaturated Model of Yucca Mountain, Nevada, for the Viability Assessment. Ernest Orlando Lawrence Berkeley National Laboratory Report, LBNL-40376.

Bodvarsson, G.S., T.M. Bandurraga, C. Haukwa, E.L. Sonnenthal, and Y.S. Wu. 1997b. Summary of the Unsaturated Zone Site-Scale Model for the Viability Assessment in The Site-Scale Unsaturated Model of Yucca Mountain, Nevada, for the Viability Assessment. Ernest Orlando Lawrence Berkeley National Laboratory Report, LBNL-40376, Chap. 1.

Costin, L. 1997. Thermal/Mechanical Observations from the Single Heater Test, Report presented at Workshop on Significant Issues and Available Data, Near-Field/Altered Zone Coupled Effects, Expert Elicitation Project, South San Francisco, CA, Nov. 5-7, 1997.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1995. *Total System Performance Assessment - 1995: An Evaluation of the Potential Yucca Mountain Repository*, B00000000-01717-2200-00136, Rev. 01, TRW Environmental Safety Systems, Inc., Las Vegas, NV.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1996a. *Test Design, Plans and Layout Report for the ESF Thermal Test*, BAB000000-01717-4600-00025 REV 01, TRW Environmental Safety Systems, Inc., Las Vegas, NV, September 20, 1996.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1996b. Scientific Investigation Implementation Package for Developing Biosphere Dose Conversion Factors, Las Vegas, NV, December 4, 1996.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1996c. *Probabilistic Volcanic Hazard Analysis for Yucca Mountain*, Nevada, BA0000000-1717-2200-00082, Rev. 0, June 1996.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1996d. *Description of Performance Allocation*, B0000000-01717-2200-00177, Rev. 00, August 15, 1996.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1997a. *Total System Performance Assessment - Viability Assessment (TSPA-VA) Methods and Assumptions*, B00000000-0171-2200-00193, TRW Environmental Safety Systems, Inc., August 13, 1997.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1997b. Biosphere Abstraction/Testing Workshop Results, Las Vegas, NV (August 14, 1997).

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1997c. *Construction of Scenarios for Nuclear Criticality at the Potential Repository at Yucca Mountain*, Nevada, B0000000-01717-2200-00194, September, 1997.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1997d. *Waste Isolation Study*, B00000000-01717-5705-00062 REV 2, May 13, 1997.

DOE (U.S. Department of Energy). 1995. *In Situ* Thermal Testing Program Strategy, DOE/YMSCO-003. Las Vegas, NV.

Ebert, W.L. 1997 Overview of Glass Testing Program to Support Waste Acceptance. Presentation at ANL on November 14, 1997.

Edwards, Alan, 1997. "RBE Values for Neutron Radiations," Radiological Protection Bulletin, National Radiological Protection Board, United Kingdom, No. 193, pages 7 - 8 (September, 1997).

EPA (U.S. Environmental Protection Agency). 1985. "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," Title 40, Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, Washington, DC (September 19, 1985).

Fabryka-Martin, J.T., A.L. Flint, D.S. Sweetkind, A.V. Wolfsberg, S.S. Levy, G.J.C. Roemer, J.L. Roach, L.E. Wolfsberg, and M.C. Duff. 1997. Evaluation of Flow and Transport Models of Yucca Mountain, Based on Chlorine-36 Studies for FY97. Los Alamos National Laboratory, YMP Milestone Report SP2224M3.

Flint, A.L., J.A. Hevesi, and L.E. Flint. (in preparation). Conceptual and numerical model of infiltration for the Yucca Mountain area, Nevada. U.S. Geological Survey Water-Resources Investigation Report, MOL. 19970409.0087, GS960908312211.003, U.S. Geological Survey, Denver, CO.

Flint, L.E. and A.L. Flint. 1994. Spatial distribution of potential near surface moisture flux at Yucca Mountain. *Proceedings of the Fifth Annual International Conference on High Level Radioactive Waste Management*, Las Vegas, NV, May 22-26, 1994, pp. 2352-2358.

Gdowski, G.E. 1991. Survey of Degradation Modes of Four Nickel-Chromium-Molybdenum Alloys, UCRL-ID-108330, March 1991.

Geckeis, H., R. Klenze and J.I. Kim (in press) Solid-water interface reactions of actinides and homologues: sorption on mineral surfaces. Presented at Actinide '97 in Baden-Baden.

