Enclosure 6

THIRD INTERIM REPORT

TOTAL SYSTEM PERFORMANCE ASSESSMENT PEER REVIEW PANEL

June 25, 1998

Peer Review of the
Total System Performance Assessment-Viability Assessment

Third Interim Report

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Preface

The members of Total System Performance Assessment Peer Review Panel greatly appreciate the helpfulness and cooperation of the DOE staff and contractors responsible for developing the TSPA-VA and their willingness to respond in a positive manner to members' requests for information and to the Panel's recommendations. We are pleased to note the increasingly improved quality of the graphic and written material being produced by the staff. Such material is essential to help interested readers grasp very complicated information without becoming overwhelmed by details or being forced to conduct extensive searches for specific information.

In addition to the assistance provided to the Panel by the TSPA team and other technical staff contributing to the TSPA-VA, we are very pleased to acknowledge three people for their contributions to our review. Susan Wiltshire serves as the Panel's technical secretary, and contributes significantly through her organizational skills, her ability to communicate clearly, and her ability to pay attention to both the overall effort of the review and the many details involved. Yanis Yortsos has been a consultant to the Panel and has contributed substantially to many areas of the review, especially those related to the analysis of thermohydrology and the unsaturated and saturated zone flow. Finally, Tom Rodgers has been our point of contact with the Management and Operating Contractor for over a year. His assistance on many organizational and administrative matters associated with the Panel's activities has been skilled and responsive.

The Panel's first three reports are interim reports that review on-going work. Frequently, the Panel has not had completed documentation to review on some topics. In other cases, documentation has become available as the Panel's reviews were being completed. This was the case with the predecisional draft of the Viability Assessment of the Yucca Mountain Repository Site Volume 3: Total System Performance, which the Panel received in early June. Although its review to date has been limited, the Panel has been impressed with this document which appears to represent a significant improvement over previous drafts. In addition, this draft report was helpful to the Panel in defining the final details of the TSPA-VA Base Case. However, due to time limitations, the Panel is unable to provide a comprehensive review of its contents at this time.

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Executive Summary

This is the third interim report of the Performance Assessment Peer Review Panel, whose objective is to provide a formal, independent evaluation and critique of the Total System Performance Assessment supporting the Viability Assessment (TSPA-VA) for the proposed high level radioactive waste repository at Yucca Mountain, Nevada. Panel comments in Report 3 are based primarily on draft chapters, provided in March, 1998, that contained supporting technical details on many aspects of the TSPA-VA. Panel comments are also based on presentations by TSPA-VA project staff, and interactions and discussions Panel members have had with the staff. The Panel received a copy of the Predecisional Draft of Volume 3: Total System Performance of the Viability Assessment of the Yucca Mountain Repository Site in early June, as this report was being completed. Although its review to date has been limited, the Panel has been impressed with this document which appears to represent a significant improvement over previous drafts. However, it contains changes that Panel members have not had time to evaluate and/or discuss. For this reason, the Panel is not prepared to comment on this document at this time.

The TSPA-VA base case analysis has clearly proved beneficial in helping the project staff plan for the preparation of the TSPA-LA. This is especially true for identifying what needs to be modeled and clarifying how the various components of the natural and man-made barriers of the proposed repository will interact. In the course of its review, the Panel has been pleased to note that the DOE staff and contractors responsible for developing the TSPA-VA have been extremely cooperative in conveying what they are doing, and they have responded in a positive manner on those matters where the Panel has sought additional details on the approach being used.

Panel members clearly recognize the difficulty of the task faced by the TSPA-VA staff and observe that most members of the staff appear to be well qualified and dedicated to the work they are doing. Panel members have benefited from interactions with them.

On balance, the TSPA-VA analysis shows improvement in the performance assessment over the 1995 TSPA, and in fact, shows significant improvements, especially in the clarity of the approach and findings, since the Panel's Second Report was written six months ago. These improvements notwithstanding, much work remains to be done. The deficiencies observed by the Panel in the technical aspects of the TSPA-VA include a lack of site-specific data as input into the analyses; the application of models without recognition of their limitations (especially in the saturated zone); the incorporation of assumptions into the analyses without adequate documentation and support; and inadequate recognition and/or assessment of the uncertainties associated with the analyses. In addition, there are expenditures of excessive amounts of time on detailed analyses of low probability events, such as the potential impacts of volcanoes; and failure to keep in mind, as exemplified by the biosphere analyses, the goals of the analytical effort, namely to identify the important radionuclides that will potentially be released from the repository, the primary pathways through which they will lead to exposures to offsite populations, and the projected dose rates that will result.

The Panel has encouraged the TSPA staff to emphasize, in future work, analyses within the first 10,000 years, as contrasted to the 10,000 to one million year time span that appears to the Panel to be the focus of the current TSPA-VA.

The current TSPA analysis indicates that substantial isolation is provided by the waste package and by cladding. The Panel recommends that high priority be given to obtaining the experimental data necessary to support the modeling of these barriers. Without a solid experimental basis for the models used for the waste package and cladding, unsupported and optimistic assumptions may be the basis of projected performance. Where performance is sensitive to such assumptions, separate analyses for alternative assumptions should be included. For example, the analysis should include the case in which it is assumed that the cladding on spent nuclear fuel provides no barrier to radionuclide releases; this would provide insights into how the different barriers within the proposed repository will function. It will also provide an increased understanding of the key elements in the defense-in-depth strategy.

I. Introduction

In this section the Performance Assessment Peer Review Panel (the Panel) discusses the nature of the Total System Performance Assessment (TSPA) peer review process, summarizes the contents of its two previous reports, and describes 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 Panel has been asked to conduct a phased review over a two-year period during the development, conduct, and completion of the TSPA-VA.

This is the third interim report of the Panel, the last of the interim reports scheduled to be issued prior to completion of the TSPA-VA. In the spring of 1998, the TSPA-VA analysis was frozen to permit documentation of the TSPA-VA report by the scheduled release date in late 1998. As a consequence, all comments in this peer review report, in which alternative assumptions or analytical methods are suggested, are intended for consideration for the TSPA analysis used for a license application (TSPA-LA). After the TSPA-VA is complete, the Panel will formally review it and prepare a final peer review report. The current plan is to submit that report by December 31, 1998.

B. Content of Interim Reports

First Report

In its first report (Whipple et al., 1997a.), 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 (NRC).

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

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

Second Report

The second report (Whipple et al., 1997b.), submitted on December 12, 1997, did not repeat comments made in the first report, except where the Panel amplified, extended, or revised its previous comments. The report covered two general areas: general topics that were not covered in depth in the first report and specific issues that the Panel selected because of their potential significance to the results of the TSPA-VA. In addition, the Panel:

- Discussed its view of the role of the TSPA-VA, the expectations that may reasonably be set for the TSPA-VA, and how results are being interpreted and limitations and uncertainties are being addressed.

- Described in more detail its understanding of how the processes and events that could affect the future performance of a repository at Yucca Mountain were being analyzed in the TSPA.

- Presented a summary of the Panel's findings to date.

The first two Panel reports are available online at http://www.ymp.gov/toc/viability.html.

Third Report

As was previously the case, this report should be considered an extension, not a revision, of the first two reports. Comments are not repeated unless the Panel has amplified, extended, or revised the results of its previous reviews. Not all significant issues are covered. In some cases, the Panel was unable to comment because the supporting documentation does not exist. In fact, in some cases the chapters that document the final TSPA-VA analysis are not yet available, a primary example being coverage of the effects of external events. In addition, analyses of the potential benefits of spent fuel cladding have been added to the base case, and the saturated zone model has been completely changed. Where the Panel comments on these types of issues, the reviews and evaluations were based primarily on presentations by, and discussions with, members of the project staff.

Draft chapters providing supporting technical details on many aspects of the TSPA-VA were provided to the Panel in March, 1998. The Panel received a copy of the Predecisional Draft Viability Assessment of the Yucca Mountain Repository Site, Volume 3: Total System Performance (CRWMS M&O.1998h, in review) in early June, as this report was being completed.

In Section II, the Panel discusses how the TSPA-VA project staff describes the way the repository would work based on what is called the "base case" analysis. Section II also reviews the importance to the current analysis of focusing on early canister failures and other events that could lead to releases and doses within 10,000 years; and considers the methodology being used for sensitivity analysis.

In Section III, the Panel describes its understanding of how the processes and events that could affect the long-range performance of a repository at Yucca Mountain are being analyzed in the TSPA-VA. As in the two previous reports, the discussion follows the major elements examined in the TSPA-VA analysis: (1) initial conditions of the site; (2) conditions as affected by the repository; (3) isolation as provided by the geologic setting in which the proposed repository is to be located, (4) isolation as provided by the waste form and the engineered barrier system; (5) release and transport of radionuclides from the repository; (6) the biosphere, dose rates, and health risks; and (7) disruptive events and climate. (See Figure I-1).

In Section IV, the Panel presents its conclusions and recommendations based on material presented in Sections II and III. After some introductory comments, the Panel presents some key aspects for consideration about the TSPA-VA, a few critical observations, and some of the Panel's more important findings.

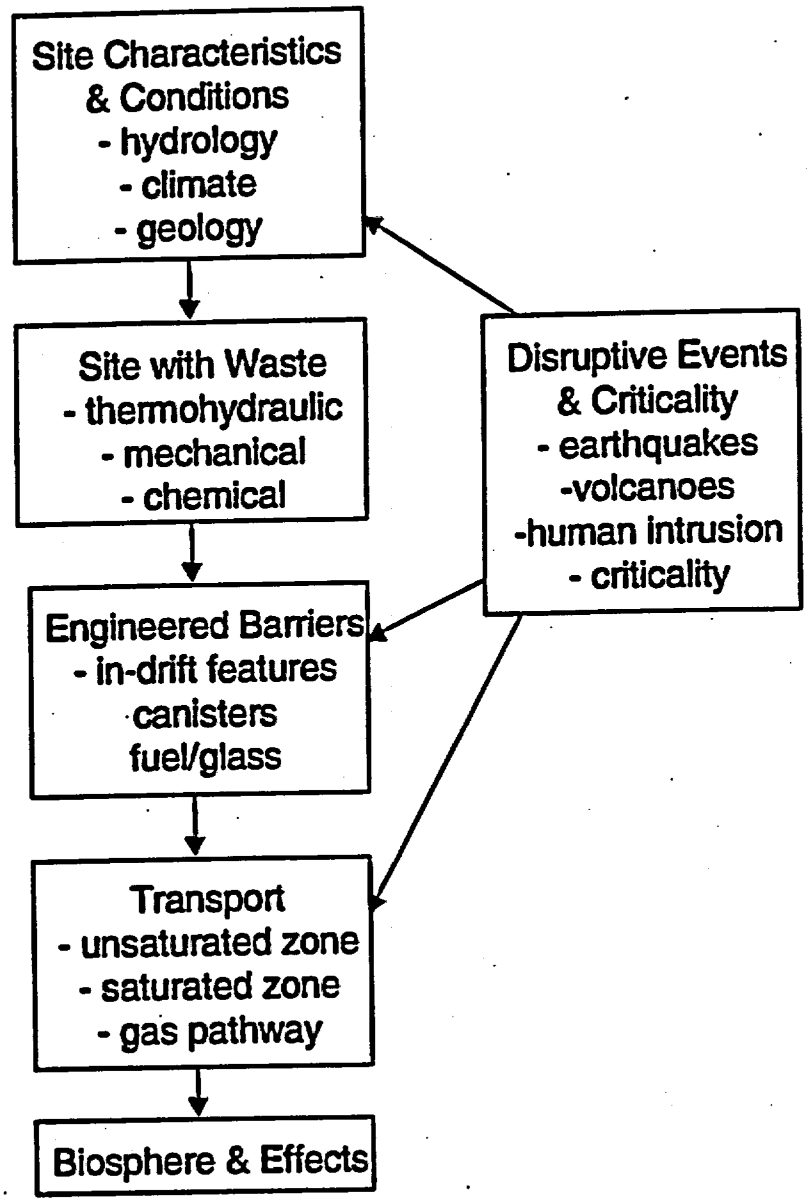

Figure I-1. Organization of TSPA-VA Peer Review.

II. The TSPA-VA Base Case Analysis

The potential repository analyzed by the TSPA-VA was designed to protect public health by: (1) isolating radioactive wastes to permit decay to reduce the radionuclide inventory in the waste; and (2) controlling the release rates of radionuclides to limit dose rates. The TSPA-VA provides estimates of the concentrations of radionuclides in groundwater that would occur over time and the corresponding dose rates that would result, at a specified distance from the repository.

This section summarizes some of the major performance elements of the TSPA-VA. The Panel's purpose in describing these elements is to review and evaluate the analytical findings that are addressed in more detail in Section III. In addition, this section addresses the TSPA-VA sensitivity studies and comments on the applicability of the analysis of performance for the first 10,000 years after closure.

A. Results of the TSPA-VA Base Case Analysis

After conducting the TSPA analysis, the TSPA staff found that the following potential repository features can be expected to significantly delay or limit the rate of radionuclide releases:

- Placement of the wastes in the unsaturated zone, well above the water table, at a site with relatively limited infiltration of water. The assumptions regarding infiltration are highly sensitive to the assumptions about future climate.

- An initial hot, dry period during which the surface temperatures of the waste packages exceed boiling. The TSPA analysis indicates that this period would be expected to last from several hundred to several thousand years.

- Corrosion resistant waste packages. The TSPA-VA staff estimates that the earliest failures of the waste packages will occur as a result of corrosion pits at approximately 3,000 years and by corrosion patches (that is, holes measuring hundreds of square centimeters in area) in the waste packages at about 10,000 years. The TSPA-VA estimate is that about 1% of the waste packages will be breached at 10,000 years. In addition to the failures induced by corrosion, the TSPA-VA staff assumes that one package of commercial spent fuel will fail at 1,000 years due to other causes.

- Cladding of commercial spent fuel. No performance credit is taken in the analysis for spent fuel with stainless steel cladding or cladding that is degraded at the time of disposal, which is estimated to comprise somewhat less than 2% of the commercial spent fuel. The TSPA-VA staff estimates that corrosion and mechanical damage will cause the cladding on the remaining fuel to fail, but at times far in the future, that is, failures beginning after some 50,000 years. Ten percent of the cladding is estimated to have failed by 200,000 years.

- Transport through the unsaturated zone. The transport time is quite sensitive to the assumed flux rate of water through Yucca Mountain. The flux rate is based on the assumed climatic conditions. Transport also depends on the sorption properties of the radionuclides. For the current climate, the travel time through the unsaturated zone in the case for technetium-99 (which is assumed not to be retarded by sorption) is estimated to be several thousand years. Under the wetter "long term average" climate scenario, the estimated unsaturated zone transport time for this radionuclide is reduced to several hundred years.

- Transport in the saturated zone. For non-sorbing radionuclides (e.g., technetium-99, iodine-129, carbon-14), transport to the Armagosa Valley through this segment of the environment is estimated in the TSPA analysis to require around 1,000 years. For other radionuclides, such as plutonium, saturated zone travel times are estimated to be 30,000 years or more.

- Low solubility of neptunium-237. The rate at which neptunium-237 is released will be limited by its low solubility. In addition, neptunium is assumed to be retarded during transport. Thus, neptunium-237 is not projected to contribute to doses within the first 10,000 years. At times in excess of 50,000 years, the TSPA-VA indicates that the dose rate is dominated by neptunium-237. At this point, the estimated concentrations of this radionuclide will be proportional to the product of the assumed solubility, the assumed water flux rate through Yucca Mountain, and the fractions of cladding and waste packages that have been assumed to have failed.

- Low solubility and sorption of plutonium. Plutonium releases will be limited by both low solubility and sorption on materials, such as clays and zeolites, along the flow pathway. Due to these characteristics, the TSPA finds that the potential for plutonium to be transported as a component of colloids is more significant than its transport as a dissolved phase.

The site for the proposed repository is in an area that is currently sparsely populated. Dose estimates were calculated at a distance of 20 kilometers from the repository, the closest distance at which sizable population groups reside. The magnitude of this distance results in longer travel times and larger dispersion than might be associated with a site in a more heavily populated area. Remaining to be confirmed are the applicable regulatory requirements concerning the locations at which dose rates are to be assessed.

