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YUCCA MOUNTAIN

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

Unsaturated Zone Hydrology Peer Review Record Memorandum

June 24, 1991

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UNITED STATES DEPARTMENT OF ENERGY

Yucca Mountain Project

Unsaturated Zone Hydrology

Peer Review Record Memorandum

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SECTION 1

Peer Review Record Memorandum - Report and Recommendations

Prepared by Allan Freeze and Peer Review Team

September, 1990

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1.0 INTRODUCTION

1.1 Objective of the Peer Review

The Unsaturated Zone Hydrology Peer Review Team (PRT) was established by the Regulatory and Site Evaluation Division (RSED) of the Yucca Mountain Project Office of the U.S. Department of Energy (DOE). The objective of the peer review was to evaluate the work done by the Yucca Mountain Project participants in developing an understanding of unsaturated zone hydrology at the Yucca Mountain site.

In order to carry out the evaluation, it was anticipated by DOE that the PRT would independently develop the concepts needed for an understanding of unsaturated zone hydrology by addressing the types of questions listed in Table 1-1. It was further anticipated that in their program evaluation the PRT would address the types of questions listed in Table 1-2. Lastly, it was expected that the PRT would provide recommendations to DOE regarding unsaturated zone hydrologic investigations at Yucca Mountain, addressing the questions raised in Table 1-3.

TABLE 1-1

GENERAL QUESTIONS REGARDING UNSATURATED FLOW AND TRANSPORT

- What evidence or types of evidence support the following hypotheses?
  1. Matrix flow
  2. Fracture flow
  3. Gaseous flow
  4. Presence and effectiveness of capillary barriers
  5. Presence and effectiveness of fracture barriers
  6. Long ground-water residence or travel time

- What are the boundary conditions, process conditions, etc. to which these hypotheses are most sensitive?

- What are the types of evidence to support the applicability of other hypotheses relevant to unsaturated zone flow and transport?

- What are the boundary conditions, process conditions, etc. to which these hypotheses are most sensitive?

TABLE 1-2

GENERAL QUESTIONS FOR EVALUATING INVESTIGATIONS OF UNSATURATED ZONE HYDROLOGY AT YUCCA MOUNTAIN

- What is the available evidence to support the applicability of the following hypotheses at Yucca Mountain?

  1. Matrix flow
  2. Fracture flow
  3. Gaseous flow
  4. Presence and effectiveness of capillary barriers
  5. Presence and effectiveness of fracture barriers
  6. Long ground-water residence or travel time

- How well does the available evidence support these hypothesis?
- What is the available evidence to support other hypotheses relevant to unsaturated flow and transport?
- How well does the available evidence support the applicability of other hypotheses relevant to unsaturated zone flow and transport at Yucca Mountain?

TABLE 1-3

GENERAL QUESTIONS REGARDING HYDROLOGIC INVESTIGATIONS OF YUCCA MOUNTAIN

1. How should hydrologic investigations appropriately address the basic physical concepts and processes embodied in unsaturated zone flow and transport?
2. What are the system sensitivities that impact these processes?
3. How should the concepts, processes, and sensitivities be treated in a model of the Yucca Mountain site?
4. What evidence supports or would support the correctness of this model?

1.2 Peer Review Process

The peer review process was initiated by Max Blanchard, Director of RSED. He did so by releasing a Peer Review Notice that outlined the objectives and scope of the proposed peer review, and by appointing a Chairperson (R. Allan Freeze), an RSED representative (Claudia Newbury), and a Technical Secretary (Marvin Saines).

In the second step of the process, this group prepared a more detailed Peer Review Plan and selected the members of the Peer Review Team listed in Appendix A.

In the next step, a limited amount of background reading material was provided to the PRT members so that they could become familiar with the hydrogeological setting at Yucca Mountain.

The first meeting of the PRT was held in Las Vegas, NV, on April 23 - 26, 1990. A representative of each of the participating agencies in the Yucca Mountain Project was invited to sit in as an observer and to act as a resource person on behalf of their agencies. The output from this first meeting was a List of Questions and Topics to be addressed by the Principal Investigators (PIs) of the Yucca Mountain Project at a second meeting of the PRT. A finalized version of the List of Questions and Topics was delivered to DOE in early May, 1990.

At this point, the PRT members were provided with a large selection of representative publications describing the hydrological work at Yucca Mountain. The reference package provided detailed background reading in preparation for the PI presentations at the second meeting.

The second meeting was held in Las Vegas on June 4-8, 1990. There were a large number of PIs and agency observers in attendance at all open sessions. All presentations were followed by relatively lengthy discussion periods, and there was considerable technical interaction between the PI's and the PRT, and among the PI's themselves.

Appendix B provides a list of attendees at both PRT meetings. Appendix C summarizes the documents reviewed by the PRT. Appendix D is a copy of the List of Questions and Topics provided to DOE by the PRT after the first meeting.

Appendix E is a Summary of the two meetings prepared by the Technical Secretary.

The final step of the peer review process has been the preparation of this Peer Review Record Memorandum (PRRM). The outline of the PRRM was established by the PRT members at the second meeting. All PRT members have contributed to the writing of the PRRM, and it has been coordinated and edited by the PRT Chairperson.

1.3 Scope of Peer Review

Having set out the objectives and general scope of the peer review in Tables 1-1, 1-2, and 1-3, it is equally important that the boundaries and limitations of the peer review process also be recognized. This subsection is intended to clarify the PRT terms of reference, as negotiated by DOE and the PRT.

First, it was agreed that the PRT would emphasize unsaturated-zone processes to a greater degree than saturated-zone processes. DOE originally requested consideration of unsaturated processes alone, but it was the opinion of the PRT members that the two sets of processes could not be totally divorced; that in fact, the hydrogeologic picture at the site would not be complete without an integrated assessment of the full projected flow routes. In particular, the PRT was anxious to evaluate the relative importance of saturated and unsaturated travel times. For this reason, the saturated zone receives limited but essential consideration in this report.