Glass, R.J., M.J. Nicholl, and L. Yarrington. 1997. Development and Experimental Evaluation of Models for Low Capillary Number Two-Phase Flows in Rough Walled Fractures Relevant to Natural Gradients. Sandia National Laboratory, SAND96-2820, September 1997.

Glassley, W., J. Johnson, K. Knauss, and L. DeLoach. 1997. Near-Field/Altered Zone Mineral Alteration, Report presented at Workshop on Significant Issues and

Available Data, Near-Field/Altered Zone Coupled Effects, Expert Elicitation Project, South San Francisco, CA, Nov. 5-7, 1997.

Grambow, B. (in press) Source Terms for Performance Assessment of HLW-Glass and Spent Fuel as Waste Forms. Materials Research Society Symposium on the Scientific Basis for Nuclear Waste Management, Davos, Switzerland, 1997.

Grenthe, I. et al., *Chemical Thermodynamics of Uranium*, North-Holland, Amsterdam, 1992.

Hevesi, J.A., A.L. Flint, and L.E. Flint. 1994. Verification of a one-dimensional model for predicting shallow infiltration at Yucca Mountain. *Proceedings Fifth Annual International Conference on High Level Radioactive Waste Management*, Las Vegas, NV, May 22-26, 1994, pp. 2323-2332.

Ibaraki, M. and E.A. Sudicky (1995) Colloid-facilitated contaminant transport in discretely fractured porous media 1. Numerical formulation and sensitivity analysis. *Water Resources Research*, vol. 31, no. 12, pp. 2945-2960.

ICRP (International Commission on Radiological Protection). 1997 “Recommendations of the International Commission on Radiological Protection,” ICRP Publication 26, *Annals of the ICRP*, Vol. 1, No. 3.

ICRP (International Commission on Radiological Protection) 1989. “Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 1,” ICRP Publication 56, *Annals of the ICRP*, Vol. 20 No. 2.

ICRP (International Commission on Radiological Protection) 1991 “1990 Recommendations of the International Commission on Radiological Protection,” ICRP Publication 60, *Annals of the ICRP*, Vol. 21 No. 1-3.

ICRP (International Commission on Radiological Protection) 1993 “Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 2 – Ingestion Dose Coefficients,” ICRP Publication 67, *Annals of the ICRP*, Vol. 23 No. 3/4.

Kersting, A.B. and J.L. Thompson. 1997. Near-field migration of radionuclides in the subsurface at the Nevada Test Site: Evidence for colloid transport of radionuclides through fractured volcanic rock. 214th American Chemical Society meeting Las Vegas, NV, Sept 7-11, 1997 ACS Division of Nuclear Chemistry and Technology section . The session was Future Directions in Radioactive and Mixed Waste Management, paper #76.

Kim, J.I. 1991. Actinide colloid generation in groundwater. *Radiochimica Acta*, vol. 52/53, pp. 71-81.

Kim, J.I. 1994. Actinide colloids in natural aquifer systems. Materials Research Society Bulletin, vol. XIX (12), pp. 47-53.

Konikow, L.F. and M. Person. 1985. *Water Resources Research*, 21, 1611.

Konikow, L.F. and E.P. Patten, Jr. 1985. *Hydrological Forecasting*, M.G. Anderson and T.P. Burt, Eds., John Wiley & Sons Ltd., pp. 221-270, New York.

Konikow, L.F. 1986. *Ground Water*, 24, 173(2).

Lichtner, P.C. 1993. *American Journal of Science*, 293, 257.

Lin, W., J. Roberts, W. Glassley, and D. Ruddle. 1997. Fracture and Matrix Permeability at Elevated Temperatures, Report presented at Workshop on Significant Issues and Available Data, Near-Field/Altered Zone Coupled Effects, Expert Elicitation Project, South San Francisco, CA, Nov. 5-7, 1997.

McKinley, I.G. and W.R. Alexander. 1992. *Waste Management*, 12, 253.

Menard, O., T. Advocat, J.P. Ambrosi, and A. Michard. in press. *Applied Geochemistry*, 1998.

NCRP (National Council on Radiation Protection and Measurements). 1995. “Principles and Application of Collective Dose in Radiation Protection,” Report No. 121, Bethesda, MD.

NCRP (National Council on Radiation Protection and Measurements) 1985 “Induction of Thyroid Cancer by Ionizing Radiation,” Report No. 80, Bethesda, MD.