B. The Plausibility of the Base Case

In evaluating the over-all credibility of the analysis, the Panel recognized that a variety of analytical features remain highly uncertain. Some of the analytical assumptions used in the TSPA-VA appear to be non-conservative (that is, they would lead to projected performance being better than might actually occur) and others appear to be conservative. Still other analytical features have uncertainties, but the Panel does not have sufficient information to know whether the manner of treatment of these uncertainties is conservative. On balance, the Panel thinks that the overall degree to which the TSPA-VA is non-conservative or conservative cannot be determined from the available information.

One potentially non-conservative assumption is the large credit taken for cladding. Within the 10,000-year period, the TSPA-VA analysis assumes that cladding prevents releases from 98% of the failed waste packages. At longer times, the analyses indicate that the cladding will provide more protection than the waste package (CRWMS M&O.1998h, Figures 3.4-10 and 3.5-5). The Panel views this result as not credible.

A second non-conservative analytic feature is the dilution assumed by using the saturated zone model when only a few waste packages have failed. This model assumes that any waste entering the groundwater is immediately dispersed within a plume that is many hundreds or thousands of meters wide. The model also overestimates the dilution that would occur under the human intrusion scenario.

Potentially conservative features of the analysis include: (a) modeling of the seeps, in which it is assumed that the packages that are dripped on are wetted continuously rather than episodically; and (b) lack of credit for retention of radionuclides in the corrosion products of the waste packages and the alteration products of the spent fuel. In addition, no credit is taken for chemical retardation of technetium in either the unsaturated zone or the saturated zone. Because no credit is taken for any chemical processes that would delay the migration of technetium or iodine, they are projected to move through the environment more rapidly than other radionuclides and are estimated to be the major contributors to dose rates at early times. Although it seems likely that the DOE will be required to demonstrate compliance with dose rate limits based on specified dosimetry assumptions, these analytical assumptions are themselves conservative. According to the National Council on Radiation Protection and Measurements, technetium-99 "presents more of a risk as a chemical toxicant than as a radiological hazard" (NCRP, 1993b), and iodine-129 "does not pose a meaningful threat of thyroid carcinogenesis in people" (NCRP, 1985).

The Panel notes one feature of the base case analysis that may reflect an internal inconsistency: the analysis of waste package corrosion and failure does not consider whether rocks that have fallen from the drift ceiling cover waste packages. The possible effects of such rock accumulations on corrosion have not been evaluated. This issue is discussed further in Section III, B, item 4.

The 10,000 Year Analysis

The TSPA-VA is based on analyses for three different time scales: 10,000 years, 100,000 years, and 1,000,000 years. The focus of attention, however, is on the time span from 10,000 to 1,000,000 years. This is evident through the significant attention given to climate change and the use of a saturated zone model more applicable when many waste packages have failed, rather than when only a few failures would have been anticipated. Indeed, the analysts assume that at 10,000 years less than 1% of the waste packages will have failed. Because it appears that both the EPA and the NRC are likely to select a

10,000-year time period for regulatory compliance, the Panel believes that a detailed analysis focused on performance within this time period will be the key to the "viability assessment" of a license application. For this reason, the Panel has focused more closely on issues related to this time span.

The base case analysis indicates that, within the first 10,000 years, radionuclide releases from the repository would result in very low dose rates. In fact, dose rates to members of the public in the accessible environment are estimated to be less than 40 µrem per year at 10,000 years and would occur primarily as a result of releases of technetium-99 and iodine-129.

The main events that, in the Panel's view, could lead to radionuclide releases within the first 10,000 years are premature or juvenile failures of waste packages and earthquakes. Juvenile waste package failures could occur through improper manufacturing and inspection or from damage in handling. The assumption that a single package fails at 1,000 years is a recent addition to the analysis. Given that the manufacturing and inspection processes have not been set, the Panel does not know of any basis on which to assume a defect rate for sealed and tested waste packages. However, the Panel supports the recognition that such failures are possible and could be a potentially significant contributor to early releases. This addition is an improvement over previous analyses.

Earthquakes could cause waste packages to fail, through damage produced by falling rocks. This scenario is also addressed by the TSPA-VA, and discussed in Section III of this report. This scenario is plausible, in part, due to the assumed absence in the base case of any backfill in the repository drifts. While backfill would reduce or eliminate the potential for damage due to rockfalls, the use of backfill at early times could lead to internal waste package temperatures that could potentially exceed the design temperature limit.

Another analytical issue for repository performance during the early part of the first 10,000 years, when thermal effects are important, is whether the analysts have adequately accounted for the movement of water. One possible issue is the hydrologic behavior during the early hot, dry period. Depending on the design details, such as the duration of the initial period during which the repository is left open, and whether the drifts are ventilated during this period, the rock between adjacent drifts can, under some scenarios, be heated to above-boiling temperatures. In this case, many years of infiltration could be stored above the repository horizon. With non-uniform heat loading, this water could flow towards cooler parts of the repository. Such non-uniformity in heat loading could occur if particular drifts were not used due to poor rock, or because operational considerations led to the disposal of cooler waste in a particular part of the repository.

Discussions with project analysts who have conducted the thermal-hydraulic studies suggest that the water would preferentially flow through the pillars between drifts rather than into the cooler drifts. However, the potential effects of non-uniform thermal loading have not been assessed in documents made available to the Panel.

C. Sensitivity Studies

In its second report, the Panel noted the difficulties of conducting an appropriate sensitivity analysis for a system as complex as the proposed Yucca Mountain repository. This concern is based both on the uncertainties in the suitability of the underlying models (that is, whether the models have correctly identified the fundamental physical and chemical processes that will occur over time) and on the mixture of bounding and best estimate parameter values used in the analysis.

These issues are addressed in a detailed and thoughtful manner in Volume 3 of the June 1998 Draft Viability Assessment, both in Sections 2.3.3 and in Section 5 (CRWMS M&O, 1998h). This report acknowledges that while a Monte Carlo simulation is useful for exploring the effects of parameter uncertainty, this method may not be useful where there are mutually exclusive alternative models of how the system will perform. Where this situation exists, it is usually more relevant to evaluate how the system performs under each model, with other parameters held constant.

The TSPA volume of the draft VA (CRWMS M&O, 1998h) also describes how sensitivity and uncertainty analyses were conducted. In this discussion, many limitations are noted. For example, "There are no system-level sensitivity analyses related strictly to thermal hydrology for the TSPA" (Section 5.2.1). In other cases, the sensitivities appear questionable, for example, with the comparative high confidence (that is, low uncertainty) assumed in the performance of cladding. The failure of the sensitivity analysis to identify cladding performance as a key feature of the base case results is puzzling. Rather than treating the performance of cladding as a parameter value to be included in a Monte Carlo assessment, the Panel recommends that dose rates be computed with no performance contribution from cladding. This would provide some perspective on the sensitivity of the TSPA-VA results to the assumed performance of cladding.

Similarly, in Section 5.3.2.2: "For the concrete-modified water case, the peak total release rate from the engineered barrier system is increased by slightly more than three orders of magnitude over that for the base case. These two peaks both occur at about 5,200 years..." Our skepticism is with the underlying models that indicate such a large sensitivity at a time when it is likely that most of the capability of concrete to increase the pH of incoming water will have been exhausted.

For these reasons, the Panel recommends that the sensitivity analysis results not be used to identify key analytical uncertainties as the program progresses toward the TSPA-LA. Instead, the Panel recommends that the TSPA sensitivity analyses be viewed as an input to the collective judgment of the TSPA and other project staff. In addition, where sensitivity analyses produce results that are inconsistent with the intuitive judgments of the project staff or advisors, the underlying models and parameters should be examined to ensure that uncertainties in performance are appropriately represented.

An informative method for presenting the results of sensitivity studies was used by the project staff in the performance "allocation" analysis for TSPA-95 (CRWMS M&O, 1996b). This study, which was based on the concentrations of specific radionuclides in groundwater at various points in space as a function of time, allowed one to see the effect of "chemistry" on different radionuclides and to distinguish between barriers that retard radionuclide releases versus those that reduce radionuclide concentrations through dilution. In the performance allocation study, an absolute performance factor (such as, radionuclide concentration) defined the effectiveness of a barrier within the system by a simple ratio of the input for a barrier to its output. The summary conclusions of this analysis were quite useful, since they identified the "key hypotheses of the waste containment and isolation strategy." As an example, the absolute performance attributed to the waste package was significantly increased if the cathodic protection model could be confirmed. The Panel expects that a similar study, conducted for the TSPA-VA, would indicate that the current analysis of expected performance attributed to the cladding is a key factor in the repository performance.

Additional comments on sensitivity analysis as related to near-field geochemistry are presented in Section III, C, item 2. In addition to the evaluation of specific barriers, sensitivity analyses of the physics and chemistry of specific phenomena will provide more insight on important parameters than calculations carried out to dose rates. Two papers illustrate the sensitivities in the analysis of colloid-facilitated transport (Ibaraki and Sudicky 1995a, 1995b). Their conclusions are directly relevant to issues of colloid-transport at Yucca Mountain.

III. Component Models of TSPA

A. Unsaturated Zone Infiltration and Flow

Three issues are addressed in the preliminary draft section of the TSPA on unsaturated zone (UZ) flow (CRWMS M&O, 1998e): estimating the infiltration rate, characterizing the hydrologic properties of Yucca Mountain, and estimating seepage in the drifts under postulated (ambient) conditions. In general, the latest efforts in addressing these issues represent substantial improvements over previous TSPA work. However, considerable uncertainties still remain. For this reason, a discussion of possible methods for reducing the uncertainties in the models and parameters, particularly in characterizing the hydrologic properties of Yucca Mountain, is a key consideration in the Panel's review.

Sources of Uncertainty

1. Estimating infiltration rates. Estimating the magnitude and variability of the infiltration rates, past and future, is a difficult task. The issue is complicated by the fact that *in-situ* rates have not actually been measured (although there is anecdotal reference in the UZ expert elicitation on this subject of a measurement of 50 mm/year in the Exploratory Studies Facility). The approach of selecting three substantially different climates, dry (present), wet (long-term-average) and super-pluvial is prudent, and represents a dramatic improvement over previous approaches, in which a constant (and much smaller) infiltration rate was used. With the present approach, it should be possible to obtain reasonable estimates of the effects of infiltration. At the same time, however, it is important that it be recognized that the climatic conditions of the base case and the postulated scenarios for switching between various climates are simply hypothetical and have large associated uncertainties.

   In the present approach, infiltration rates and their spatial maps are calculated using water balance models which contain a number of simplifying assumptions on processes, such as evapotranspiration, run-on and run-off, soil depth, flow dimensionality, and so forth. In the absence of experimental data to test them, it is not clear how realistic these projections of future conditions will be. This is particularly true for the infiltration for future climates, where the rates as presented in the infiltration maps are calculated using present-day values for various model parameters (including vegetation, cloudiness, etc.). The accuracy of these projections was subject to criticism in the UZ expert elicitation. Since the infiltration rates affect practically all other TSPA components, it is not known how sensitive the repository performance is to the lateral variability of infiltration contained in these maps. The project staff needs to demonstrate convincingly their validity and relevance.

2. Characterizing hydrologic properties. The characterization of the hydrologic properties of Yucca Mountain is based on a combination of experimental data from boreholes, laboratory measurements, pneumatic tests, air injection tests, field measurements and inverse computer modeling to estimate parameter values. This is a

very complex problem. Ongoing efforts to address it through research are commendable and impressive. Key findings include observance of a strong anisotropy (ratio of approximately 10) between vertical and horizontal fracture permeabilities above the repository, deduced from large-scale air flow data, and the need for substantial changes in the assumptions relative to the fracture-matrix interaction (namely, a reduction) in order to match saturation data under the present infiltration scenario. This characterization is the result of estimating a large number of parameters (at least 150) from a relatively small number of data points (less than 300) and cannot be considered unique, at present.

3. Modeling seepage into the drifts. This is a difficult process to model, and the current analysis of seepage is an improvement over past efforts that were more *ad hoc*. The modeling assumes that seepage will occur when the rock at the top of a drift is saturated. No consideration is given to the degradation of the shape of the drift ceiling with time, nor is consideration given to whether the water arriving at the repository horizon may do so episodically, rather than at a rate that remains uniform within any climatic period.

Approaches to Reduce Uncertainty

On the basis of its review, the Panel believes that there is a critical need to reduce the uncertainties associated with UZ flow and thermohydrology. Possible approaches through which this can be accomplished include:

1. Use a 3-D rather than a 1-D model. At the present time, data are matched to simulations assuming strictly vertical flow and vertical variation in properties. This 1-D philosophy is also adopted in other parts of the TSPA (for example, in the simplified description of thermohydology). Although consistent with the strong anisotropy in some of the layers, this assumption may fail across stratigraphic discontinuities which favor lateral flow (as in the perched water zone), or where the system is isotropic. Capillary dispersion, due to fine-scale heterogeneity, must also be examined, given the lateral variability in infiltration, as reflected in the infiltration maps. The Panel believes that an inversion based on a 3-D model will significantly increase confidence in the hydrologic characterization of the site.

2. Scale-up the infiltration process to the coarse grid-scale. In the existing calibration approach, experimental data, which are essentially point values, are matched against numerical results computed from coarse grid simulation (the numerical grid blocks span tens of meters in at least two directions). The errors introduced by this coarse discretization will affect the estimated parameter values. These errors have not been assessed. The Panel recommends that an effort be made to scale-up the infiltration process in this fractured system to the coarse-grid scale used in the simulations. Such a model should be designed to incorporate small-scale heterogeneities, including correlated structures, anisotropy in fracture permeability, saturation gradients, and the effect on transport fluxes of abrupt changes in properties, expected along stratigraphic discontinuities. The latter has already been shown to be sensitive to the particular

flux-weighting scheme used in the simulations. A by-product of this effort would be the ability to assess the effect of connectivity within the fracture network and to deduce the effective capillary characteristics of the network.

3. Determine the dependence of the reduction factor (to handle the reduction of the surface area at the fracture/matrix interface) on system parameters. This interaction surface in two-phase flow is a key issue that remains unresolved. Reducing, in the calibration procedure, the matrix-fracture interaction by as much as four orders of magnitude has allowed the TSPA team to accommodate changes in the revised infiltration rate, without significant changes in the other hydrological properties. At the same time, this reduction represents a conceptual change in the physics of the process. The reduction reflects events not simply at the scale of a single fracture, as emphasized by the staff in the chapter on UZ transport (CRWMS M&O, 1998b), but rather over the scale of a numerical grid block, which contains a multitude of such fractures and matrix blocks. The methods currently used, namely to assume that the reduction factor is an adjustable parameter (or equal to the water relative permeability), or to introduce a matrix satiation saturation equal to the arithmetic mean between the measured saturation and unity (as in the generalized-equivalent continuum or G-ECM model), are largely *ad hoc*. This represents a weakness in the process and reflects the lack of progress in the scale-up of two-phase flow, as was also noted above. Given its significance in other TSPA components, such as seepage fluxes into the drifts and thermohydology and UZ transport, the dependence of the reduction factor on the system parameters needs to be conclusively and unambiguously determined.

4. Reconcile the issue of transient response to changes in ambient conditions. The issue of the transient response of Yucca Mountain to changes in ambient conditions (including episodic flow) must be reconciled with the analysis presented in the draft TSPA-VA chapter on UZ transport (CRWMS M&O, 1998b), where transients are estimated to last over a period on the order of tens of thousands (rather than a million) years. The Panel recommends that the apparently new analytical model of transient two-phase flow, derived in that chapter, be used to provide consistent estimates of characteristic times and distances for the damping of imposed pulses and for the propagation of new steady-states.

   Additionally, the Panel notes that, in the present approach, samples of "non-detectable" permeability, which represent more than 30% of the total, are not taken into consideration. This misrepresents the effective matrix permeabilities. The rationale behind this approach is not apparent.