Second, it was decided that the PRT would emphasize water flow rather than solute transport. It was DOE's wish that emphasis be placed on the natural hydrologic system; they felt that consideration of transport processes would involve the PRT in issues associated with radionuclide release rates and repository design, and also with geochemical issues, that might deflect deliberations from the natural unsaturated hydrologic processes that they wanted to be the focus of the review. The PRT accepted this condition somewhat reluctantly, recognizing the strong coupling that exists between the transport processes that will ultimately determine site suitability, and the flow processes that produce the advective component of transport. It was agreed that the PRT would be free to draw attention in this report to those aspects of the unsaturated hydrologic system that have implications for the assessment of transport processes.

Consideration of these two emphases in light of the regulatory framework at Yucca Mountain (Appendix F) clarifies two additional aspects of the PRT deliberations: they emphasize site-characterization issues rather than performance-assessment issues, and they emphasize conceptual issues rather than regulatory issues.

Lastly, it must be recognized that the PRT has not reviewed the entire Yucca Mountain Project, nor perhaps, even the full suite of ongoing or proposed hydrologic studies at Yucca Mountain. The PRT was requested to identify important issues and questions on basic physical concepts and processes. The project-evaluation aspects of the report are presented within the context of the unsaturated processes identified as important. Hence, this report does not constitute an evaluation of the full scope of hydrologic studies at Yucca Mountain.

The PRRM is presented in six sections. Programmatic considerations such as program integration, interagency communication, and the setting of priorities are treated in Section 2.0. Consideration of general technical methodologies that apply across the breadth of the program are discussed in Section 3.0. Consideration of issues associated with individual hydrologic processes are discussed in Section 4.0. Travel-time considerations are presented in Section 5.0. Lastly, Section 6.0 summarizes the conclusions and recommendations of the peer review.

2.0 PROGRAMMATIC CONSIDERATIONS

2.1 Program Integration

The Yucca Mountain Project brings together many strong research teams from several agencies and national laboratories with international reputations. The PRT was highly impressed with the presentations of the principal investigators. It is very clear that most PI's are highly motivated to carry out good scientific research that is directed toward project objectives.

It is less clear, however, whether there is sufficient program integration and coordination between the various research teams. Program integration requires interpretations of geological data, geochemical data, geophysical data, and hydrological data that can be used to produce a conceptual model of the important processes controlling flow and transport at Yucca Mountain. This conceptual model should be consistent with all available data. It can be used to focus data collection activities and perform hypothesis testing. As data collection and hypothesis testing progress, the conceptual model needs to be updated.

The work of Scott et al. (1983) represents an early conceptual hydrologic model of Yucca Mountain. This model was refined by Montazer and Wilson (1984). It appears that little refinement then occurred until Hoxie (1989). In part, this reflects the slowdown in the data collection program. It may also result from a site characterization program that is highly subdivided among several different parties, where each group focuses on their particular technical area.

It is not clear who is responsible for the program integration effort. Because of the many parties involved, integration requires an interagency technical overview team that periodically reviews data and updates the conceptual model, providing recommendations that may redirect data collection activities and hypothesis testing. The overview team should include both data collectors, theoreticians, and investigators from performance assessment who are the ultimate users of the conceptual model. The program integration effort will require interagency exchange of information, data, and models, as outlined in the next subsection.

2.2 Interagency Communication

The complexity of the Yucca Mountain site and the multiple parties involved make interagency communication critical to success of thesite characterization work. Technical interaction meetings on a project-wide level should be held annually. The format of these meetings can vary but they should promote formal and informal exchanges of ideas, models, and data. The need for such meetings was demonstrated by the large attendance at the Committee's review meeting of June 4-6, 1990. Many of the participants at this meeting indicated that information exchange is very important and that it needs to be done on a more regular continuing basis.

Subsequent to the PRT meetings, the PRT learned of steps that have been taken within the USGS to promote project integration. A "Committee for the Advancement of Science in the Yucca Mountain Project" (CASY) was formed in early 1989 to provide a forum for USGS scientists to exchange technical information and to express concerns over aspects of the Project that are perceived to hinder the conduct of science (W.E. Wilson, personal communication, July 3, 1990). A symposium was held at Death Valley, CA., under the auspices of CASY, that was attended by 220 people, mostly USGS scientists, but also including representatives from the National Laboratories and DOE. The PRT strongly supports this initiative, and encourages the Project participants to use CASY as a base on which to build broader interagency interaction.

Establishing a database management system that will be updated and released annually is another important aspect of this communication effort. In addition, it is important that publication of interpretive reports be expedited. A faster publication process helps the esteem and morale of individual researchers and promotes sequential cross-agency building on previous work. As part of this effort, we recommend that DOE and its contractors streamline their review process. Discussions indicated that publication of interpretative reports are often delayed by a review process that may take two or more years. This is unacceptable, both as a scientific procedure, and in terms of project management. The review process should be reduced to less than a year.

Another important area of exchange concerns computer codes that are developed and used as part of the Yucca Mountain project. These codes and their documentation should be available, at a minimum, to other DOE contractors working on Yucca Mountain, and ultimately to the public. The potential for staff turnover also makes documentation important in order to minimize duplication of effort and to maintain continuity. Code-sharing should be promoted and model proliferation should be discouraged.

2.3 Need for Prototype Studies

The PRT was disappointed to learn that there appears to be little change in current project policies that restrict the access of research teams to Yucca Mountain for prototype testing of equipment, methods, and models.

The need for prototype studies at the Yucca Mountain site cannot be overemphasized. There is currently no significant experience base or body of literature on which researchers can rely for equipment or test design. Consequently, they must develop, in many cases from first principles, test interpretation and analysis methods, as well as equipment and experimental methods. The feasibility of the most appropriate testing equipment and experimental designs can only be established after prototype studies have "worked out the bugs."