Nordstrom, D.K., *Proceedings of the 5th CEC Natural Analogue Working Group Meeting*, Oct. 5-9, 1992, EUR Report 15176 published by the CEC. 1994.

National Research Council. 1990. *Health Effects of Exposure to Low Levels of Ionizing Radiation*, BEIR V Report, Committee on the Biological Effects of Ionizing Radiation, National Academy Press, Washington, DC.

National Research Council. 1995. *Radiation Dose Reconstruction for Epidemiologic Uses*, Committee on an Assessment of CDC Radiation Studies, National Academy Press, Washington, DC.

National Research Council. 1995. *Technical Bases for Yucca Mountain Standards*, Committee on the Technical Bases for Yucca Mountain Standards, National Academy Press, Washington, DC.

NWTRB (Nuclear Waste Technical Review Board). 1997. Transcript of a “Meeting of the Panel on Environmental Regulations and Quality Assurance,” Fairfax, Virginia (October 21, 1997).

O’Connell, W.J., W.L. Bourcier, J. Gansemer, and T.-S. Ueng. 1997. Performance Assessment Modeling for Savannah River Glass HLW Disposal in a Potential Repository at Yucca Mountain. Symposium on Science and Technology for Disposal of Radioactive Tank Wastes, American Chemical Society National Meeting. DRAFT UCRL-JC-127352.

Olsson, W.A. and S.R. Brown. 1994. Mechanical Properties of Seven Fractures from Drillholes NRG-4 and NRG-6 at Yucca Mountain, Nevada, Sandia National Laboratories Report, SAND94-1995, Albuquerque, NM.

Oreskes, N., K. Shrader-Freschette, and K. Belitz, 1994. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences, *Science*, vol. 263, pp. 641-646.

Raven, K.G. and J.E. Gale. 1985. Water flow in a natural rock fracture as a function of stress and sample size. *Int. J. Rock Mech. Min. Sci. and Geomech*., Abstr. Vol. 22, No. 4, pp. 251-261.

Savage, David (editor). 1995. *The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Waste* (John Wiley & Sons) pp. 164-165.

Strachan, D.M. and T.L. Croak, In press. The Dependence of Long-Term Dissolution on Glass Composition, to be presented at the 1998 International High-Level Radioactive Waste Management Conference, Las Vegas, NV, May 11-14, 1998.

Strachan, D.M., B.P. McGrail, M.J. Apted, D.W. Engle, P.W. Eslinger. 1990. Preliminary Assessment of the Controlled Release of Radionuclides from Waste Packages Containing Borosilicate Waste Glass. PNL-7591, UC-802.

Tsang, Y. 1997. Thermal-Hydrological Processes at the ESF Single-Heater Test – Observations and Modeling. Report presented at Workshop on Significant Issues and Available Data, Near-Field/Altered Zone Coupled Effects, Expert Elicitation Project, South San Francisco, CA, Nov. 5-7, 1997.

USNRC (U.S. Nuclear Regulatory Agency) 1983. “Disposal of High-Level Radioactive Waste in Geologic Repositories,” Title 10, Code of Federal Regulations, Part 60.101 (a)(2), U.S. Nuclear Regulatory Commission, Washington, DC.

Weber, W.J., R.C. Ewing, C.A. Angell, G.W. Arnold, A.N. Cormack, J.M. Delaye, D.L. Griscom, L.W. Hobbs, A. Navrotsky, D.L. Price, A.M. Stoneham and M.C. Weinberg. 1997. Radiation effects in glasses used for immobilization of high-level waste and plutonium disposition. *Journal of Materials Research*, vol 12(8), 1946-1975.

Whipple, C., R. Budnitz, R. Ewing, D. Moeller, J. Payer, and P. Witherspoon. 1997. First Interim Report, Total System Performance Assessment Peer Review Panel, prepared for Civilian Radioactive Waste Management and Operating Contractor, Las Vegas, NV. June, 20, 1997.

Witherspoon, P.A. and N.G.W. Cook. 1979. Thermomechanical experiments in granite at Stripa, Sweden, Proceedings, First Annual Information Meeting, Office of Nuclear Waste Isolation, Columbus, OH, Oct. 31-Nov. 1, 1979.

Wu Y.S., J.H. Li, and G.S. Bodvarsson. 1997. Percolation flux analysis using the UZ model. The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment. Bodvarsson, G.S., T.M. Bandurraga, and Y.S. Wu, eds. Ernest Orlando Lawrence Berkeley National Laboratory Report., LBNL-40376, Chap. 20.