5. Improve estimates of seepage into the drifts. The discussion of seepage into the drifts is a new and very interesting part of this chapter in the TSPA-VA. In using this approach, the project staff is relying heavily on the resulting analysis in order to estimate the fraction of waste packages that will be contacted by water seepage and the corresponding fluxes. Sensitivity studies presented at the DOE/NRC TSPA-VA meeting (Wilson,1998) show this fraction to be the parameter with the highest effect

on the overall system performance. Thus, even though only recently investigated, the review and evaluation of this process represents a major component of the overall TSPA-VA. The analysis is based on the postulate that drifts are capillary barriers, which will retain infiltrating water until their saturation at the drift wall reaches a maximum value (of one) at which point seepage commences. In general, the numerical analysis presented is innovative, emphasizing the important effect of heterogeneity in creating early seepage and of the fracture-matrix interaction on transient infiltration pulses. Given not only its importance, but also the short time that has been available for its study, the Panel believes that further work must be done in this area before resulting estimates (based on an extrapolation in the base case that projects that only 0.5% of the total infiltration will contact the waste packages) can be adopted with confidence.

Issues to be Addressed

The following issues need to be addressed:

- Since capillary barriers essentially reflect boundary effects, seepage will be sensitive to the particular geometric and wetting conditions in a small region around the drift wall. This emphasizes the need to analyze the specific geometries for matrix and fractures and their interaction near the drift at various flow rates.

- Given that the actual fracture spacing is of the same order as the grid block size (grid spacing of 0.5 m) used in the dual permeability (DKM) model, it would appear that, for the seepage study, discrete fracture models would be more appropriate.

- One would expect the outcomes of the models to be sensitive to the assumed correlation structure, and to the heterogeneity and the fracture capillary properties. The analysis by the project staff of a critical flux, below which no seepage takes place, may reflect incomplete sampling due to the limited number of realizations. The importance of the heterogeneity and fracture capillary properties underscores the need for their accurate characterization around the drifts. Efforts should be undertaken to develop such characterizations.

- Although experimental data are reported to be consistent with the seepage analysis, those data are for cases in which the seepage is many orders of magnitude larger than the estimated infiltration rate. Further testing in a well-characterized system would add confidence to the model. The Panel recommends that such tests be conducted.

- In the TSPA conceptual model, seepage into the drifts is being decoupled from thermohydrology, and, in fact, will only take place following the end of the thermal period and under ambient flow conditions. Such a process is transient and will be subject to the fracture-matrix interaction. Furthermore, irreversible phenomena or processes that have occurred during the thermal period should be taken into account in the seepage analysis. Such effects could include, for example, closing of fractures around the drift, due to coupled thermal-hydraulic-mechanical-chemical effects, or inversely, the possible rockfall during the thermohydrological period.

B. Thermohydrology

Heat released by the decay of radionuclides in the waste will influence hydrologic, chemical, and mechanical conditions in both the near-field and the far-field. The degree of heating will be a function of the repository areal mass loading. For the areal mass loadings currently under consideration, the thermal fields that will be generated will influence the repository environment for many thousands of years after waste emplacement. The primary emphasis of the studies associated with thermal perturbations for the TSPA-VA has been on thermohydrology (TH). In this regard, the Panel identified the following needs:

1. Better analysis of fracture-matrix interactions. As indicated in the discussion on the UZ Flow, more effort needs to be directed to the development of an appropriate method of handling the interaction of fluid flow between fracture and matrix. During the thermohydrological period at Yucca Mountain, where non-isothermal conditions will prevail over long periods of time, there is an additional problem as phase transformations occur in both the zones of boiling and of condensation. Water vapor in the boiling zone will move toward regions of lower temperature where condensation will occur. The way in which the condensate migrates will depend on the fracture-matrix interactions. Above the repository, the condensate returns either by gravity (mostly in the fractures) or by imbibition (mostly in the matrix). Below the repository, a different situation exists. This means that the fracture-matrix interaction above and below the repository is not subject to the same mechanisms. This interaction, which involves competition between flow in the fractures and capillary diffusion in the matrix, needs further analysis.

2. Justification of treatment of coupled effects of thermochemical interactions. Although briefly described, the coupled effects of the thermochemical interactions that take place at the locations of boiling and condensation are not included in the analysis of the TH component. If these effects, which could lead to irreversible changes in permeability of the rock mass that may be important in controlling the overall behavior of the repository, are considered second order and are to be ignored in the TSPA-VA, an appropriate justification for this interpretation is needed.

3. Justification of treatment of coupled effects of thermomechanical interactions. The Panel believes a comprehensive analysis of the coupled effects of the thermomechanical interactions surrounding the repository is needed to confirm that the TSPA staff can continue to neglect these effects. The analysis of these effects that is given in the TSPA-VA is based on a 1989 report (Mack et al., 1989) that does not appear to be applicable to the proposed repository.

   To investigate this problem, the Panel has conducted some preliminary investigations using temperature estimates provided by Dr. Thomas Buscheck on the development of the thermal field 10 and 50 years into the future. According to these estimates, temperatures above and below the repository will increase in a manner such that the thermal field will be fairly uniform at any given vertical distance from the repository. In other words, for thermomechanical purposes, the heat released in the repository drifts acts like a planar thermal source, and consequently, horizontal planes of constant temperature that extend almost to the edges of the repository will develop above and below the repository. Under these conditions, there is only a general expansion of the rock mass, with shear forces developing only near the tunnel walls and at the edges of the repository. Consequently, there is a region surrounding the emplacement drifts, above and below the repository, the size of which increases with time, where fractures can only close. This leads to a consequent decrease in permeability. This result (Damjanac, 1998) is significantly different from that given in the Mack et al. 1989 report.

4. Comprehensive analysis of combined effects of coupled interactions. In a similar manner, the analysis of the combined effects of the coupled thermal-hydraulic-mechanical-chemical (THMC) interactions is a complicated problem because the thermomechanical and thermochemical effects operate on different time scales. Thermomechanical effects occur simultaneously with changes in the temperature of the rock mass, whereas thermochemical effects are subject to the kinetics of the geochemical reactions (dissolution-precipitation) between the fluids and minerals. Important coupled effects of this kind include fracture healing, as reported by investigators at the Lawrence Livermore National Laboratory. Mineral deposition during the evaporation of refluxing water is another effect of potential significance. The resulting irreversible changes will impact the seepage fluxes into the drifts. As in the case of the effects of thermochemical interations on the TH component, if these THMC effects are considered second order and are ignored in the TSPA-VA, an appropriate justification for this interpretation is needed.

5. Evaluation of alternative interpretations of effects of rockfalls. As noted above, in the thermohydrology component, the mechanical response of the waste package due to the impact by falling debris was assumed to be negligible. The waste package was assumed to remain intact after the rockfall has taken place. This leads to the question whether the accumulated debris from the rockfalls can cover the waste package in such a way that there is a significant increase in canister temperatures during the thermal period. Depending on when the rockfalls take place as well as their extent, the resulting canister temperatures may be able to exceed 325° C, in which case the cladding may fail sooner than expected. The Panel recommends that these possibilities be reviewed and evaluated.

6. Improved analyses of rock mass response in the Drift Scale Test. The response of the rock mass in the Drift Scale Test will have to be carefully analyzed to determine those features that are applicable in projecting the anticipated behavior of the repository. For example, the thermomechanical investigations, mentioned above, that the Panel has conducted also include an analysis of the effects that can be expected from the Drift Scale Test that was initiated in December 1997. This analysis

(Damjanac, 1998) indicates that the thermomechanical effects in the Drift Scale Test will be very much different from those that can be projected for the repository. This is due to the fact that the thermal field that will develop from the combination of heat sources in the single drift and wing heaters is significantly different from the planar thermal field that is expected to develop in the repository. Furthermore, the Drift Scale Test is designed to reach its maximum temperature in about one year, and the heating period is tentatively scheduled to terminate after four years. It should be possible to gather important results from the Drift Scale Test on the problems of drift stability. However, it appears that, in addition to the thermal fields, the time scales in the Drift Scale Test could be quite different from those of the repository and will not produce the thermochemical and thermomechanical effects on rock parameters that are needed in developing a basic understanding of repository behavior. The TSPA project should investigate whether a thermal test that can generate the effects of a planar thermal field in the repository is needed.

C. Near-Field Geochemical Environment

Importance and Potential Value of the Near-Field Analysis to the TSPA

The near-field geochemical environment (NFGE) is one of the more important parts of the TSPA analysis (see Murphy, 1991 for a brief summary of relevant phenomena and processes in the near-field). The importance of the NFGE is underscored by the following observations.

- Far-field processes (such as percolation rate and thermal-hydrologic processes) interact with the waste forms and canisters within the near-field environment. The near-field environment is considered to include all materials and processes that occur within the volume encompassed by the rock face of the adit. The NFGE model specifically focuses on major-element geochemistry within the potential emplacement drifts. The Panel notes that there will be important boundary effects due to the interaction of the in-drift chemistry with rock units immediately adjacent to the adit walls, probably extending for some meters into the repository rock. The thermal-mechanical-hydrological-chemical interactions within this boundary are probably not captured by simply "handing off" output from the NFGE models to the UZ models

- The chemistry of fluids within this near-field environment affects the corrosion rates of the canister, spent fuel, and vitrified waste. The near-field chemistry also affects the solubility limits of important radionuclides, the form of the radionuclides in the solution (dissolved species or colloids), and the types of radionuclide-bearing, secondary phases that may form.

- The near-field environment is the source term for the far-field environment. This coupling is well illustrated in the flow diagrams that link the information needs of the analysis to the process-level and abstracted models used in the TSPA analysis (see for example Fig. 1.2.1-1 of the Preliminary Draft TSPA-VA Section 2.5: Near-Field Geochemical Environment). Such diagrams not only emphasize the importance of the near-field environment (providing input for waste package degradation, waste form degradation and engineered barrier system (EBS) transport models) but also illustrate that the definition (boundary conditions) of the near-field geochemical environment depends critically on the site hydrology, site geochemistry, repository design, waste package design and EBS design.

Despite the complexity of this part of the system, the project staff should direct far more attention to gaining a better understanding of the near-field environment. An improved understanding of this environment could help them develop defensible limits for the source term, based on dissolution rates, solubility limits of dissolved species, or transport mechanisms (such as, release from partially corroded canisters). This is possible because TSPA analysts can:

- Determine from the design criteria the types and amounts of material that are to be placed in the repository, although, importantly, they will not know the exact composition and volume of fluids (water and gas) entering the near-field environment.

- Define important boundary conditions. The temperature in the near-field and its evolution over time can be bounded because it depends on parameters, which are, in principle, well known. These include the initial composition of the nuclear material (a function of burn-up, reprocessing history and age), ambient temperature, thermal loading, the spatial configuration of the heat sources, and an analysis of the heat transfer mechanisms (convection, conduction and radiation). The thermal history can, however, be substantially altered by the hydrologic characteristics of the repository system and chemical reactions (dissolution and precipitation) as discussed in the previous section.

- Use the buffering capacity of the ambient site geochemis*try to set limits on the ranges of important parameters (such as, pH and ionic strength).

Approaches for Improving the Analysis

Having emphasized the importance and value of a detailed analysis of the near-field environment, the Panel offers the following suggestions and/or recommendations:

1. Use design changes to improve the ability to model the near-field environment. As noted in the summary of the workshop held on the near-field geochemical environment, the expert groups that ranked the issues according to importance were often not able to reach a consensus. Instead, there was a bimodal distribution in the rankings. These differences reflect the very real complexity of the system and the present lack of definition of the near-field environment. When all issues were considered across categories, the volume and flux of water into the drift were identified as the most important. The uncertainty in the percolation rate of water and the gas phase composition assumed to be in equilibrium with the evaporating water have a profound effect on the chemistry of the near-field environment. Again, this

emphasizes the degree to which the subsystem models are complex and coupled. Due to the importance of these issues, the Panel recommends that the project staff evaluate whether engineering design changes can be made to mitigate these effects or narrow the range of possible behaviors in order to simplify the geochemical model.

2. Distinguish between sensitivity analysis and experimental studies. In its present form, the TSPA-VA will still only be able to provide a crude model of the near-field geochemistry. First-order approximations may be necessary at this stage of the analysis, but this calls into question the reliability of sensitivity analysis in identifying critical and non-critical parameters. Throughout the NFGE report, sensitivity analysis is proposed as a method by which the range of important parameters and phenomena might be reduced. This is probably unrealistic and imprudent. Sensitivity analysis of important parameters should not be used in place of experimental studies of the actual phenomena. As an example, throughout the report there is an emphasis on pH and carbonate concentrations because these are important output parameters of the models. There is the implication that these may be the only chemical parameters used, subject to the results of a sensitivity analysis. Although these are clearly important chemical parameters, they may not be the only important ones. The values of the key chemical parameters are best determined by experiment rather than by further analysis using admittedly simple models.

3. Clarify the basis for abstracted models. According to the draft NFGE report (CRWMS M&O, 1998f, page 165), the near-field geochemical environment will be described by a mixture of "abstracted models with some process level components." The Panel recommends that the TSPA-VA staff pay careful attention to its own definition of the model abstraction process. The abstraction should be a simplification of a more fundamental process-based model, and it should provide the same range of critical values as does the more complicated process-based model. On the basis of presentations by the TSPA-VA staff, the Panel understands that the abstracted models will be compared to the more complicated process-based models as part of a validation process. The NFGE portion of the TSPA-VA report indicates that "models of the chemical interactions of this system are not readily available (although the soon to be finished Near-Field Models Report will provide some needs in this area)." What then is the basis for the abstracted models? The Panel recommends that the project staff clearly explain the basis of the abstracted models and their relationship to process-based models.

4. Prepare an early analysis of expected degree of success. The project staff should make an early analysis of the degree to which they can expect to successfully model the near-field environment. The Panel is not recommending sensitivity analysis of the models, but rather a "reality check" of the data bases and the usefulness and applicability of the conceptual models. Geochemists in the project are well aware of the limitations and difficulties of developing models of the NFGE, as shown from the following quotes from the overview description of the NFGE (CRWMS M&O, 1998f, page 4):

"Although a number of major aspects of the NFGE are shown schematically within Figure 2.5.1.1.1-1, a full description of the near-field geochemistry is not currently possible, however, it would include evolution of the abundances and compositions of the aqueous phase, solid phases, gas phase, colloidal phases, and microbial communities in the potential emplacement drifts for the time period of interest."

"The general TSPA model architecture is based on the ability to decouple system behavior both spatially and by type of process, i.e., it assumes weak feedback spatially and amongst processes. This assumption is least tenable when applied to the near-field geochemical environment, which may be highly coupled in a nonlinear fashion, being influenced by thermal, hydrologic, and multi-component chemistry."

5. Examine potential effects of radiolysis. Radiolysis can have important effects on the near-field environment. Estimates show that gamma radiation dose rates may be as high as 10^4 rad/hr at the surface of the canister. This will result in radiolysis of liquid water which can lead to the production of H_2 and O_2. Radiolytically produced H_2O_2 can lead to the formation of H_2O and O_2. The NFGE Report (page 25) notes that recent work by Finn et al. (1996) suggests that hydrogen peroxide may be responsible for a highly oxidizing environment during the corrosion of spent fuel. In its discussion of the near-field environment, the TSPA-VA staff should summarize the potential impacts of the γ-field and explain the extent to which such phenomena are considered relevant to models used in the TSPA.

6. Although it will continue to be difficult to develop credible, detailed models of the NFGE, the project should use the NFGE model to bound the corrosion environment of the waste packages. Even broadly bounded NFGE conditions may substantially reduce uncertainties related to waste package corrosion and life times.

D. Waste Package Degradation

Waste packages that maintain their integrity over long periods of time are essential for the long-term control of radionuclides. The containment strategy is twofold: first, complete isolation until the first, full penetration of the waste package and, secondly, subsequent retardation of the egress of radionuclides from the leaking waste package. Localized corrosion processes, such as, pitting, crevice corrosion and stress corrosion cracking, are the largest, realistic threats to waste package performance. Therefore, it is prudent and sound engineering practice to base materials selection and design for waste packages primarily on corrosion resistance. In general, the key issues, processes, and materials performance for corrosion are reasonably well understood. The specifics for application to a proposed Yucca Mountain repository are still being developed and need further work.