Prototype studies serve several purposes, including equipment testing, method development (particularly in the areas of test interpretation and analysis), and model validation. In addition, prototype studies offer on opportunity to develop the constraints and performance specifications under which experiments can be run within a formal, high-level quality assurance program. The prototype studies would probably best serve the technical needs of the researchers if they are conducted at a lower level of quality assurance than required by NQA-1 or equivalent procedures. Lower level quality assurance provides the advantage of documentation and traceability without necessarily attracting the relatively high costs normally associated with higher level quality assurance programs such as NQA-1.

Prototype studies also have the advantage of being relatively insensitive to location. Alternative sites that are similar to Yucca Mountain are available and may be suitable for evaluation of equipment and experimental or data-analysis methods. If Yucca Mountain is not going to become available for such studies within the next 6 to 12 months, alternatives such as G-Tunnel, Rainier Mesa, other NTS tunnels, or the Apache Leap site should be provided. Each of these sites has limitations in that they are not exactly like Yucca Mountain. Nonetheless, given the generally broad technical scope and capabilities of the models that require validation data, the test methods that need to be developed, and the equipment that needs to be field-tested, data from real sites with similar characteristics to Yucca Mountain would be invaluable.

2.4 Decision Point Prioritization

The Yucca Mountain Project is a very large program with many component studies being carried out by a large number of agencies, laboratories, and consultants. There is a tendency in large programs of this type for individual projects, once they are established, to carry on forever, regardless of their continued relevance to project objectives. While the PRT did not identify any specific projects that appear to have reached this stage, we believe that the Yucca Mountain Project is likely to be prone to this type of problem in project coordination.

We would recommend an approach to project prioritization that involves the following steps: (1) identify issue, (2) establish clearcut objectives and performance measures, (3) design a program to meet the objectives, (4) carry out the program and analyze the results against the predetermined performance measures, (5) make a decision on whether to terminate, continue, or expand the project.

Larger projects can be broken down into their component parts and the same five-step procedure applied to the sub-objectives. The result will be a series of decision points for termination, continuation, or expansion.

Termination or downscaling may be advisable, not only for projects whose relevance to overall program goals is low, but also for relevant projects in which methodological problems preclude meeting project objectives and standards.

Prioritization of the many individual projects that make up the Yucca Mountain hydrology program is in order at this time. The PRT believes that some projects may be approaching the period of marginal return that precedes eventual termination or downscaling. The PRT is hesitant to suggest candidate projects for early termination without carrying out a detailed analysis of the type we recommend, but some obvious examples would include evapotranspiration measurements (which are unlikely to ever reach a suitable stage of reliability at the Yucca Mountain site), and mercury-intrusion studies (which are of questionable validity). As an example of a research project that requires upgrading, we point to the fingering studies in porous media (which are unlikely to be relevant in fractured rocks). Fingering studies may well be relevant to the site hydrology, but they should be investigated in fractured rock or analogous media.

2.5 Conflicts in Priorities

The PRT could not help but notice the conflict in priorities faced by many principal investigators between the program goals of the Yucca Mountain Project and research goals driven by desires for career advancement. We believe that this conflict often discourages interagency cooperation and communication. We are worried that the recommendations contained in Section 2.2 with respect to interagency cooperation will not come to fruition unless this deeper management problem is addressed. Research, by its very nature, is often an individual affair, and both the USGS and the national labs have to a greater or lesser degree, a publish-or-perish environment. We recognize that the agencies have attempted to develop a different reward structure for their contributing members within the Yucca Mountain Project, but it is also clear that these same members may wish to keep their options open for future career paths in more traditional research environments. We encourage the USGS and the national labs to continue to try to develop management policies that will reward those who meet the objectives of the Yucca

Mountain Project in a timely and efficient manner. There is much publishable research to be done within the Yucca Mountain project, but its impact will be greatest if it comes from interdisciplinary, interagency teams.

The Yucca Mountain program is, of course, not just a series of research studies. It is a large engineering endeavor. As such, the needs of performance assessment will ultimately outweigh those of concept assessment. Field measurement networks currently under design must meet the needs of both objectives. Those members of the PRT who have been involved in the project in different capacities over several years are pleased to see the improvement in cross-agency communication and cooperation between the technical groups responsible for site characterization and performance assessment. It is important that this interaction be encouraged and continued during the design of field experiments and field measurement networks.

2.6 Quality and Productivity

The current quality assurance (QA) program in the Yucca Mountain Project is apparently impacting and delaying technical progress. In the opinion of the PRT, the QA procedures have become over-formalized. They are inconsistent with current project requirements and with the current early stages of study at the site. They are apparently largely responsible for the inability of project researchers to access the site. This is leading to lower staff morale and the loss of excellent researchers and technical staff from the project.

Quality assurance is a valuable and necessary component of any program subject to the technical, legal and public scrutiny that the Yucca Mountain Project faces. However, at this early stage in the project, it is equally important to provide a technical environment which is productive and stimulating as well as one that is capable of withstanding scrutiny from the QA viewpoint. In the opinion of the PRT, progress and productivity in the Yucca Mountain project are inextricably linked with access to either Yucca Mountain or other alternative study area such as G-Tunnel, Rainier Mesa or the Apache Leap site. With a specific site on which to focus activities, then it is clearly the responsibility of DOE and its management advisory contractors to create a 'consistency of purpose' among all participants in the Yucca Mountain project. The 'purpose', in this context, is clearly the theoretical understanding, measurement and performance evaluation of the unsaturated zone at Yucca Mountain. With strong leadership by DOE, a clearly stated purpose to which all participants can relate, and a study area that provides the opportunity for hypothesis testing and prototype studies, procedures can be developed that meet both productivity goals and QA goals at this early stage of the project.

The PRT recommends that consideration be given to using the quality and productivity methods that industry is successfully applying to replace the traditional over-formalized QA (Scherkenbach, 1988).

2.7 Prevention of Site Disturbance

A programmatic consideration of a somewhat different type concerns the prevention of site disturbance.

The PRT in its site visit felt that the existing roads, pads, borrow pits, and other disturbances at several test sites and construction locations may be changing the drainage patterns by damming valleys and creating a potential for ponding. The issue was raised in the List of Questions and Topics generated at the first PRT meeting, and the response from site construction personnel stated that no large-scale change in drainage patterns has resulted from construction activities. However, this response elicited several comments from project researchers who demonstrated concern relative to these disturbances. Clearly, the principle investigators at the site were not in charge of the construction activities, and as such believed that there was a substantial potential for site disturbance. With increased activity anticipated at the sites and with the building of a major new pad 700 feet on a side, site disturbance issues should be discussed with the principal investigators to insure that anthropogenic activity does not alter the natural hydrogeologic system.

During drilling and construction activities, different kinds of fuels, hydraulic fluids, and solvents may be used at the site. The large hydraulic fluid spillage at UZ-

8 prompted the PRT to inquire into the potential for contaminated fluids to enter the subsurface environment. Every driller is concerned about the ease of removal of drilling tools and casing, and it is recognized that lubricating fluids are often clandestinely sprayed or smeared on downhole tools. The potential for tool degreasing, hydraulic fluid line ruptures and gasoline spillage should be strictly controlled. The hydraulic fluid spill at UZ-8 is still visible after four years. Established procedures should be put in place to immediately clean up these contamination events.

During the site visit the PRT noted apparent caving or slumping of material adjacent to the surface seals in the shallow neutron bore holes. Although procedures manual HP-84 covers the sealing of neutron access hole casings and specifies that 2 feet of casing are required above the land surface, the problem may be with the pad itself. HP-84 speaks to a 6 inch deep x 12 inch wide pad of bentonite and cement surrounding the well casing, but it would appear that the 6 inch depth is made up mostly of bentonite with a thin layer of cement on top which may have cracked. In future installations, cement thickness should be increased.

The PRT was not comfortable with the issue of security and possible vandalism associated with the unlocked caps on most bore holes. In the unsecured areas such as Crater Flats, the USGS has secured the geologic, hydrologic, water table, and neutron bore holes with locking caps to prevent vandalism. Within the NTS area, however, locking caps are not used. The rational that only badged persons can enter these areas does not preclude damage. The PRT feels that locking caps should be used within the restricted area as well.

During the site visit the PRT noted several wells that were no longer in use. It was brought to the attention of the PRT that no well abandonment procedure is in place for the waste management program. Wells are abandoned for a variety of reasons including no further need of certain kinds of data, or due to obstructions, caving, bridging, or loss of materials in the bore holes. Consideration should be given to well abandonment procedures, including the development of sealants that possess the physical requirements necessary to maintain integrity indefinitely.

3.0 TECHNICAL CONSIDERATIONS

3.1 Complexity of Hydrogeologic Setting

It is relatively easy to appreciate the attractiveness of the Yucca Mountain site from a hydrologic viewpoint. The water table is at considerable depth, precipitation is low, potential evapotranspiration is high, and infiltration should be minimal. However, these attractive aspects of the site also contribute to its complexity and complicate the measurement of its properties. The theoretical complexity of the hydrogeologic system at Yucca Mountain is evidenced by the numerous modeling studies focused on understanding the principles and constitutive relationships governing liquid and vapor phase flow through unsaturated fractured media. Uncertainties in the results of these modeling studies serve to underscore the need to proceed with prototype studies and field experiments as soon as possible.

The fact that the water table is at great depth, below the repository horizon, precludes dependence only on saturated zone measurements. It is obvious in this case that the unsaturated zone plays the most important role in affecting repository performance, so it is imperative that measurements be made of the important hydrologic processes occurring throughout the unsaturated zone.

The questions to be addressed are: "What are the important hydrologic processes or parameters? How can these important processes/parameters be measured? Can the system be quantitatively described with models so as to predict with confidence their behavior over time?" The infiltration term is critical to understanding the hydrologic behavior of the Yucca Mountain unsaturated zone. It is clear, from observations as well as process modeling within the Yucca Mountain Project, that infiltration occurs beneath the washes during and after infrequent run-off events. However, this type of infiltration may yield only a small percentage of the total estimated infiltration throughout the area; a significant part of the infiltration likely takes place on the slopes, ridges, and upland areas.

Since the infiltration will occur through fractured tuffs, the theory of unsaturated flow through fractured media becomes important. The conditions necessary to generate saturated fracture flow through the tuffs have been addressed within the program. These conditions apparently occur (under current climatic conditions) infrequently enough so as to be quantitatively insignificant to long-term ground-water recharge. However, such events could conceivably introduce tritium and chlorine-36, for instance, to the hydrologic system at depths and concentrations which are inconsistent with the concept of matrix-dominated infiltration.

Although rapid infiltration through surface fractures appears to occur, several mechanisms exist which serve to attenuate percolation of the infiltrated water. The greatest attenuation of percolation appears to occur in the non-welded Paintbrush Tuff and Calico Hills units. The unsaturated hydraulic characteristics of these units, which are regionally extensive and characterized by high porosity and relatively infrequent fracturing, could conceivably control site-scale percolation, both above the repository horizon from the surface down (Paintbrush Tuff) as well as below the repository horizon to the underlying regional water table (Calico Hills units).

Air flow through Yucca Mountain is an additional phenomenon that must be quantitatively understood. Active air movement through the upper part of Yucca Mountain may provide an additional percolation attenuation mechanism, as well as a means for redistributing subsurface moisture. It is also conceivable that air flow could promote the transport of vapor phase constituents to depths perhaps beyond what the unsaturated flow system would otherwise suggest.

It is clear from the above simplified discussion of system complexities that travel time calculations in the unsaturated zone are not a simple task. In addition to preferential or channelized flow in fractures, percolation attenuation and air flow, the processes of matrix diffusion of dissolved constituents and matrix imbibition of infiltrating water are also important aspects of the hydrologic system. Both of these latter processes present research areas that are relatively new, requiring significant experimental and theoretical effort to understand and quantify.