The Panel's comments in the sections that follow are intended to be relevant to TSPA-VA and to anticipate the needs of the TSPA-LA. In these comments, the Panel addresses four topics related to waste package degradation:

- The base case design and alternate designs
- Physical events and processes considered in the TSPA analyses
- Determination of environmental conditions at, on, and within the waste package
- Use of appropriate and relevant data, and related research needs

The Base Case Design and Alternate Designs

Determination of the final design for the waste packages is still underway. Materials selection involves various combinations of steel and corrosion resistant metals (CRM). There appear to be three design concepts under consideration: large waste packages of steel/CRM, large waste packages of CRM/CRM and smaller packages of CRM. Large waste packages require thick walls to pass design requirements for dropping and tip-over during manufacture and emplacement.

The Panel notes the following concerns about waste package design.

1. The base case design is a large, steel/CRM waste package that comprises an outer barrier of 10-cm of steel over an inner barrier of 2-cm of Alloy C-22. Some concerns regarding the use of steel include a relatively high corrosion rate during wet periods, the effect of ferric ion from the corrosion of steel on the corrosion of the CRM layers, and the effect of voluminous iron oxide, corrosion products. Steel is eliminated from the two alternate designs; only corrosion resistant metals are used. Various layers and thicknesses of C-22, titanium and other corrosion resistant metals are design options. Among the issues that arise:

   - Steel provides mechanical and shielding benefits but lacks corrosion resistance. Steel is strong, ductile, tough and readily fabricable. Under hot/dry conditions, it oxidizes at a moderately low rate. In moist conditions (approximately RH $\geq$ 60%), the corrosion rate is substantial. Under dripping and wet conditions, the corrosion rate is more rapid. The result is that steel does not offer much long-term protection after any dry-out period is over. Penetrations of 10-cm steel can occur in as little as tens of years if wet conditions persist on a given package. Longer times to penetration will pertain if wet conditions are not continuous.

   - CRM waste packages without steel have superior corrosion resistance. Several alternative designs use single and multiple layers of C-22 and titanium. Both of these metals have excellent corrosion resistance in oxidizing solutions and the nominal repository environments. While further confirmation and documentation is required, it is possible that these metals will remain passive under repository conditions (even with dripping water). Corrosion penetration rates for metals in the passive state are on the order of a micrometer per year or less. If these corrosion rates pertain, waste package lives of 10,000 years or more per centimeter of CRM are projected, even if the waste packages were continually wet.

2. The crucial issue for CRM canisters is whether they will resist localized corrosion in the realistic range of repository water compositions and the frequency of wetting over time within the repository. Crevice corrosion is of most concern for C-22, and embrittlement by hydrogen is of most concern for titanium.

3. The Panel notes that there are insufficient data and analysis to support fully or discard any alternative of a final waste package design from these options. The processes and events identified in the TSPA-VA are relevant to all of the designs. The process models, analyses and data for the TSPA-VA are also relevant. The same data needs pertain for each of the design options, i.e. the determination of the ranges of realistic water compositions and the determination of corrosion performance of metals, e.g. C-22, titanium, 825 and 316 L, in these environments. The research needs identified later in this section address data that will support a final design selection. A rationale is required for the specification of metals (both sequence and thickness) for waste package canisters.

4. Backfill is not included in the TSPA-VA base case. Because of the complex and coupled effects of backfill on repository response, the Panel does not believe that the effects of backfill can be properly addressed by "sensitivity" analysis within the TSPA-VA. Backfill has a major effect on both the time-temperature response and on the distribution and movement of water. The long-term ability of backfill to modulate the water chemistry from ambient conditions is questionable.

5. The use of backfill for the reduction of water contact with waste packages would be beneficial, if successful. Both capillary barriers and drip shields have been considered. With capillary barriers, the concerns are emplacement control, long term stability, settling and movement. Designs and concerns related to alternative drip shields include: (a) a monolithic canopy – long term stability; (b) a ceramic coating—application and adhesion; and (c) a thin outer layer of Ti or C-22—fabrication and durability. The expansion of steel corrosion products is an issue to be addressed. The analyzability of backfill and drip shield design alternatives is an issue for both the VA and LA.

Physical Events and Processes Considered in TSPA Analyses

The Panel agrees with the emphasis of the TSPA staff on two important waste package degradation processes: general corrosion of steel and localized corrosion of CRM (C-22). Steel corrodes as soon as it is wet and lasts as little as a few tens of years. Alloy C-22 is susceptible to localized corrosion only when wet in a critical temperature range. If C-22 remains passive in this range, its anticipated life, prior to penetration, is thousands of years. If it is not passive, then its life, prior to penetration, is as little as a few tens of years. The time sequence and duration in the critical temperature range is a key factor. Once the temperature is below the critical value, corrosion damage essentially stops for thousands of years. The passive corrosion rate of CRM pertains and lives of thousands of years before penetration are projected.

The Panel's concerns about consideration in the TSPA of the effects of physical events and processes on waste canisters include the following:

1. As noted above, a major concern for thick, steel canisters is the effect of the large volume expansion on the formation of iron oxide corrosion products from steel (roughly a factor of two expansion). This has not been dealt with in TSPA-VA. The corrosion products, by expanding in volume, can spall coatings and deform materials in contact with the steel. Growth of the corrosion products between the steel and CRM layers can deform the CRM similar to the phenomena of "denting" in the steam generators in pressurized water reactors and the "pack-out" of structural steel beams. Consideration of the likelihood and effects of this phenomenon is required when steel is used as either an outer layer or an inner layer of the waste package.

2. Fabrication and placement effects are not dealt with in sufficient depth. This adds to uncertainty. Weld procedures, heat shrink assembly of canisters, canister support on pedestals and other features can have significant effects on corrosion and performance.

3. Analysis of stress corrosion cracking of C-22 and other Ni-Cr-Mo alloys is still underway. The performance of the alloys is a function of the corrosive environment, metallurgical condition and tensile stress state. Further analysis and experimental data are needed for this process.

Determination of Environmental Conditions at, on, and within the Waste Packages

The amount, distribution, and composition of waters within the drifts and their effects on the waste packages are key factors in the waste package design and determination of performance. An aqueous phase in the form of thin films, droplets or immersion is required for corrosion of the corrosion resistant metals. There is essentially no corrosion when the metal is dry, but there is a threat of corrosion when the metal is wet. Determination of the spatial and temporal distribution of water is complex and uncertain. Therefore it is prudent to design for wet conditions.

1. The ambient waters at Yucca Mountain are innocuous to corrosion resistant metals. From the perspective of corrosion of CRM, the modulations to these waters that occur outside of the drifts from thermal hydrological effects are not crucial. The waters remain innocuous. It is the modulations to the incoming waters that occur within the EBS and in particular on the waste package surfaces that must be determined and considered.

   Water compositions in contact with waste package metal surfaces will be the controlling factor in terms of the performance of the CRM, and local modulations (near surface) are likely to overwhelm changes at the drift wall and in the surrounding rock. The major processes are: (a) increased concentration and deposit formation on hot surfaces; (b) compositional changes and their effects on the formation of, and interaction with, corrosion products; and (c) compositional changes within crevices. Metal/nonmetal crevices are formed with CRM and corrosion products, deposits, rock and debris. Metal/metal crevices are formed with C-22/steel, C-22/C-22, C-22/Ti and other metal combinations depending upon the design.

2. The water seepage pattern during the period when a waste package is in the critical temperature range for CRM corrosion is not well defined. This is when major damage can occur. There is a need to determine the critical temperature range, and the times in this range when different scenarios can occur. The liner and drift wall condition with time are not well defined. This adds to uncertainty. Questions to be answered include: When will the liner collapse? When will the drift collapse? When will the rock and debris consolidate? To what extent and how long will concrete affect water chemistry?

3. The corrosion behavior of the waste packages with backfill or rock debris covering the waste packages is not well defined. Intentional backfill, rock and concrete debris, calcareous deposits and precipitated salts, and corrosion products will all affect the composition and distribution of waters in contact with the waste package. Without backfill, the waste package/engineered barrier system is likely to be covered by rock rubble, calcareous deposits and precipitated salts, and corrosion products after a few hundreds of years. It is important to recognize that the waste package surfaces will be covered and water droplets are not likely to impact surfaces directly, but rather water will move by film flow and result in local conditions that may be saturated or unsaturated depending upon the amount of water.

Use of Appropriate and Relevant Data, and Related Research Needs

The project experimental data are sparse, insufficient, and inadequate for determining (a) the performance of various alloys under anticipated conditions within the repository, and (b) the composition of the water that will interact with the waste packages. Many thermodynamic data and kinetic rate constants are unknown or uncertain. Experimental data are required to verify and validate models. Some important areas of need are presented below.

1. Realistic range of waters to contact waste package metals. No rational materials selection can be made without knowledge of the characteristics of the waters in contact with the waste packages. These characteristics include: temperature, pH, Eh and ionic concentrations (Cl, SO_4, NO_3, CO_3, Fe^{+++}, Ca, etc.) During discussions at recent workshops on waste package materials, two types of water were suggested: (a) a J-13 type water that is relatively benign for corrosion of CRM's; and (b) a pH 2 acid, chloride-sulfate-nitrate water that is more aggressive. Ultra-aggressive environments, such as concentrated ferric chloride, were deemed to be unlikely and unrealistic under the anticipated repository conditions. While these conditions were useful to guide materials selection discussions, it was emphasized by participants that

a more rigorous determination of water chemistries is required for resolution of these questions.

2. Realistic extreme boundaries of water compositions in contact with the waste package surfaces. The combinations of pH, Eh, Cl, NO_3, SO_4, CO_3, Fe^{+++}, Ca, Mg, and so forth need to be determined experimentally, and the results used to validate and verify the models of water chemistry. The ensemble of properties and species need to be considered, not any property or species in isolation. For example, it is not realistic to consider chloride ion effects alone; mixed chloride, nitrate, sulfate effects are more realistic.

3. Highest temperature for waters in contact with the waste packages. Corrosion will not occur at temperatures above a certain value (above boiling) because no liquid water would be present. As a result, it is mandatory that the highest temperature at which water can contact waste package surfaces and the composition of the waters at this temperature be determined. These are critical to the selection of materials and the assessment of the anticipated performance of the waste packages.

4. Lowest temperature at which crevice corrosion can continue (T_{CREV}). This temperature is a critical factor for materials selection and performance assessment. At temperatures below T_{CREV}, the metal will remain passive, and crevice corrosion will not occur. The value of T_{CREV} is a function of both the corrosion resistance of the metal and the composition of the environment. A more corrosion resistant metal has a higher T_{CREV}, and a more aggressive environment lowers the T_{CREV}. The values of T_{CREV} for the extreme boundaries of water compositions need to be determined experimentally. The Panel recommends that alloys such as 316L, 825, 625/C-276 be included in the corrosion tests to determine a multiplying factor or level of comfort for the more resistant C-22.

5. Corrosion resistance of titanium. Embrittlement by hydrogen is the most important concern with respect to the corrosion of titanium. The relevance of two situations to repository conditions needs to be determined: (a) titanium in contact with carbon steel; or (b) titanium in hot, alkaline solutions. Fluoride ion is present in the repository waters and can be aggressive to titanium. The Panel recommends that the likelihood of corrosion due to fluoride be evaluated. However, this analysis must consider the effects of mixed-ion solutions, because the fluoride ion will not be present alone without other anions and cations in solution.

6. Corrosion penetration rate and morphology of attack for metals in the passive state for long periods of time (thousands of years). A realistic range of values for the penetration rate of passive metals (in the passive state) is required for determination of penetration times for the waste packages. The morphology of corrosion damage and penetrations in the waste package are needed to estimate the transport of radionuclides and to assess the anticipated performance of the repository.

7. Stress corrosion resistance of C-22. The Panel recommends that corrosion studies of C-22 include the addition of double U-bend specimens and the measurement of crack growth rates for pre-cracked specimens.

8. Effects of fabrication and emplacement procedures on waste package performance. Issues such as welding, shrink fit, pedestal material and geometry are not addressed in the TSPA-VA. They should be addressed in the LA.

9. Short term corrosion and electrochemical tests. These are needed to support the conceptual behavior and process models for localized corrosion.

10. Thiosulfate and other reduced sulfur species. The effect of these species on localized corrosion of C-22 needs to be resolved. They are known to extend the corrosion regions of nickel alloys.

11. White papers and critical reviews. These are needed to articulate the position of the project staff on waste package behavior and degradation modes, other relevant (non-project) literature, and natural analogues.

E. Waste Form Alteration/Mobilization

Neptunium Solubility

The TSPA-VA staff have recently completed a reanalysis of the data for neptunium-237 solubility which lowered the range of neptunium-237 concentrations by several orders of magnitude (Sassani and Siegmann, 1998) as compared with the values used in the TSPA-93 and TSPA-95. Previous estimates had been based on the work of Nitsche et al. (1993, 1994). The main points in the recent TSPA reanalysis are: (1) the solubilities given by Nitsche et al. (1993, 1994) are considered to represent metastable equilibrium between the aqueous solutions and metastable Np-phase(s); and (2) Np concentrations measured in dissolution experiments are directly relevant to a system which will approach steady-state conditions from undersaturation.

Four sets of spent fuel dissolution tests by Wilson (1990a, 1990b), Finn et al. (1995) and Gray and Wilson (1995) were used in combination with the calculated Np concentrations in equilibrium with NpO_2 under various conditions in order to derive additional constraints on the aqueous concentrations of Np for J-13-like fluids which initially have no dissolved Np. Based on the analysis, the TSPA team proposed a revised distribution with lower Np concentrations (but with the same distribution) (Sassani and Siegmann, 1998).

The revised distribution of Np concentrations is probably a better estimate than those previously used; however, one must consider the present range to be a very qualitative estimate for which experimental support is still lacking. The Panel concludes that it is essential that the project determine the dominant process(es) (precipitation, coprecipitation, sorption, etc.) which control Np concentration. This will necessarily require that the Np-bearing phases be identified in experiments.

The Panel bases this recommendation on the following:

1. Lack of thermodynamic equilibrium. In the oversaturation experiments (Nitsche et al., 1993,1994), Na-neptunyl carbonate hydrates and Np_2O_5 precipitated, and the neptunium concentrations at steady-state were 5-10 orders of magnitude higher than the calculated solubility of NpO_2 (Janecky et al., 1994). Thus, thermodynamic equilibrium was not attained in these experiments. This observation makes the reanalysis of the data by Sassani and Siegmann (1998) necessary and useful.

2. Lack of saturation of Np concentrations. The spent fuel dissolution experiments used in the reanalysis did not identify Np-phase(s) and found that the steady-state Np concentrations in the dissolution tests, conducted at 25°C at atmospheric oxygen fugacity (25°C and 90°C), were 2-3 orders of magnitude lower than the calculated solubility of NpO_2. Table 3-2 of the reanalysis lists lower calculated solubilities of NpO_2 at the higher temperatures. This result is due to the assumed much lower log fo_2 (-12 to -30.5) in the calculation than that in the experiments (theoretical analysis and calculations demonstrate that oxidation potential, Eh or fo_2, has a significant effect on the Np-solubility) and suggests that the Np concentrations were not saturated with respect to NpO_2 in these experiments. Nevertheless, Sassani and Siegmann (1998) suggested that NpO_2 solubility be used to place constraints on the solubility limits for TSPA.

3. Possible kinetic inhibition of NpO_2 precipitation. Although the Np-concentration was oversaturated by several orders of magnitude with respect to NpO_2 in the oversaturation experiments by Nitsche et al. (1993, 1994), steady-state was achieved without the precipitation of NpO_2. This indicates that the precipitation of NpO_2 may be kinetically inhibited on the laboratory time scale. Additionally, because of the reduction of Np(V) to Np(IV) during the precipitation of NpO_2, precipitation of NpO_2 may also be kinetically inhibited under repository conditions.

4. Effects of solubility of Np-phases. For the semi-static tests of Wilson (1990a, 1990b) and the later periods of the drip tests by Finn et al. (1995), the steady-state concentrations of actinides in solution were determined by both dissolution of spent fuel and the precipitation of secondary phases, while for the faster flow-through tests actinide concentrations were determined by the spent fuel dissolution rate only. However, the Np concentrations determined for the last cycles of all tests are in fair agreement, and Np enters the aqueous phase congruently with uranium as the fuel dissolves in all tests. This suggests that Np-release in these experiments may not be controlled by the solubility of Np-phases.