Adding to the theoretical complexities are the equally challenging problems associated with instrumentation and measurement in the Yucca Mountain unsaturated zone. Instrumentation and interpretive methods must be developed which can be used to measure the flow-and-transport parameters and processes, both near the ground surface and at depth. Considerable advances have been made by the project researchers in instrumentation. For instance, the borehole instrumentation package for measurement of in-situ properties has clearly undergone rigorous evaluation and verification with respect to accuracy and precision. The next step is to conduct the prototype in-situ experiments with the instruments in order to develop the installation methodology and quality assurance procedures which will yield defendable long-term data from the Yucca Mountain site.

The issues introduced in this section are treated in greater technical detail in later sections. Infiltration is discussed in Section 4-2, unsaturated-zone water flow in Section 4-3, and unsaturated-zone gas flow in Section 4-4.

3.2 Current Understanding of the Hydrogeologic Setting

Despite the complexity of the theoretical and experimental nature of Yucca Mountain, there appear to be several aspects of the hydrogeologic system which are reasonably well understood at this point in the program. The concepts that the PRT identified as "understood" are not necessarily an exhaustive list, but rather those which are considered as important milestones in the research program. There are clearly specific theoretical or experimental components within each of the following points which will continue to be evaluated and quantified. However, the PRT considered that the important conceptual milestones should be enumerated.

1. There is a source of water and a mechanism of infiltration that escapes evapotranspiration and introduces infiltration on the ridges, slopes, and upland areas of Yucca Mountain, in addition to the infiltration that occurs in the washes. It appears that the upland infiltration occurs either (a) during low-intensity, long-duration winter precipitation, which may yield a broad moisture front primarily controlled by matrix properties; or (b) during high-intensity storms which may result in short-term saturated flow in fractures. The former may account for the majority of the long-term moisture which ends up as recharge to the saturated zone. The latter may account for rapid introduction of

relatively small amounts of water to depths of tens of meters or more.

2. Large-aperture surface fractures can deliver infiltration water to several tens of meters or more in a short time. Anomalously young tritium and chlorine-36 values have been exhibited by some fluid samples from depths of several hundred meters. Other mechanisms, such as vapor phase transport and moisture redistribution by the circulating gas system, may also account for the apparently anomalous isotope distributions. In any case, the PRT believes that these distributions offer incontrovertible evidence of near-surface fracture flow.

3. Unsaturated-zone vapor-phase transport has the potential to redistribute moisture and isotopes within the shallow unsaturated zone to a significant degree.

4. There will almost certainly be perched zones of saturated conditions that will develop at depth. These perched saturated zones, which will undoubtedly be encountered in drill holes, adits, or drifts, should not in and of themselves disqualify the site or the concept of an unsaturated zone repository at Yucca Mountain. The perched saturated zones should rather be considered a part of the hydrologic continuum from recharge zone to discharge zone, and be quantitatively accounted for in the modeling analyses and instrumentation programs.

5. It is unlikely that horizontal, open fractures create a significant barrier to moisture infiltration throughout Yucca Mountain. Although open fractures undoubtedly act as capillary pressure barriers at the microscopic scale and at the local scale, we doubt that horizontal fractures are sufficiently continuous, open, and interconnected so as to represent a physical discontinuity capable of significantly retarding the downward movement of moisture at the site scale. It is clear that in most cases the matrix is effectively connected, both across and around the fractures. The matrix connection across the fractures occurs over the fracture "contact area" and asperities. The lateral extent of any single open horizontal fracture is limited by the mechanical properties of

the rocks.

6. There are many potential mechanisms that could lead to the generation of preferential saturated flow paths in the tuffs at the repository horizon. These include high-intensity precipitation events, development of perched saturated conditions, lateral flow above sloped geologic discontinuities, and channeling and fingering among interconnected fracture systems. On the other hand, there are potentially relatively large-scale mechanisms that could significantly delay and attenuate such flow. Most important are the attenuation potential of the bedded and non-welded Paintbrush Tuff and the Calico Hills Tuff, above and below the repository horizon. The potential significance of these regionally extensive units suggests that they should receive considerable attention in the research program.

Contrary to the above list of accepted concepts, there are several areas which the PRT believes are still in the very early stages of both conceptual and quantitative understanding. These include:

1. The processes describing matrix-fracture interaction and the theoretical basis of current models that quantify these processes, especially the assumption of overlapping continua.
2. The role of faults, on both the local and regional scale, in the unsaturated and saturated zone hydrologic system.
3. The role of fracture coatings and fillings (i.e., are the coatings hydrophobic or hydrophilic, and how do they influence the fracture-matrix interaction?).
4. The role of gas flow through Yucca Mountain with respect to moisture redistribution and infiltration attenuation.
5. The interpretation of the isotope data, particularly the tritium and chlorine-36, at depth.

The above questions are not necessarily a list of prioritized research topics. Rather, they are simply examples of research areas that are currently being investigated by the project and that have yet to be sufficiently quantified, validated, or interpreted.

3.3 Hypotheses Testing

We have made the point in Section 3.1 that the Yucca Mountain site is extremely complex. It is unlikely that a site characterization program could ever be designed that would remove all uncertainty as to the three-dimensional character of the layered stratigraphy, the locations of vertical faults, the continuity and connectivity of fracture systems, or the presence or absence of zones of saturation within the unsaturated zone.

We have made the point in Section 3.2 that there are certain facets of the unsaturated-zone hydrological processes that are now understood and certain facets that are not.

Thirdly, we make that point that performance assessment modeling will undoubtedly show variable sensitivities to these various processes and the conditions they create. There may not be a good correlation between the things that we understand best and the things that are most important.

Given this state of affairs, the PRT believes that the traditional approach to site characterization is not likely to be successful. In the traditional approach, models accept field-based measurements of the hydrogeological parameters (such as hydraulic conductivity) as input, and produce predictions of state variables (such as hydraulic head) as output. The predicted values of the state variables are compared against values observed in the field. The models identify the parameters of greatest sensitivity and also the locations where these parameters have the greatest uncertainty. Field measurements from an ever-increasing net of measurement locations reduce the uncertainty. The calibration process continues in an iterative fashion until relatively accurate predictions of site response to proposed engineering projects can be made.