5. Effects of neptunium concentrations. Considering the high Np-concentration at steady state in the oversaturation experiments (Nitsche et al., 1993, 1994) and the observation in point #4 (above), pure Np phases probably did not precipitate during

the spent fuel dissolution experiments by Wilson (1990a, 1990b) Finn et al. (1995) and Gray and Wilson (1995). The decrease of Np-concentration in the semi-static experiments was more probably the result of incorporation of Np as an impurity element into the secondary uranyl phases. Thus, the Np concentrations may have little to do with solubility-limiting Np phases, but rather are due to a coprecipitation or sorption process.

6. Estimation of solubility limited Np concentrations. The reanalysis concludes that the distributions for solubility-limited Np concentrations should be shifted to lower values by two orders of magnitude than that used in TSPA-95. The same distribution of values is preserved. Because the spent fuel dissolution experiments showed that higher initial concentrations of Np decreased until a steady state was attained at low Np concentrations (10^{-8}-10^{-9} moles/liter), the revised distribution of Np concentrations is probably a better estimate than those previously used. However, one must consider the present range to be a very qualitative estimate for which experimental support is lacking.

The Role of Secondary Alteration Phases

As discussed by the Panel in its first report (Whipple et al., 1997a), in the presence of water or water vapor, the alteration and corrosion rate of UO_2 is relatively rapid under oxidizing conditions. Under such conditions an assemblage of uranyl oxyhydroxides, silicates, phosphates, carbonates and vanadates will form depending on groundwater compositions (Langmuir, 1978; Finch and Ewing, 1992). It is expected (Burns et al., 1997) and has been shown experimentally (Buck et al., 1998) that certain radionuclides will be incorporated into the structures of these secondary phases, thus removing those radionuclides from solution (coprecipitation or sorption) and retarding their transport from the near-field environment.

At present, the project staff does not take credit in the TSPA-VA for this type of retardation; however, such a possibility is under consideration and sensitivity analysis results have been presented. This type of retardation may become a feature of the TSPA-LA. The Panel notes that at present there are only limited data on the structures and stabilities of the phases that form as alteration products of UO_2. Proper evaluation of the effect of secondary phases on radionuclide concentrations in solution will require:

1. Determination of the chemical phases formed under anticipated conditions. There is a need to determination the chemical phases that form over the range of relevant conditions anticipated in the proposed repository. Experimental work will be difficult because metastable phase assemblages may form during short-term experiments, and the phase assemblage and phase compositions may change over time.

2. Determination of the behavior of critical radionuclides in various phases. The extent to which critical radionuclides (Pu, Np, Tc, Se and I) may be incorporated into the structures of these phases will have to be determined.

3. Evaluation of the thermodynamic stability and/or solubilities. The thermodynamic stabilities and/or solubilities of these phases must be determined. At present the thermodynamic data base for these uranyl phases is limited and in some cases contradictory (Grenthe et al., 1992). Additionally, it has been suggested that some uranyl minerals show retrograde solubilities, that is, they become more soluble with decreasing temperature (Murphy, 1997).

4. Demonstration of "protective layer." In a few of the presentations concerning secondary phases, there has been a tendency to refer to their formation as providing a "protective layer." This must be demonstrated and certainly may not be the case. There is considerable evidence in studies of the alteration of uraninite that the alteration is pervasive and that the secondary alteration products do not provide a protective layer which stops the corrosion process (Finch and Ewing, 1992).

The Panel calls these areas of need to the attention of the project staff because formation of secondary, alteration phases may, in fact, provide an effective means of radionuclide retardation. However, substantial experimental work will be required to support this approach.

Colloid Transport

The TSPA-95 (CRWMS M&O, 1995) did not include a consideration of the 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 a future TSPA. Colloid transport will be included in the TSPA-VA and several members of the Panel met with project scientists and analysts on April 22, 1998, to review the present status of colloid-transport models that will be used in the TSPA-VA.

On the basis of this meeting and its review of progress-to-date, the Panel makes the following observations.

The project staff has made considerable progress in formulating its approach to modeling colloid transport. The project team has assessed the potential implications of colloid formation and transport, reviewed the relevant literature, and actively consulted experts in this field (C. Degueldre and J.I. Kim).

The challenge in modeling colloid transport lies in the fact that colloids can have a wide variety of effects on radionuclide transport, for example: a.) travel times may be faster than indicated by conservative tracers; b.) colloids may be retarded by sorption on the rock matrix; and c.) the colloids may be totally filtered/removed from the water. The exact behavior depends on the type of colloid (intrinsic actinide colloids vs. "pseudo" colloids), the water chemistry, the types of corrosion products formed in the near-field (e.g., interactions among concrete, tuff and canister materials), and the characteristics of the repository rock units (e.g., fracture size and distribution, types of minerals that coat fractures). These features will vary over time, along the flow path and with increasing spatial scale.

Conceptually, the present TSPA approach is reasonable, but the usefulness of the output of the models of colloid behavior will be limited by the lack of appropriate input data. In the present analysis, the TSPA-VA staff uses two simple models to capture the anticipated extremes in colloid behavior: a.) a reversible model in which equilibrium is instantaneous and desorption is slow; and b.) an irreversible model in which irreversibly attached Pu is treated as a nonsorbing tracer. Colloid concentrations will be estimated as a function of ionic strength, which will vary along the pathway (at present, this is most difficult to estimate in the near field, but probably well known in the far field). Despite the conceptual utility of the models, the analysts finally will have to rely on the utilization of partition coefficients (K_ds) to quantify radionuclide sorption on colloids. There is considerable discussion in the waste management literature concerning the appropriate use of experimentally determined K_ds to represent the field-scale behavior (see, for example, the summary discussion by Langmuir, 1997). This literature is not reviewed in this Panel report, but the Panel simply notes that the K_d values will be very sensitive to certain parameters, e.g., pH, that are presently not included in the model (Griffin and Shimp, 1976; Bidoglio et al., 1989). In the absence of a well defined geochemical environment, the uncertainties will be large.

Finally, the TSPA-VA staff must decide how to distribute the sorbed radionuclides between mobile and immobile sorption sites, and how to determine the fraction of actinide-bearing, mobile colloids that exist at the interface between the EBS and UZ models. Both of these judgments will be highly speculative unless geochemical boundary conditions limit colloid formation or sorptive capacity. All of these estimates introduce considerable uncertainty into the analysis.

Reducing uncertainty and substantiating the colloid model will require:

1. A considerable experimental data base. This will be needed to confirm the behavior of actinides in the batch scale experiments over a range of conditions. Ideally, extrapolated results of laboratory tests should be confirmed by field-scale tests in relevant rock units.

2. Use of supplementary field data. Because experiments with Pu and Np will be time consuming and the results cannot be confirmed by field-scale tests, the Panel recommends that the project staff utilize the experimental data base and field experience (e.g., uranium ore deposits, mill tailings, natural analogue sites) to confirm that their TSPA models can capture the range of behaviors exhibited by the most abundant actinide at the Yucca Mountain repository, uranium.

3. Demonstration of consistency with local observation. The TSPA models should demonstrate that modeled results are at least consistent with observations of colloid transport at the Nevada Test Site.

In the NFGE Report (CRWMS M&O, 1998 f, page 31), the scientists in the project also pointed out the difficulties of modeling colloid formation and transport:

> "As pointed out by Triay et al. (1995a), the abundance, stability, and ability to migrate should determine the relative impact to the performance of a potential repository for each of these groups of colloids. In general, the detailed quantitative constraints and models for each of these aspects are not available, and it is therefore difficult to eliminate any of the potential colloid types from consideration or to develop a comprehensive Performance Assessment model of the effects of colloids . . . "

Colloid formation and transport remain a major challenge for the TSPA-VA staff.

The Role of Fuel Cladding

General corrosion (oxidation) of cladding under dry, moist, or wet conditions at temperatures below 250°C will be extremely slow and failure by this mode is unlikely. However, other mechanisms of failure remain to be investigated experimentally: (a) pitting and crevice corrosion; (b) hydride-induced cracking; and (c) "unzipping" of cladding due to secondary phase formation (e.g., U_3O_8 or higher oxy-hydroxides of uranium). At present, there does not appear to be a set of studies available by which one can rule out the possibility of crevice corrosion in Zircaloy. At temperatures less than 100°C, there are no relevant databases for irradiated Zircaloy and no information for oxidizing conditions near 100°C in dilute salt solutions (L.H. Johnson, Waste Form Degradation Expert Elicitation Meeting, January 27-28, 1998). The definition of the near-field chemistry (e.g., Cl concentration) remains critical to the analysis of corrosion mechanism and subsequent failure.

Future experimental work may provide the necessary substantive basis for claiming credit for cladding; but these studies are not presently available. The experimental data needed to support the use or rejection of credit for Zircaloy cladding should address the concern and perception that hydride formation and embrittlement may occur. Factors that need to be determined to resolve the issue of how much credit should be taken for cladding include: (a) the condition of Zr cladding on arrival at the repository and after emplacement, (b) the likely environments and exposure conditions of Zr, and (c) the determination of Zr performance under these conditions.

For these reasons, the Panel has concluded that the use of fuel cladding as a barrier to radionuclide release should not be included in the base case for the TSPA.

F. Unsaturated Zone Transport

The organization and discussion of Unsaturated Zone (UZ) Transport is one of the better written chapters in the TSPA-VA report (CRWMS M&O, 1998b), with the exception of Section 2.8.6.5, where a description is given for an analytical model that is more detailed than necessary. The Panel offers the following suggestions that hopefully will lead to further improvements in this component.

1. The problem of UZ transport shares many of the issues of saturated zone (SZ) transport, in particular dispersion and the description of the flow path of the descending plume. As will be discussed below in SZ transport, the numerical models must adequately capture intra-grid dispersion that arises from permeability heterogeneity within grid blocks. The flow path of the radionuclide plume, while mostly vertical immediately below the repository, will be subject to substantial lateral diversion in the deeper perched zone and at dipping interfaces of units with contrasting properties. Furthermore, a complex flow path is expected in the CHn due to the spatial variability of vitric and zeolitic rocks. This situation has common aspects with that in the SZ, where the project staff, in a drastic recent move, abandoned its previous approach and adopted a streamtube-based formalism. An important difference between the two is that the particle-tracking algorithm used here apparently eliminates numerical dispersion. The merits of the two approaches, namely of the revised SZ treatment versus the particle-tracking method, should be compared and, if feasible, a uniform approach should be adopted for both cases.

2. The particle-tracking algorithm is essentially a Continuous Time Random Walk and has also been used in other contexts of transport in heterogeneous porous media. One of the questions that needs to be addressed is the ability of the model to describe non-linear interactions, in which case, the residence time distribution cannot be computed analytically, as was the case with simple convection-dispersion. Because of the unsaturated flow conditions, the fracture-matrix interaction plays a substantial role in UZ transport. This issue was repeatedly encountered above, and will also arise in SZ transport below. In general, a more accurate upscaling of transport to the grid-block scale, than currently available, should be provided. Because the modeling approach taken here is the same as in the chapter on UZ flow, it is subject to the same criticism as described earlier. In addition, the nature of the interaction under episodic flow conditions (namely whether in the form of films, lenses, etc.) must be carefully investigated. In this regard, the Panel has noted two contrasting tendencies on the part of the project staff in addressing issues related to UZ transport: (a) the lack of significant experimental data at the laboratory and field scales to support the currently used model for UZ transport; and (b) the exclusive reliance on numerical simulations (as outlined in section 2.8.3. of the draft TSPA-VA (CRWMS M&O,1998b) to address the relevant issues. The Panel believes that confidence in the numerical model to simulate real processes would be considerably enhanced from tests with real rather than simulated data. On the other hand, the laboratory experiments on the interaction of plutonium with iron oxides and the stability of colloids are useful and worth noting.

3. In section 2.8.6.5 of the draft report (CRWMS M&O, 1998b), the description for an analytical model, in the opinion of the Panel, is more detailed than necessary for a TSPA-VA. Nonetheless, this semi-analytical effort to describe transient infiltration and transient mass transfer in a dual porosity system has certain commendable features. Although the system considered is rather simple, the approach is quite useful, as it allows for analytical insight of the two processes and provides estimates on the characteristic times for damping or propagation of transient disturbances. In

particular, the decaying shock-like character of transient pulses is well-captured by the mathematical approach taken, that is, the method of characteristics. Some further refinement may be needed (for example, in conjunction with the fracture-matrix reduction factor, which is assumed to be the relative permeability of water). As pointed out in the review of UZ flow, this approach should be reconciled with the numerical results used there. However, more work is needed before the modeling can be accepted with confidence, given that comparisons with fully numerical solutions are not satisfactory. This perhaps reflects the linearization of the non-linear diffusion in the matrix. In addition, it would be necessary to extend the method to a dual permeability model, which is the preferred description for UZ flow and transport.

4. A comment is necessary regarding the magnitude of the diffusion coefficient in the matrix, where values as low as 10^{-30} m^2/s are cited. The Panel is unaware of physical processes with such extremely low diffusivity values. The project staff ought either to define the processes responsible for such low diffusivities or to restrict the sensitivity studies to realistic ranges.

5. The capacity of zeolitic rocks to adsorb radionuclides should be further investigated. If the zeolites act as molecular sieves, as is implied, most of the "action" will be limited to a thin surface layer, in which case further access to the interior of the zeolitic rock could be severely limited. The geostatistical description of zeolitic abundance is interesting and indicative of the need for a more accurate characterization. It should be pursued.

6. The modeling of colloidal transport, although significantly improved, still suffers from the need to fit too many parameters. For example, matching the C-Well Tracer test required the introduction of the processes of colloid filtration and remobilization and their respective kinetic constants. If these processes are important, they should be investigated more thoroughly. Colloidal stability is an important factor. Given that it is mainly dependent on the ionic strength, namely on the local chemistry, the implications of its uncertainty on colloidal transport should be carefully assessed. Radionuclide release will be accompanied by water having an in-drift chemistry. The effect of the latter, including hyperalkalinity, should be assessed.

7. Another issue related to ionic strength is the adsorption of particles on surfaces, which is also mediated by the ionic strength through double-layer interactions. For example, the mobilization of fines in petroleum reservoirs when water at reduced ionic strength is introduced, leads to pore-throat plugging and the substantial reduction of permeability. Corresponding effects in the present context must be assessed.

G. Saturated Zone Flow and Transport

The current treatment of saturated zone (SZ) flow and transport at Yucca Mountain is not satisfactory. There are some inherent problems in the treatment of the SZ that make it difficult to reach satisfactory closure on this subject. A first report entitled, "Saturated

Zone Flow and Transport Preliminary Draft Chapter (2.9) of TSPA-VA" (CRWMS M&O, 1998f) was published February 13, 1998. As a result of comments and recommendations provided by the experts on the Saturated Zone Flow and Transport Elicitation Project (Geomatrix Consultants and TRW, 1998a), this preliminary draft has been found by the project staff to be unacceptable and it has been replaced by a revised interpretation of the SZ flow and transport process. In the opinion of the Panel, some of the inherent problems remain, and further work on this critical subject is needed. The Panel offers the following comments.

1. The lack of field data presents a major difficulty. There is a broad area along the projected SZ flow path from Fortymile Wash to the Armagosa Valley, 10 km or more in length, with no boreholes. This means a lack of data on key subjects such as: (a) subsurface geology, (b) watertable configuration, (c) hydraulic parameters, etc. In other words, the characterization of the SZ flow path over about one half of its 20 km length is currently not complete. A more detailed discussion of the serious uncertainties resulting from this lack of data is presented in a report submitted to the U.S. Nuclear Waste Technical Review Board (Gelhar, 1998). This report was prepared by one of the members of the expert panel for the elicitation project.

2. The difficulty in evaluating the effects of retardation on radionuclide transport, which is needed in determining radionuclide release rates, is another inherent problem. There are two critical aspects to this problem: (a) the division of flow between the matrix and fractures in the SZ zone, and (b) the magnitude of the K_d values to be used.

   According to the Expert Elicitation Panel, groundwater flow over the 20-km path from the repository site occurs mostly in the volcanic units and alluvium, and flow occurs in only 10% to 20% of the fractures. As indicated above, field data are needed to verify this picture of the SZ zone. The division of flow in the fractured volcanics is one more aspect of the fracture-matrix interaction problem that has been discussed above in sections III A and B. However, the migration of radionuclides into the matrix will also depend on diffusion as well as whatever advection may be taking place.

   According to Donald Langmuir (Geomatrix and TRW, 1998a), it is necessary to know what percentage of the radionuclides are in the matrix of the volcanic rocks, because their K_d values (especially for Np) can be 10 to 100 times higher than those in the fractures. Presumably, laboratory data on rock samples could help clarify this matter. Gelhar (1998) has also indicated that K_d values cannot be used without knowing how representative they are of field conditions. Thus, we see that there is a serious lack of field data upon which to base the analysis of retardation.

3. The criticism raised by the Expert Elicitation Panel on the Saturated Zone Flow and Transport (Geomatrix and TRW, 1998a) is essentially due to the misrepresentation of the dispersion process by the coarse-grid numerical models used (200m x 200m x 20m). The large dispersion of the plume in the numerical results is due to artificial

numerical dispersion introduced by the incomplete resolution of the plume in the numerical model. This serious shortcoming has apparently precipitated the drastic revision, mentioned above, in which the previous approach is abandoned, in favor of a new formulation based on flow streamtubes in the SZ that carry the core of the plume released at the UZ/SZ interface. While a streamtube approach is most appropriate, the manner by which dispersion and dilution are handled in the new version is unsatisfactory (at least to the degree that we can infer from the set of transparencies provided to the Panel to represent the new approach). Essentially the project staff has moved from a sophisticated, but poorly implemented, numerical approach, to an opposite extreme of a simplistic model, to provide the path for the core of the plume, but which treats dispersion-dilution quite empirically. The Panel believes that a numerical approach based on a streamtube formalism, well-resolved near the plume and with a correct representation of dispersion and retardation, is feasible and should be pursued (provided that a good description of the heterogeneity from field data is available). This would allow for sensitivity studies of the effects of various parameters, including geostatistics, and would circumvent the necessity to rely so heavily on estimates from the expert panel (which currently appears to be the case). On a positive note, the proposed convolution approach is quite useful, assuming that processes, such as adsorption and retardation, remain in the linear regime, and the flow field is at steady state.

4. The issue of numerical resolution also appears in the regional model used to represent the large-scale hydrology, where only 3 vertical layers (spanning 2,750 m) are used and a typical grid has a linear (horizontal) size of the order of 1500 m. Obviously, intra-grid heterogeneity cannot be captured with such a resolution. The same remark also applies for the site-scale model, which involves a grid resolution of 200 m. Given the large range in permeabilities, which spans 7 orders of magnitude, this very limited resolution raises the issue of the relevance of the numerical results regarding the flow field postulated on a regional scale.

5. A point should be raised regarding the fracture-matrix interaction. In the model, flow is assumed to occur only through the fractures, the water in the matrix being stagnant. Instead of explicitly modeling mass diffusion from the fracture to the matrix, the approach taken is to introduce an effective, time-independent porosity for the entire system. Thus, low porosity values reflect small diffusion, and larger values a more enhanced diffusion. The problem with this representation is that the degree of fracture-matrix interaction is fixed *a priori*, rather than being a time-dependent process. In reality, diffusion is time-dependent, and the effective porosity should also be time-dependent. This needs to be assessed.

6. A potentially conservative aspect of the analysis concerns the modeling of the saturated zone flow as it travels toward the Armagosa Valley. The current analysis takes no credit for infiltration of fresh water on top of contaminated water in the saturated zone. Such recharge along the flow path could lead to a substantial layer of clean water above the contaminated water. In his report to the NWTRB, Gelhar (1998) suggests that such a layer could be 100 to 150 meters thick. If so, it would call

into doubt the basic biosphere model, in which a farm family is assumed to pump contaminated water from the plume. In the current analysis, it is assumed that recharge along Fortymile Wash enters the groundwater to the east of the plume, but does not come in on top of the contaminated water.

7. Regardless of the method used, however, these models are relevant only insofar as they include realistically the SZ permeability heterogeneity. As mentioned above, it is doubtful that an adequate site characterization is available. In addition to the issues raised, one notes the apparent difficulty in estimating vertical flow in the SZ and the location of the lower boundary, the lack of account for anisotropy and heterogeneity, etc. This is rather perplexing, given that transport and dilution in the SZ appears to be the principal natural barrier and a dominant factor in estimating radionuclide doses.

8. The overall saturated zone model being used is non-conservative and inappropriate for estimating doses within the first 10,000 years. Within that time frame, the TSPA-VA analysis estimates that that leakage of radionuclides from waste packages will be associated with rare, isolated failures. As noted earlier, it projects that fewer than 1% of the waste packages will have failed, and of those failed waste packages containing commercial spent fuel, fewer than 2% will have cladding that has failed. For such isolated failures, the Panel believes that it is unrealistic to assume that radionuclides released from a single waste package will produce a uniform concentration in the groundwater beneath the repository across a flow path that is hundreds to thousands of meters wide. The assumption that the releases from a single or few waste packages would be uniformly mixed over hundreds or thousands of meters may result in a significant overestimation of the dilution that would occur for a small, localized release. Even if multiple releases were to occur at early times, these first waste package failures could be close to each other in the repository. Such a situation could occur due to a locally aggressive corrosion environment or the fact that adjoining waste packages share common fabrication problem.

   At later times, when many waste packages have failed, the model used for the saturated zone is appropriate. Under such conditions, the radionuclides entering the saturated zone can be expected to be spread throughout the area of the repository footprint. The analytical assumption of uniform mixing within each of six zones is appropriate. The use of a dilution factor as recommended by the Saturated Zone Expert Panel is also appropriate.

   The Panel believes that a separate model is needed for the case in which a small number of waste packages may have failed. Such a model would differ from the current streamtube model in several respects. First, the initial source volume would be sufficiently small that an inappropriate degree of initial mixing is not assumed. Second, the degree of dilution that occurs to the waste during transport would be much larger than is assumed for the current model using large streamtubes. The dilution factor for such a plume will depend on the scale of the plume, and the transverse dispersion associated with a small source would be much larger than that associated with a plume that is many hundreds of meters wide. Within the first 10,000 years, longitudinal dispersion is also likely to be important, especially for a pulsed input of technetium-99 and iodine-129 as might be analyzed in the human intrusion scenario. Retardation and matrix diffusion are also likely to be more effective in delaying radionuclide transport at times when the contaminated groundwater has first begun to come into contact with the rock along the flow path.

H. Biosphere

Certain important questions are not adequately addressed in the biosphere analyses in the draft TSPA-VA (CRWMS M&O,1998g). Comments of the Panel on the more important issues may be summarized as follows:

1. The Panel recommends that the project staff conduct a study to provide comparisons of the dose rates that would be estimated using the dose coefficients in the 1959 International Commission on Radiological Protection (ICRP) Publication 2, the 1979 ICRP Publication 30, and the more current 1996 ICRP Publication 72. This would provide an understanding of the impact of the changes that have occurred as newer information has been developed and incorporated into these coefficients.

   The GENII-S code, being used by the project staff for the "all pathways" analyses, incorporates the dose coefficients in ICRP Publication 30. EPA's regulations for radionuclide concentration limits for the protection of groundwater resources (40 CFR 141) are based on dose coefficients in ICRP Publication 2. Hence, the TSPA-VA will include some dose estimates based on dose coefficients from ICRP 2 and some based on dose coefficients from ICRP Publication 30. None will be based on the latest dose coefficients published in ICRP Publication 72.

   Before proceeding with the current approach to the "all pathways" analyses, the TSPA-VA staff needs to understand how the analyses will differ, depending on which sets of these dose coefficients are used.

2. The Biosphere section of the draft TSPA-VA does not provide answers to the fundamental questions that the Panel expected it to address. These questions include:

   - For exposure pathways: Which are the most important exposure pathways for each radionuclide, what specific characteristics (or input parameters) make these pathways important, and how do the pathways compare on a relative basis for individual radionuclides?

   - For exposure standards: Which standards (groundwater resource protection or all pathways dose rate limits) are more restrictive for which radionuclides and under what circumstances?

   The answers to these questions will depend on a variety of interlocking considerations, such as the location of the receptor, the specific dose coefficients that are applied, how the groundwater is used, and the percentage of food consumed that is grown locally and irrigated with contaminated groundwater. For these reasons, the outcomes of the analyses will provide useful insights into the issues raised by the questions above.

3. Based on a comparison of food consumption estimates with the EPA Exposure Factors Handbook (EPA, 1997), it appears that unrealistically high estimates have been used for meat and fish consumption.

4. The Panel urges that closer cooperation and coordination be established between the TSPA-VA staff members who are conducting the geosphere analyses and those who are conducting the biosphere analyses. The lack of such coordination appears to be exemplified by the fact that the dose estimates provided in the TSPA-VA are based on assumed unit concentrations of individual radionuclides in the groundwater entering the biosphere. While such analyses may be useful, it would have been much more informative if the biosphere staff could have taken into consideration which radionuclides and at what relative concentrations might be anticipated to be present in the groundwater. If the observed situation is indeed due to a lack of interaction between these two groups, it should be corrected.

5. If, as the TSPA-VA staff has indicated, they plan to provide the 5 and 95 percentile limits for their dose rate estimates, care should be exercised to assure that these limits fully incorporate the range of uncertainties and conservatisms in the underlying calculations.

   That this will not be the case is illustrated by a noted lack of:

   - Site-specific data on factors that play an important role. These include the soil to plant uptake for specific radionuclides, and the absorption of specific radionuclides through the human GI tract. Also to be taken into consideration is the fact that these factors may vary depending on the chemical and/or physical form of the radionuclides, their concentrations, and the presence of stable elements having similar chemical properties, many of which are site-specific. According to the recently issued Volume 3 of the Viability Assessment the draft TSPA-VA(CRWMS M&O, 1998i), the abundance of calcium and magnesium in the soils in the Amargosa Valley may render certain radionuclides unavailable for plant uptake. Having said this, however, the TSPA-VA staff then states that the "values used in modeling are generally for more neutral pH soils." The Panel is left not knowing whether these features of the Amargosa Valley soils were taken into consideration in the analyses.

   - Adequate recognition of the magnitudes and sources of the uncertainties in the various input parameters for the analytical models. In addition to the factors cited above, these include those required for converting absorbed doses into equivalent doses, for calculating committed doses, and for converting organ doses into effective (whole body) doses. The draft TSPA-VA (CRWMS M&O, 1998l) indicates that a "fixed value" of the dose conversion factors will be used in estimating the dose rates to exposed population groups. The consideration of uncertainties should include a review and evaluation of the impacts of the adoption of this approach.

- Adequate understanding of the magnitudes and sources of the conservatisms in the parameters and models being used. Since they incorporate the concept of a linear no-threshold (L N-T) relationship between dose and effect, the methods for calculating the tissue weighting factors, and applying these factors in estimating the committed and collective doses due to radionuclide intakes by exposed population groups, incorporate significant degrees of conservatism. In fact, the Federal Radiation Council (FRC, 1960) and the International Commission on Radiological Protection (ICRP, 1966, page 60) have stated on numerous occasions, that applications of the L N-T hypothesis in this manner provide an upper bound on the associated risk to the exposed individuals. Also to be considered is that the concept of committed dose may overestimate the actual dose by a factor of two or more (NCRP, 1993a, page 25). Although the Panel recognizes that DOE will need to comply within whatever dose limits are established by the regulatory agencies, a thorough understanding of these conservatisms will be extremely useful to the project staff both in the conduct of sensitivity analyses and in their ongoing discussions with the agencies that will be regulating the proposed repository.

I. Disruptive Events and Climate

Volcanic Events

The Panel notes that not every class of event, particularly very low-probability events, requires detailed analysis. Indeed, for disruptive phenomena, such as volcanic and seismic phenomena, a detailed probabilistic analysis of performance in terms of dose at a particular "receptor point" may be of only limited value. The analysis of the potential effects of volcanic activity at the repository is an example of this.

In preparing the TSPA-VA the project staff has attempted to study the consequences of various volcanism scenarios, were they to occur. This is exemplified by the discussion of disruptive events in the newly released Volume 3 of the TSPA-VA, which includes a review of the results of model evaluations of two such scenarios. However, the descriptions in Volume 3 are not sufficiently detailed to permit an in depth review. Compounding the problem is the statement in Volume 3 that "the doses from the base case are added to the doses calculated for each of the two volcanic scenarios to arrive at a total dose to the reference receptor." In the opinion of the Panel, the uncertainties of an analysis that requires estimates of parameters such as dike width, number of events in the repository area, fragmentation of waste-package containers as a function of depth, the durations and volumes of various volcanic events, and wind directions and velocities during the range of postulated eruptions are so large that the results are close to being unusable by the broader TSPA-VA project. This is true despite valiant attempts by the analysts to capture the various phenomena. The project is not alone in pursuing such speculative analyses (see, for example, Brown and Crouch, 1982); however, the Panel believes that the value of such speculative analyses, in terms of contributing to our overall understanding of the risks from a Yucca Mountain repository, is very low.

There are two very negative impacts of such an analysis: (a) First, such an analysis focuses attention and discussion on unknowable and, as best we can tell, unimportant parameters; and (b) This type of highly speculative analysis may be confused with the much more rigorous analysis that forms, or should form, the basis for the TSPA-VA.

A way of placing this criticism in perspective is to imagine that the annual probability was not in the very-low range around 10^{-8} or smaller, but in a range where it would be important, say in the range around 10^{-3}/year (where the likelihood of a volcanic event in the regulatory period of 10,000 years would be high. If this were the case, would the analysis undertaken here be acceptable? Without having reviewed it in detail, the Panel's preliminary answer would likely be "of course not ... much more resources would be necessary to develop a defensible analysis."

For volcanism, the essential insight arises from the fact that the estimated annual probability of a volcanic event that could affect the Yucca Mountain site is very small. The project has completed a very detailed probabilistic volcanic hazard analysis (PVHA) that involved some of the most knowledgeable volcanism experts, and that has received considerable attention in the scientific press (Kerr, 1996). The results of the PVHA have been reviewed by the NWTRB (1997, 1998), and the estimated annual probabilities are in the range of 10^{-10} to 10^{-7}, with a mean around 10^{-8}. Thus it would appear that the annual probabilities are low enough that the issue is not important to the overall TSPA-VA analysis.

Of course, the project staff must be alert to new data that could change the estimated annual probabilities (for example, due to different interpretations of the clustering of volcanic centers, see Conner et al., 1997.)

To understand the Panel's overall perspective, one can ask two questions: (a) What will actually have been accomplished when the current ongoing volcanism analysis has been completed; and (b) What use will the results be to the project staff? Again, this is not to criticize the efforts of the project analysis team. Working with only limited resources, they are seeking to grasp and resolve a very difficult problem.

Earthquakes

Although an analysis is also underway of earthquakes and their effects, but it has also not yet been documented in a reviewable draft report. As with other aspects of the TSPA-VA, however, members of the Panel have been briefed about the technical approach that has been adopted. As is the case with volcanism, the project staff has completed a probabilistic seismic hazard analysis (PSHA) that involved many of the most knowledgeable experts. In this PSHA, estimates are provided for the annual probabilities of both seismic ground motion shaking and seismic displacement. The Panel is not in a position to provide an expert review of the PSHA, although we are aware of recent new strain-rate measurements (Wernicke et al, 1998) that we understand are now being studied by the project staff. The Panel understands that additional data expected to come in during the next few years should help to clarify whether these strain-rate data affect the outcome of the PSHA.

According to the TSPA-VA staff, the effects of future earthquake activity are thought to be dominated by rockfalls within the drifts that could damage the canisters, especially after the strength of the canisters has been degraded several thousand years hence. The project staff has shared with the Panel their preliminary thinking about how they plan to proceed with this analysis. The Panel will review their report when it is completed.