Given the size and complexity of the Yucca Mountain site, it is unlikely that this process would be successful, even if economics would allow an unlimited number of site characterization boreholes. However, in the case of a nuclear waste repository, there is the added limitation that the number of boreholes should be minimized in order to protect site integrity.

Under these circumstances, the PRT feels that a more appropriate approach to site characterization is one based on the results of hypothesis testing. This approach links site characterization to performance assessment. Rather than calibrating hydrologic models with respect to the state variables themselves, one calibrates the models with respect to integrated performance measures. For example, if sensitivity analysis indicates performance sensitivity to the development of perched-water zones due to hydraulic conductivity contrasts across stratigraphic layers, then a performance measure could be set up based on the level of conductivity contrast that leads to unacceptable flow conditions. Site characterization in the field would then be directed toward the testing of hypotheses about the presence or absence of such contrasts.

Hypotheses could also be set up for such issues as vapor transport across fractures, surface infiltration, or the attenuation of moisture flow across non-welded tuffs. The approach emphasizes the identification of "acceptable" parameter ranges and critical data needs. Results are related to site acceptance or rejection.

3.4. Theoretical Constraints

Section 3.1 offered a descriptive introduction to the technical issues treated in more detail in Section 4.0. This section carries the technical introduction further by providing a general overview of the theoretical constraints that limit a complete physically-based treatment of unsaturated-zone fluid-flow processes.

The Yucca Mountain geologic formations are composed of tuffaceous materials involving, in much of the mountain, both porous and fractured materials. Accordingly, in order to estimate the long-term migration of radionuclides to the accessible environment, the water movement must be evaluated both in the rock matrix and fractures, under partially saturated conditions, and with consideration of the natural material heterogeneity.

The complex processes involved in moisture movement in such an environment pose major challenges to present capabilities for analysis, measurement, and evaluation. Such challenges include important technical issues that likely will continue as theoretical constraints in the long-term assessment of the waste repository performance. Accordingly, these complex interacting processes of moisture movement and their related theoretical constraints warrant careful consideration.

The several flow processes occurring in the mountain need to be considered together to better understand the various interactions and to provide a complete assessment. However, the discussion to follow begins by addressing only part of the flow process and then gradually adds more flow mechanisms to the discussion. This should better clarify the individual flow components, while also giving some appreciation of the interactions involved. We begin with isothermal porous-media arguments. Temperature-induced vapour movement and fracture flow effects are discussed later.

In the vadose zone under isothermal conditions, both the rock wetting water phase and the continuous non-wetting gas phase (which is a mixture of air and water vapour), occupy the media pore space together as two immiscible fluid phases. The different pressures in the water and gas phases coupled with the rock pore properties control the relative water and air saturations present in the two-phase fluid system.

Whenever liquid and gas are present as separate continuous phases in the pores or interstices of the porous material, then each of the fluids will move primarily within their respective immiscible phase. The rate of movement of either fluid depends on (1) the particular hydraulic conductivity at the fluid content involved, (2) the combined pressure gradient and gravity body force in the fluid phase involved, and (3) the fluid properties (such as density and viscosity) for that particular phase. Hence, the vadose zone as described to this point involves isothermal multi-phase flow in heterogeneous porous materials involving two immiscible fluids.

Experience and studies over more than 50 years in evaluating only the water flow aspects in the vadose zone have provided useful idealizations and simplifications of the actual two-phase system in the vadose zone. When the simplifying assumptions are appropriate and realistically represent the actual system, then good estimates of water flow can be obtained with fewer measurements and with less analysis.

The approximations necessary to reduce the two-phase fluid flow analysis in the vadose zone to that of water flow alone come from assuming either: (1) gas flow is small, its interaction with the water phase flow is negligible, or (2) gas viscosity and density are constant, and are small compared to those of water, so that the effects of the gas impelling forces on water flow are negligible.

For such conditions, the pressure in the gas phase is effectively constant throughout the system and so may be conveniently set to atmospheric pressure. With a constant gas pressure of zero, the conservation of mass equation is identically satisfied and there remains only one non-linear conservation equation describing the water dynamics in the vadose zone. This approximate expression for the water flow is known as "Richard's equation."

The long-established Richard's equation is well accepted as providing realistic water flow results in the vadose zone, but it has two limitations. Firstly, the results obtained can only be reliable to the extent that the idealizing assumptions are realistically met, and secondly no evaluation is possible for gas flow if such information is needed in the vadose zone.

The addition of temperature-related moisture movement effects to the already discussed two-phase water and gas flow in Yucca Mountain is a next step toward more completely representing the unsaturated zone moisture flow. In the deeper strata of Yucca Mountain, temperature changes involve primarily the geothermal gradient; however, in shallower parts of the mountain, additional temperature variations appear to occur. There are consistent measurements in the shallower wells of vapor-laden air flow in response to changing surface temperatures and pressures. Accordingly, thermally related moisture movement in some parts of the mountain contributes to the overall flow interactions in the system.

Though thermal- or temperature-related variations affect flow in both the water and gas phases of the vadose zone, the effects are generally greater in the gas phase. Two thermally induced effects dominate the added movement in the gas phase. First, the changing temperature causes variations in gas phase properties, primarily the density, which aided by pressure and with the relatively low viscosity can induce convection effects in the gas phase. Second, temperature gradients in the moving gas phase cause movement of the water-vapor component within the moving gas phase. The smaller effects in the water phase are primarily through changing fluid properties such as density and viscosity with their associated flow consequences.

Temperature-related interactions between the water and gas phases, though generally small, involve temperature-related effects on wettability of the porous solid, changing surface tension properties between the water and gas phases, and thermal-related changes to moisture transfer between the liquid-water phase and vapor component in the gas phase.