The Panel is concerned about an apparent disconnect between the tentative insights from this seismic-rockfall analysis and work in another part of the TSPA-VA project. Specifically, the Panel understands that the TSPA-VA projects that after several thousand years, after the concrete drift liner has deteriorated, potential rockfalls (either seismically-induced or from other causes) could be numerous enough to fill the drift with rock debris. Whether individual rockfalls might be large enough to damage a canister remains to be seen (this is the objective of the seismic-rockfall analysis); but one way or the other, if the drifts become filled with rocks, then they may begin to behave like "backfill," albeit not engineered backfill. This scenario appears to be inconsistent with the assumption, elsewhere in the TSPA-VA project, that the drift volume remains open -- an assumption used, for example, in the seepage-into-the-drift part of the modeling. The Panel calls attention to this inconsistency, which may or may not represent the actual modeling situation.

Climate Change

Predictions of climate change are notoriously difficult to make and, of course, impossible to confirm, but based on the existing state-of-knowledge, climate-change experts believe that the current interglacial period, which has lasted for the past several thousand years, will inevitably end when another glacial period comes. Exactly when this will happen is not known, but the historical record over the last two-million-years-plus appears to be most consistent with glaciation returning several thousand years hence. But it could happen sooner. It is considered unlikely to be delayed to, say, the 20,000-plus-years-hence period. Were its onset to be delayed as far into the future as that, it would be inconsistent with the current interpretation of the historical record.

For purposes of the TSPA-VA, the assumption is made that the glacial conditions will return sometime between 1,000 and 10,000 years hence. (The return time is "sampled" uniformly over this interval.) The infiltration rate through Yucca Mountain is projected to increase from the estimated present-day value of 7 mm per year to a long-term average value of about 40 mm per year. This change will have a pronounced effect on repository performance thereafter, because such a large increase in the amount of water percolating through the mountain affects many key phenomena, all of which must be modeled differently than in the case where current interglacial conditions prevail.

The four performance factors most affected seem to be the fraction of waste packages that experience liquid drips, the transport time through the unsaturated zone, and the transport time and dilution in the saturated zone. The number of waste packages experiencing drips is highly sensitive to infiltration rate. The TSPA-VA staff has estimated that this fraction will increase from about 1% under current climatic conditions to about 30% after the interglacial period ends. (This is important because the current model projects that packages not experiencing drips will generally last 100,000 years or more before failure.)

Since no one knows when the current interglacial period will end, the Panel recommends that: (a) for purposes of the base case, the assumption be made that current climate conditions will prevail for the full 10,000-year "regulatory period", and (b) assumptions about other scenarios, such as a return to glaciation at 5,000 years, be examined through sensitivity studies. This approach has the advantage of revealing directly the phenomena and outcomes under various differing assumptions, without confounding them by other factors and uncertainties. This is in contrast to the analytical approach being used in the base case, in which the climate is assumed to change at a time that is sampled between 1,000 and 10,000 years hence, and then that whole scenario is run as a unit analysis.

Additional climate changes are modeled in the TSPA-VA even farther out in time, for example about 100,000 years hence when another interglacial period may return, and then about 250,000 years hence when a regime of even higher rainfall, a so called super-pluvial condition, might come. (In superpluvial conditions, dose rates in the Amargosa Valley are likely to be significantly higher than under today's interglacial conditions or under ordinary glaciation conditions, because of the estimated significantly increased percolation flux through Yucca Mountain.) The Panel recommends in a similar fashion that the analysis be done both with and without assuming such a superpluvial condition, so as to provide insights that can help provide a better understanding of the implications.

IV. Conclusions and Recommendations

A. Introductory Comments

The Panel is pleased to note that the TSPA-VA base case analysis has been beneficial in helping to plan for the preparation of the TSPA-LA. This is especially true for identifying what needs to be modeled and clarifying how the various components of the natural and man-made segments of the proposed repository will interact. The Panel also wishes to acknowledge that the DOE staff and contractors responsible for developing the TSPA-VA have clearly conveyed what they are doing, and have responded in a positive manner on those matters where the Panel has sought additional details on the approach being used.

Although its review to date has been limited, the Panel has been impressed with the recently issued Volume 3, Total System Performance for the Viability Assessment of the Yucca Mountain Repository Site (CRWMS M&O, 1998I). It appears to represent a significant improvement over previous drafts. However, it contains changes that Panel members have not had time to evaluate and/or discuss. For this reason, the Panel is not prepared to comment further on this report at this time. What is presented in this Third Interim Report is based primarily on the materials provided to the Panel up to the time of issuance of Volume 3, supplemented by interactions and discussions Panel members have had with TSPA-VA project staff.

Panel members clearly recognize the difficulty of the task faced by the TSPA-VA staff. The Panel has observed that most members of the TSPA-VA staff appear to be well qualified, they are dedicated to the work they are doing, and Panel members have benefited from interactions with them. Unfortunately, for some issues, the same types of interactions do not appear to be taking place between the scientific staff that is providing input into the analyses and the staff that is developing the TSPA-VA.

The Panel is concerned that aspects of the repository program appear to be fragmented. For some issues, even in those cases where important scientific data are available, they sometimes do not seem to find their way into the TSPA system. Although there could be several reasons for this situation, one may be that the scientific staff has not become sufficiently involved with the TSPA process to enable them to make effective, timely, and substantive contributions to this effort. Another possible explanation is that the rate at which project deadlines apply to the TSPA work is too rapid for the scientific programs to keep pace.

B. Critical Observations and Findings

Consistent with the project's quality assurance plan, the Quality Assurance Requirements and Description (DOE, 1992), the Panel identified six aspects that they would consider within the context of the long-term performance of the proposed repository. As would be anticipated, these six aspects have commonality and overlap. They do, nonetheless, provide a framework for presenting these facets of the conclusions and recommendations of the Panel in an integrated manner. With that thought in mind, the summary of the conclusions and observations of the Panel is presented below using these six aspects as an organizational framework.

Physical Events and Processes Considered

Coupled phenomena

As in its previous reports, the Panel finds that the TSPA analysts are superficial in their consideration of coupled phenomena. A primary example is the treatment of chemical and mechanical interactions in the thermohydrological analysis. A more comprehensive consideration and analysis of the potential effects of such interactions is needed to confirm whether this approach can be justified. In this regard, it is important to recognize that thermomechanical and thermochemical processes operate on different time scales. As a result, they can lead to varying effects on the permeability of the rock mass.

Degradation of the drift with time

The long term character of the drift should be more directly coupled into the analysis. The seismic analysis suggests that after the drift liner has degraded (within hundreds of years), debris from rockfalls will accumulate in the drifts. This debris can cover waste packages to produce a significant increase in canister temperatures during the thermal period. In addition, the corrosion analysis for waste packages in contact with rubble differ from that for waste packages in air. As rockfalls alter the drift ceiling, the seepage model may become inappropriate. The Panel recommends that these issues be reviewed and evaluated.

Dispersion and dilution in groundwater

Similar problems exist in the considerations related to the dispersion and dilution of radionuclides in the groundwater, specifically:

- The revised saturated zone model is inappropriate for modeling cases in which only isolated waste package failures have occurred. Under the current saturated zone model, contamination is assumed to be widespread and uniformly mixed within large stream tubes. This modeling approach results in a calculated dispersion of wastes in groundwater that is extremely non-conservative. A second saturated zone model capable of representing small source areas at the groundwater surface is needed to deal with the both the first 10,000 years and with the human intrusion analysis.

- The possibility of recharge of the groundwater due to infiltration is also neglected in the analysis. Water that infiltrates is assumed to move the plume to the west without mixing.

- It does not appear that adequate consideration has been given to matrix diffusion as a possible mechanism for retarding radionuclide transport. More consideration also needs to be directed to colloidal transport.

Misdirected effort

There are physical events and processes for which the TSPA-VA staff appears to have devoted more attention than is deserved. This is exemplified by the extensive consideration directed to the analysis of the potential impacts of volcanic events. On the basis of analyses by both NRC and DOE and their contractors, the probability of such an event is so remote that its consequences need not be assessed. The Panel recommends that no additional effort be devoted to such an event.

Use of Appropriate and Relevant Data

Site-specific data

One of the striking features of the TSPA-VA analysis is the lack of use of site-specific data, as well as an absence of adequate efforts to fill these voids. A major example is the fact that no groundwater sampling or underground testing has been conducted within a 10 km segment of the projected SZ flow path from Fortymile Wash to the Amargosa Valley. Site-specific studies of the relative temperatures and chemistries of various groundwater bodies, beneath the proposed repository and surrounding areas, could lead to a better understanding of groundwater flow patterns.

An important factor in terms of the transport of radionuclides in groundwater is the values of the K_ds used for evaluating their sorption within the soil. Existing data show that differences in these values can range over several orders of magnitude. The problem is exacerbated by the fact that the analysts do not appear to have attempted to use readily determined characteristics of the soil, such as the pH and clay content, as a mechanism for estimating site-specific K_ds. The Panel recommends that more effort be directed to identifying the likely chemical nature of specific radionuclides in the groundwater under Yucca Mountain and the specific values that should be assigned to the K_ds under the anticipated circumstances. Also in need of additional study and evaluation is matrix diffusion. This represents what might be called "pseudo sorption." It is extremely important in the case of soluble radionuclides, such as iodine-129, whose chemical sorption within the soil is essentially zero. Another area where additional field data are needed is with the analysis of colloid transport.

Although a significant effort has resulted in data on local (i.e., site-specific) food production and consumption, there is a lack of site-specific data for important parameters required for estimating doses. Lacking specific data on radionuclide uptake by various plants, careful analyses of the soils in the Amargosa Valley would provide the basic information for estimating such uptake factors. More effort should be made to obtain site-specific data, for example, on soil to plant uptake factors. These data should apply to the specific soil characteristics and plants grown at the point of compliance with the standards, and should relate these data to the anticipated chemical forms of the important radionuclides. Lacking specific data on radionuclide uptake by various plants, careful analyses of the soils in the Amargosa Valley would provide the basic information for estimating such uptake factors. These types of approaches need to be explored. The anticipated chemical form of the radionuclides may also influence the efficiency with which they are absorbed through the GI tracts of members of the exposed population.

Data from experiments

Where the TSPA-VA staff has attempted to fill some of the existing voids through the conduct of experiments, there are questions in the approach and interpretation of the results. For example, the TSPA-VA team has recently completed a reanalysis of the data on the solubility of neptunium-237 and has, as a result, reduced the range of neptunium-237 concentrations in the groundwater by several orders of magnitude. The Panel is concerned about a number of factors related to the experiments on which this decision was based. These include the facts that thermodynamic equilibrium was not reached and that the observed results may have been influenced by a lack of information on important co-precipitation or sorption processes. A related factor is the degree to which the chemical nature of the radionuclides and their solubility are dependent on the pH of the groundwater. The assumption made in the TSPA analysis is that Np-concentrations in solution are controlled by the solubility limits of a Np-phase. The project should conduct experiments to determine the processes that do in fact control Np-concentrations (e.g., precipitation, coprecipitation or sorption) and identify the Np-bearing phases in the experiments. These are important data to the analysis and can be obtained by experiment in reasonable amounts of time.

Determination of the final design for waste packages is a work in progress. Materials selection involves various combinations of steel and corrosion resistant metals (CRM). The Panel notes that there are insufficient data and analyses to support fully or discard any alternative for a final waste package design from among the options being considered. A rationale, backed by data, is required for the specification of metals for waste package canisters, including the order and the thickness of metals to be used.

Data from published literature

Compounding these problems is the over-reliance on the use of data generated by scientists working on the project, and only limited use of published literature. This deficiency appears to be generic throughout the analyses being conducted in support of the TSPA-VA. For example, the soil to agricultural crop uptake factors for the key radionuclides anticipated to be released from the repository are those contained in the GENII-S model. No adjustments have been made to refine the uptake factors based on literature values appropriate for the local soil conditions and farming practices.

Assumptions Made

Coupled processes

One of the most critical assumptions (see below) is that the effects of the fully coupled thermal-hydraulic-mechanical-chemical interactions are of second order importance and can be ignored in the TSPA-VA. An appropriate justification for this assumption is needed.

Additional assumptions needed

At the same time, there are other assumptions whose incorporation the Panel believes would be useful in providing insights into the anticipated performance of the proposed repository. One example would be to assume that the proposed repository were ventilated for a prolonged initial period. This would serve as a mechanism to remove both heat and moisture. Such an analysis has been suggested by the Nuclear Waste Technical Review Board. The Panel concurs that the potential effects of ventilation should be analyzed in more detail. This analysis would provide useful information on the sensitivity of performance to the initial thermal period. Other assumptions that would provide useful insights are presented in Section C below.

Abstraction of Process Models

Abstraction process

Because of the inherent complexity of the performance assessment, the detailed process-level models must be abstracted to reduce the number of simulations that need to be analyzed. As the Panel noted in its first report, before any abstraction model is used the results it generates must be compared to those produced by the more detailed model and be shown to be reasonable and conservative. While the ideal goal for the TSPA-VA is a realistic estimation of performance, often this is not possible and a conservative or bounding analysis must be used. An abstracted model should be applied only if the process-level model confirms that its use is justified. The Panel also recommends that reviews be conducted to assure the adequacy of the abstraction process as applied to the TSPA-VA analysis. One way to accomplish this would be to verify the accuracy of the analytical capabilities of the abstractions through stringent comparisons of their analytical outcomes with field data.

Separate groups of analysts have been working on particular parts of the TSPA-VA, for example, on analyzing waste form alteration and mobilization, and on the behavior of the near-field geochemical environment (NFGE). In the latter case, the TSPA-VA staff has stated that the NFGE will be described by a mixture of "abstracted models with some process level components" (CRWMS M&O, 1998f, page 165). The Panel recommends that the staff pay careful attention to its own definition of the model abstraction process. The abstraction should be a simplification of a more fundamental process-based model, and it should provide the same range of critical values as does the more complicated process-based model. On the basis of presentations by the TSPA-VA staff, the Panel understands that the abstracted models will be compared to the more complicated process-based models as part of a validation process. The NFGE portion of the TSPA-VA report indicates that "models of the chemical interactions of this system are not readily available (although the soon to be finished Near-Field Models Report will provide some needs in this area)." What then is the basis for the abstracted models? The Panel recommends that this matter be clarified.

Integration of abstracted models

A key to the success of the TSPA-VA will be to integrate properly the abstracted models developed by the separate groups. On the basis of the reviews conducted to date, the Panel has reason to question whether this requirement is being met and whether the abstracted models accurately simulate the system they are supposed to represent. For example, in applying the abstraction process the TSPA-VA staff has assumed that, following a change in climate, the groundwater flow in the Saturated Zone will immediately change to a new steady-state without significantly changing its direction. The staff has also assumed that there is no need to consider any changes in the elevation of the water table following a change in climate, and that such an approach is conservative. Yet, they have assumed that the percolation flux changes instantaneously, even though important transients exist, the effects of which will depend on how the matrix-fracture interactions are assumed to perform. The Panel believes that these aspects of the abstraction process, in particular, need to be carefully reviewed and confirmed to be acceptable.

The TSPA-VA analysis, including the abstractions used, appear to the Panel to be tailored for the time of peak dose, when many waste packages have failed and wastes have reached near-equilibrium conditions along the unsaturated zone and saturated zone flow paths. This analysis is inappropriate in some aspects when applied to the performance within the initial 10,000 years. This issue is discussed in Section C.

Application of Accepted Analytical Methods

Limitations

There are several examples within the TSPA-VA in which models have been applied without recognition of their limitations. One is the recent major change in the approach being used by the TSPA-VA staff to address flow in the Saturated Zone. It is also exemplified by the application of models incorporating one set of dose coefficients for the groundwater pathway analyses and another set for the all pathways analyses. (The Panel notes that in this case, the TSPA-VA is based on existing EPA regulations). Exacerbating the problem is that, for many of the models, the required input data are either in question or non-existent. As a result, one could readily question the usefulness of the outcomes on any types of sensitivity and uncertainty analyses that are being conducted. What is needed is an approach that will provide an accurate representation of the fundamental relationships between the important physical and chemical processes.

Thermohydrology Model

Several shortcomings in the thermohydrology model need attention: (a) improved modeling of fracture/matrix interactions to properly treat condensate return fluxes and the associated chemical coupling; (b) accounting for coupled effects of thermochemical and thermomechanical interactions in both the near and far fields; and (c) consideration of the fully coupled thermal-hydraulic-mechanical-chemical (THMC) interactions. In addition, the response of the rock mass in the Drift Scale Test needs to be carefully analyzed to determine those features that are applicable to the problem of estimating the future behavior of the repository. Important problems associated with this analysis include the assumptions that the relation between the TH properties, such a relative humidity and air mass fraction, and the drift temperature remain the same as calculated for an isolated symmetric drift, regardless of its environment, the history and sequence of loading, or the possible lack of symmetry around the drift. As a result, TH interactions between adjacent drifts and natural convection effects are not properly accounted for.

Unsaturated Zone Flow

In the treatment of flow in the Unsaturated Zone, there is a need to reduce uncertainty in the models and parameters with respect to three areas: (a) the infiltration rate, (b) the hydrologic properties of Yucca Mountain, and (c) seepage into the drifts under postulated ambient conditions. While the repository performance is somewhat sensitive to the results of the seepage model at all timeframes, it appears to be most sensitive for the 10,000 year analysis. There is also a need for additional study of the effects on radionuclide transport of fracture-matrix interaction and zeolite formations. There is a similar need for additional studies of the mechanisms of colloidal migration.

Waste Package Performance

The analysis of Waste Package Performance in the TSPA-VA focuses on the corrosion performance of the metal canisters as the most realistic process that will lead to penetrations of the waste packages. The Panel agrees with this emphasis. This leads to the development of models for the localized corrosion of corrosion resistant metals, such as, C-22 and titanium, and the general corrosion of carbon steel. There has been significant progress in the development of localized corrosion models for corrosion resistant metals.

The Panel views crevice corrosion as the most realistic threat to waste package performance, and, therefore, concludes that process models and abstractions to determine the likelihood and extent of crevice corrosion are required. Crevice corrosion is more conservative than pitting corrosion in that crevice corrosion can occur under environmental conditions that will not sustain pitting. The Panel recommends that emphasis be placed on demonstrating whether crevice corrosion will persist under realistic environments within the repository.

The crucial issue for CRM canisters is whether they will resist localized corrosion in the realistic range of repository waters and the frequency of wetting over time in the repository. If C-22 remains passive, canister life prior to penetration is projected to be thousands of years. The time sequence and duration in the critical temperature range for crevice corrosion is a key factor. Further development of models for the determination of realistic, extreme environments in contact with metals within crevices and beneath deposits is required.

Water compositions in contact with waste package metal surfaces will be the controlling factor for performance of the CRM, and local modulations (that is, chemical conditions near the waste package surface) are likely to overwhelm changes at the drift wall and in the surrounding rock. Experimental data on water chemistries under realistic conditions are required to validate and verify the models.

The Panel views stress corrosion cracking as the second most realistic threat to waste package performance. The analysis of stress corrosion cracking of C-22 is a work in progress, and this failure mode is closely coupled to the waste package fabrication procedures. This adds to uncertainty. Because the models and treatment of stress corrosion cracking in TSPA-VA are tentative, the Panel recommends further development for TSPA-LA. The stress corrosion cracking resistance of waste packages is intimately coupled to the fabrication procedures, such as, welding and shrink fit canisters and to stresses from any deformation during placement or rock fall and movement subsequent to placement. The fabrication and placement effects on waste packages are not addressed in sufficient depth. The analysis of fabrication and placement effects would also contribute to analyses of juvenile canister failures (those, for example, that have defective welds) The TSPA-VA indicates that juvenile canister failures will dominate the release of radionuclides from the proposed repository within the first 10,000 years.

There is a need for an improved description of the progression of corrosion damage, the morphology of the eventual penetrations, the distribution of penetrations on any waste package, and the distribution of penetrations across the inventory of waste packages. A more realistic conceptual description and treatment of corrosion damage evolution is required. The results are coupled to other important processes and describe important parameters: (a) the time sequence of waste form exposure to the repository environment, (b) the transport of water and other species into the waste packages, and (c) the release and transport of radionuclides from the waste packages.

Models for steel corrosion under dry and wet corrosion conditions are fairly well developed. The rate of corrosion of steel and the generation of thick corrosion products in crevices between steel and corrosion resistant metals is an area of increased interest for analysis of the behavior of multilayer canisters.

Backfill is not included in the TSPA-VA base case. The Panel does not believe that the effects of backfill can be properly addressed by "sensitivity" analysis within the TSPA-VA. The long-term ability of backfill to modulate the water chemistry from ambient conditions is questionable. The ability to analyze any of the backfill and drip shield alternatives is an issue for both the VA and LA.

Mechanical models for the effects of rock fall on deformation and fracture of waste packages appear to be fairly well developed. The need is to apply these models to the range of scenarios that pertain to the repository.

Cladding

The credit taken for the performance of cladding appears to the Panel to be non-conservative. For example, the analysis estimates that at times around 100,000 years into the future, the protection provided by the cladding is equivalent to or better than that provided by the waste package. The contribution from cladding to waste isolation is sufficiently large that other processes and mechanisms modeled in the TSPA-VA are masked. The sensitivity analysis did not adequately describe the uncertainties regarding cladding performance. The Panel recommends that a case be analyzed in which no credit is taken for cladding. Any credit taken for cladding in the TSPA base case needs to be supported by experimental evidence.

Saturated Zone Flow

As would be anticipated, components of unsaturated and saturated zone flow and transport share common issues, such as dispersion, retardation, and colloidal transport. The consistent treatment of these common mechanisms should be considered in the TSPA-VA. Other issues needing to be addressed in the case of SZ flow and transport include: (a) better resolution of the numerical models on regional and site scales, and (b) improved characterization of the properties in the SZ, such as vertical flow and anisotropy. However, the problems in modeling SZ flow and transport extend beyond these considerations. As noted by the Expert Elicitation Panel, the SZ flow model used in the February 1998 SZ zone flow and transport preliminary draft section of the TSPA-VA (CRWMS M&O, 1998g) misrepresents the dispersion process through the use of coarse-grid numerical models. The projected large dispersion of the plume is due to artificiality introduced by the incomplete resolution of the plume in the numerical model. This shortcoming, which is serious, has apparently precipitated a major revision in which the previous approach has been abandoned in favor of a new formulation based on flow streamtubes. The Panel agrees that this approach is more appropriate. However, the manner by which dispersion and dilution are represented in the new version is unsatisfactory. In essence, the TSPA-VA staff has moved from a sophisticated, but poorly implemented, numerical approach to an opposite extreme of a simplistic model. The Panel believes that a numerical approach based on a streamtube formalism, with well-resolved characterization of concentrations near the plume and with a correct representation of dispersion and retardation, is feasible and should be pursued. Whether such an approach is adequate to address the shortcomings of the six streamtube model during the first 10,000 years is unclear; what is clear is that an alternate approach to that used is needed.

On the basis of its review, the Panel has concluded that the current treatment of SZ flow and transport in the TSPA-VA is not satisfactory.

Verification

In all these components, there is an overwhelming need to verify as much as possible the hypotheses, models and abstractions. This can be accomplished by stringent comparison of the analytical results with field and laboratory data. The Panel urges that this avenue of inquiry be pursued.

For example, a major limitation to the verification and validation of models of localized corrosion of waste canisters is the paucity of experimental data in two areas:
(a) determination of realistic, extreme environments at metal surfaces and
(b) determination of the performance of corrosion resistant metals in these environments.

Treatment of Uncertainties

Aggregation of uncertainties

One of the primary problems in the TSPA, as now being developed, is that the analysts have "lumped" many types of uncertainty (e.g., data base, conceptual models, and boundary conditions over time and space). The net result is that the outcomes of the analyses may be inappropriately insensitive to some aspect of the actual behavior of the repository system.

At best, the current TSPA provides a sensitivity analysis of the models being used. The outcomes may be only remotely related to the identification of the important parameters in the actual physical and chemical systems that are operative within the proposed repository. An alternate use of the sensitivity analysis is to use the sensitivity results to identify where process models or their abstractions may be unreasonable. For example, the finding that the performance is relatively insensitive to cladding performance adds to the Panel's concern that the cladding model is overly optimistic.

One possible approach for resolving these problems would be to increase the effort in testing subsystem models. This could be accomplished by extracting some of the coupled subsystem models, and designing experiments that could be used to test the efficacy and uncertainty in the modeled results. Specific approaches that need to be considered include the use of field-scale tests to confirm extrapolated results of laboratory experiments; the use of natural analogues as a source of data for factors whose time scale is too long to be determined by laboratory tests; and the evaluation of the outcomes of TSPA models for colloidal transport with observations at the Nevada Test Site.

Dose rate uncertainties

In a similar manner, the Panel has observed that the TSPA-VA staff has not recognized, or at least they have not provided adequate consideration of, the uncertainties associated with the multitude of factors necessary for estimating dose rates to the public, once the concentrations of individual radionuclides in the groundwater have been calculated. These include the uncertainties associated with the uptake of radionuclides by agricultural food crops, their subsequent intake and uptake by humans, and the various parameters and coefficients required to estimate the accompanying dose estimates and health impacts. To the extent practical, efforts should be made to estimate the sources and magnitudes of these uncertainties.

C. Other Issues

Although the items listed above represent a number of the observations and findings of the Panel, they do not include them all. Some of the more important of these are listed below.

Time Frame for Analyses

At the moment, the TSPA-VA team appears to be focusing almost exclusively on the time frame from 10,000 to 1,000,000 years. The TSPA-VA analysis, including the abstractions used, appears to the Panel to be tailored for the time of peak dose, when many waste packages will be assumed to have failed and the radionuclides that have been released will have reached near-equilibrium conditions along the unsaturated zone and saturated zone flow paths. This analysis is inappropriate in some aspects when applied to the performance within the initial 10,000 years.

The Panel believes that this effort should be augmented by a similar level of attention to the initial 10,000 year time frame. The Panel acknowledges that, if credit is taken for a long canister lifetime and the benefits of the fuel cladding, the expected rate of radionuclide releases during the first 10,000 years should be minimal. However, analyses during the first 10,000 years can be revealing. For example, the contribution of the site and natural systems to waste isolation could be assessed if the assumption is made that the canisters have a zero lifetime and no credit is taken for the cladding. Such an analysis would provide considerable insight into how the different barriers within the proposed repository will function during the initial 10,000 years and, equally important, the significance of the various assumptions that are being made. It would also help the TSPA-VA staff more thoroughly understand and be satisfied with the key elements of the defense-in-depth strategy. Another incentive for directing more attention to analyses over the 10,000 year time frame is that the sensitivities of various input parameters would likely be very different from those at later time periods.

Additional Needs for Supporting Research

Regarding the use of appropriate and relevant data and research needs for waste canister performance:

- Research is needed to determine the realistic, extreme boundaries of water compositions in contact with the waste package surfaces. No rational materials selection can be made without knowledge of the environment in contact with the metals. The ensemble of properties and species need be considered and not any property or species in isolation.

- There is a need to determine the lowest temperature at which crevice corrosion can continue (T_{CREV}): This temperature is a critical factor for materials selection and performance assessment. At temperatures below T_{CREV}, the metal will remain passive, and crevice corrosion will not occur

- There is a need to determine the effects of fabrication and emplacement procedures on waste package performance and specifically on the stress corrosion cracking resistance of metals. Issues such as welding, shrink fit, pedestal material and geometry are not dealt with in the TSPA-VA, and they must be dealt with for the LA.

The research needed to answer questions about the waste canisters is but one example of the challenges in this area. Looking at the problem from a broader perspective, the Panel has observed hesitancy on the part of the project to undertake supporting research in those cases where it may require several years to complete. A good example is the need for studies of the solubilities of neptunium-237, which is estimated to be one of the more important contributors to doses to offsite populations in the long time frame. Another example, more relevant to the performance within 10,000 years, is the interaction of technetium-99 with waste package corrosion products. This type of information is needed and the necessary research should not be delayed. The history of the repository project has clearly demonstrated that lack of adequate time is not a justifiable reason not to undertake research.

In this regard, the Panel is pleased to note that Table 6-2 in Section 6 of the newly released Volume 3 contains a listing of the types of additional information that will be needed to reduce uncertainty in the principal factors affecting post closure performance of the proposed repository. Similar lists, but in a less organized manner, have been presented by the Panel in this report. The Panel applauds this type of review, assessment, and evaluation. At the same time, however, it has become increasingly clear to the Panel that, regardless of the approach, much of the necessary data will not be available in time to support the analyses required for the TSPA-LA. This is especially true in terms of certain important items relative to colloid behavior, canister corrosion, performance of irradiated cladding, solution chemistry, and certain aspects of the repository system, for example, the near field geochemistry. For this reason, the Panel believes that the TSPA staff should begin planning now on changes that need to be made to take these data needs into consideration.

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Acronyms and Abbreviations

CFR	Code of Federal Regulations
CRM	corrosion resistant metal
CRWMS	Civilian Radioactive Waste Management System
DOE	U.S. Department of Energy
EBS	Engineered Barrier System
Eh	Oxidizing potential
EPA	U.S. Environmental Protection Agency
FRC	Federal Radiation Council
ICRP	International Commission on Radiological Protection
L N-T	Linear no-threshold
M&O	Management and Operating Contractor
NCRP	National Council on Radiation Protection and Measurements
NFGE	Near-field geochemical environment
NRC	U. S. Nuclear Regulatory Commission
NWTRB	Nuclear Waste Technical Review Board
PSHA	Probabilistic seismic hazard analysis
PVHA	Probabilistic volcanic hazard analysis
SZ	Saturated zone
THMC	Thermo-hydrological-mechanical-chemical
TSPA	Total System Performance Assessment
TSPA-LA	TSPA to support a license application
TSPA-93	TSPA completed in 1993
TSPA-95	TSPA completed in 1995
TSPA-VA	TSPA supporting the Viability Assessment
UZ	Unsaturated zone
VA	Viability Assessment
WP	Waste package

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98120400073

[redacted]

D-9

[redacted]

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**BCAJ00000-01717-2700-86030 REV.00
REPOSITORY DESIGN SUBSURFACE VENTILATION DUCTED EXHAUST ARRANGEMENT CONSTRUCTION CONDITION 1**

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98120400074 D-10

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BCAJ00000-01717-2700-86031, REV. 00: REPOSITORY DESIGN SUBSURFACE VENTILATION DUCTED EXHAUST ARRANGEMENT CONDITION 2

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9812040075

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D-11

[redacted]

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BCAJ00000-01717-2700-86043, REV. 00: REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 4, SHEET 2 OF 2

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BCAJ00000-01717-2700-86042, REV. 00: REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 4, SHEET 1 OF 2

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[redacted]

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BCAJ00000-01717-2700-86041, REV. 00: REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 3, SHEET 2 OF 2

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[redacted]

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BCAJ00000-01717-2700-86040, REV. 00: REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 3, SHEET 2 OF 2

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[redacted]

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BCAJ00000-01717-2700-86039,
REV. 00:
REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 2, SHEET 2 OF 2

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9812040135

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D-16

[redacted]

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BCAJ00000-01717-2700-86037, REV. 00: REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 1, SHEET 2 OF 2

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[redacted]

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**BCAJ00000-01717-2700-86036,
REV. 00:
REPOSITORY DESIGN SS VENT -
DUCTED EXHAUST MONITORING, P&ID
CONDITION 1, SHEET 2 OF 2**

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BCAJ00000-01717-2700-86038,
REV. 00:
REPOSITORY DESIGN SS VENT - DUCTED EXHAUST MONITORING, P&ID CONDITION 2, SHEET 1 OF 2

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[redacted]

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BCAJ00000-01717-2700-86022, REV. 00: REPOSITORY DESIGN SS VENT ROADHEADER VENTILATION ALTERNATIVE LOW FLOW BYPASS SYSTEM

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BCAJ00000-01717-2700-86024, REV. 00:

REPOSITORY DESIGN SS VENT DUST SUPPRESSION AT CONVEYOR TRANSFER STATION

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