The vadose zone as described to this point then involves non-isothermal, two-phase fluid flow in heterogeneous porous materials. This provides a rather satsifactory and generally acceptable theoretical formulation describing vadose zone flow in porous media so long as there are no fractures.

For the various Yucca Mountain tuff formations which are composed of both fractures and porous materials, additional fracture and matrix flow processes are involved. These additional flow processes have only in recent years been comprehensively studied. Accordingly, flow processes in fractured systems are neither as well understood nor has there been sufficient critical testing of the various proposed alternative modeling approaches. In fact, much of the better understanding and theoretical basis for description of fracture flow, including interactions with the porous matrix materials, has come over the last decade from studies involving nuclear waste repositories in Sweden, Canada, Switzerland, and the United States. Significant contributions toward better theoretical understanding of fracture fluid flow have come from research by contractors associated with the Yucca Mountain studies (Wang and Narasimhan, 1985; Klavetter and Peters, 1986; Peters and Klavetter, 1988).

Among the theoretical approaches developed for incorporating fracture flow effects in the vadose zone is the derivation of a form of Richard's equation that describes water flow in overlapping fracture and matrix continua. The dependent pressure in this specially derived Richard's equation is shown to be nearly the same in both the fracture and matrix continua to an appropriate order of approximation, except across any wetting front that advances into an initially dryer portion of the system. The wetting front in the latter case is represented as an advancing instantaneous shock wave. Required material characteristics for such a Richard's equation are composite hydraulic properties for the combined matrix/fracture system. The wetting front in the latter case is represented as an advancing instantaneous shock wave. Required material characteristics for such a Richard's equation are composite hydraulic properties for the combined matrix/fracture system. These include composite hydraulic conductivities and combined moisture capacity coefficients, both expressed as functions of the pressure head. This carefully thought-out and well-documented approach to considering fracture and matrix flow holds for the analysis of water flow under isothermal conditions, so long as the Richard's equation assumptions discussed above are adequately satisfied.

Another approach for treating the hydraulics of fractured rock is the equivalent continuum approximation, which combines the fracture and matrix into a single porous media equivalent that is considered either isotropic or anisotropic (Snow, 1969a, 1969b). This approach begins by identifying a representative volume of the rock-fracture system large enough so that a meaningful continuum fracture porosity can be defined. This fracture porosity is the ratio of fracture volume to the total bulk rock volume. The matrix porosity is defined as the fraction of voids in the matrix to the matrix volume. A bulk equivalent porosity can then be defined as the total void space fraction.

Given the fracture and matrix saturations, the equivalent bulk water saturation is provided by appropriate fracture and matrix porosity weighting. In this way, the total water phase equivalent capillary pressure characteristics as a function of bulk water saturations are provided. Porosity weighting is also used in providing the equivalent bulk hydraulic conductivity. This provides the equivalent relative permeability as a function of the bulk saturation in the combined matrix and fracture continuum. The resulting bulk pore velocity from this approach will not necessarily represent a velocity observed in either the matrix or fracture; rather it represents the bulk liquid water average. Though perhaps somewhat less detailed in representing the fracture and matrix flow, the approximate equivalent continuum approach does open the way for gas-phase evaluation when needed, and it also provides possibilities for incorporating some of the thermal effects (Nitao, 1988).

A still more involved approach may be required to represent fracture and matrix flow more realistically. It would consider the fractures explicitly by zoning them into the system as a second region with much different properties than those of the matrix region. Each such region would involve separate capillary pressures, wetting phase saturations and hydraulic conductivity characteristic properties. It would be necessary to appropriately interrelate the regions through the water and gas phase pressures and capillary pressures involved. Some studies have used this approach as part of special research projects. While perhaps suitable for laboratory or small scale field studies, such a technique is not yet suited to larger site-scale numerical simulations, nor is it yet possible to characterize the range of smaller fractures at the overall site scale.

From considering the theoretical approaches for analyzing fracture effects on flow the PRT concludes:

1. The fundamental theory available today is not a single coherent and complete theoretical package capable of evaluating all facets arising in the unsaturated zone at Yucca Mountain.
2. Commendable technical progress has been made and must continue toward providing the much needed coherent and more complete theoretical approach for analyzing flow in the fractured unsaturated rock.
3. In the mean-time, the emerging, less-complete approximate theoretical approaches of the type now available for flow in fractured materials can and should be applied

selectively, consistent both with satisfying the specific assumptions involved and as recommended in Section 3.3.

4. Although the emerging, less-complete, and approximate theories are rigorous under the assumptions involved, meeting some of those assumptions are doubtful enough that careful validation through field and laboratory experimentation must proceed as a high priority.

3.5 Uncertainty and Stochastic Modeling

Given the complexity of the hydrologic setting as outlined in Section 3.1, and the theoretical constraints outlined in Section 3.4, it is clear that hydrologic modeling of the unsaturated-zone processes at Yucca Mountain will be accompanied by considerable uncertainty in model predictions. The research teams in the Yucca Mountain Project that are responsible for hydrologic modeling have recognized this fact and have begun to consider stochastic modeling approaches. It is important at this stage that these research teams examine not only the methods, but also the overall purposes of the stochastic modeling. There is little inherent value in knowledge of the predictive level of uncertainty. Stochastic modeling must be related to those program goals that can be placed in a probabilistic framework. The PRT can identify three types of applications: (1) hypothesis testing, (2) groundwater travel-time calculations, and (3) data-collection network design.

The philosophy of a hypothesis-testing approach to site characterization was described in Section 3.3. The testing of hypotheses is a statistical procedure, and the acceptance or rejection of a hypothesis is accompanied by a confidence level that can be generated by stochastic modeling. In this case, the output from stochastic modeling is related to an accept/reject, go/no-go, terminate/expand type of decision. The stochastic modeling is not carried out simply to identify the level of uncertainty, rather, it is an aid to decision making.

The calculation of unsaturated-zone travel time is discussed in Section 5.1. This calculation has been the traditional application of stochastic modeling in the nuclear waste program. The need arises from the probabilistic framework in which the regulatory criterion concerning travel time has been set. Continued stochastic modeling for travel time calculations will be required in the Yucca Mountain Project.

The stochastic modeling framework includes the ability to assess data worth. Data reduces uncertainty, decreases risk, and increases the level of confidence in decisions. It is possible to assess the potential value of a proposed data collection program prior to taking the measurements. This facet of the stochastic framework can be of considerable use in the design of data collection networks. The PRT urges the modeling research teams in the Yucca Mountain Project to keep abreast of research developments in this emerging field.

3.6 Model Verification and Validation

Because all work associated with Yucca Mountain will undergo critical public scrutiny, computer codes used in the site characterization effort must be mathematically verified and, to the extent possible, experimentally validated.

Verification should include comparisons to known solutions and intercode comparisons. In the material reviewed, model documentation and verification sometimes appeared to be lacking. As an example, results of TOSPAC were presented, but benchmarking results are apparently not yet available. Verification should precede published results to give more credibility to the code results. Another important aspect of code quality assurance is the inclusion of mass balance routines in the codes. This not only helps insure convergence to a correct solution; it also provides valuable information on the flow system. In the material reviewed, mass balance results for the various models were not reported.

Many of the technical assumptions underpinning the theory of the models are not yet supported by field observations. This emphasizes the importance of model validation. If it will not be possible to validate models at Yucca Mountain itself for some time, other similar sites should be used. Tunnels in Rainier Mesa, for example, encounter fractures that transmit water. The rock types are similar to those at Yucca Mountain, although welded tuffs are less common at Rainier Mesa, and the climate is wetter. Isotopic and chemical data indicate a short residence time for water in fractures in the tunnels (Clebsch, 1960a and b). While the Rainier Mesa setting is different, it may provide data for validation (or nonvalidation) of some of the models that have been proposed for use at Yucca Mountain.

4.0 HYDROLOGIC PROCESS CONSIDERATIONS

4.1 Precipitation and Evapotranspiration

Characterization of the meteorological conditions in the Yucca Mountain area is necessary to develop an understanding of the spatial and temporal variability of potential infiltration. The mechanisms of infiltration at Yucca Mountain are strongly dependent on the nature of the precipitation events. For instance, high-intensity storms which are sufficient to produce local ponding or rivulets can contribute to saturated flow through vertical fractures and channels, while low-intensity, long-duration events are likely to develop broad infiltration wetting fronts controlled by the matrix properties. Given the potential variability of infiltration mechanisms, it appears important to continue the study of the spatial and temporal nature of precipitation, both locally and regionally.

On the other hand, evapotranspiration measurements in the Yucca Mountain climatological environment are of relatively low priority. Actual evapotranspiration rates are so close to precipitation rates, that the accuracy of measured differences between the two is very low. It is these differences that are available for infiltration and runoff. It appears appropriate to concentrate more directly on understanding the relationships between precipitation and infiltration. Potential evapotranspiration in the Yucca Mountain area water balance will most likely always be an estimate based on theoretical calculations, and results will not be particularly meaningful to either the actual evapotranspiration or to the understanding of the remainder of the hydrologic budget.

4.2. Surface Infiltration

4.2.1. Introduction

Estimating net infiltration at Yucca Mountain is an extremely difficult undertaking. The problem is complicated by the significant spatial variability of the infiltration process over the area. Still, infiltration is one of the most crucial input variables in any modeling exercise of the Yucca Mountain unsaturated zone since it specifies the upper flux boundary conditions for the water flow subroutines. Hence, reliable estimates of the infiltration rates are important. Unfortunately, while a variety of methods exists for estimating infiltration, most are flawed by experimental or instrumental complexities arising from regional spatial variability and local heterogeneity of the surface soils and rocks. Section 4.2.2. briefly addresses possible infiltration mechanisms. Methods for estimating infiltration are reviewed in section 4.2.3. Data requirements are discussed in section 4.2.4. Instrumental needs and methods of analysis are reviewed in a more general framework in sections 4.2.5. and 4.2.6, respectively.

4.2.2. Infiltration Mechanisms

Evidence indicates that a variety of infiltration mechanisms are present at Yucca Mountain. These can be grouped into two broad categories: (1) "classical" flow as described by Richards' equation for relatively homogeneous surface materials, and (2) preferential flow caused by topographic irregularity, soil surface heterogeneity, unstable flow due to soil wettability conditions, flow into surface-connected fractures, lateral flow at or near the soil surface, and flow directly or indirectly into and through the major faults in the area. Because of the very low average annual recharge rate at Yucca Mountain, net infiltration by means of preferential flow may well be the most important infiltration mechanism in the region.

Infiltration is a spatially distributed process, with different mechanisms and rates occurring on the Yucca mountain crest and ridges, the slopes, and in the washes. As such, rates of infiltration vary depending upon the presence or absence of a soil cover, the exposure of surface-connected fractures, and the local and regional topography of the surficial soil or rock surfaces. The PRT believes that there is now sufficient evidence to indicate that rapid infiltration occurs into the surface connected rock-fractures. This evidence is augmented by information from isotope and other studies. Infiltration governed by classical flow (as described by Richards' equation) may be most important in the washes, especially during the wetter winter months. Unfortunately, the infiltration process for the washes is obscured by soil heterogeneity and preferential flow caused by irregular wetting, macropore flow, and lateral flow induced by sloped microscopic soil lenses and/or macroscopic soil stratification.

The PRT believes that net infiltration along the ridges and especially the slopes of Yucca Mountain can be equally or more important than infiltration into the washes. The washes provide an opportunity for buffering infiltrated runoff/rainfall water volumes, especially for relatively thick soil profiles. On the other hand, exposed fractured rock surfaces along the slopes have little or no buffering capacity, and hence are potentially very conducive to rapid and nonreversible infiltration. Hence the PRT suggests that an equal amount of work be invested in determining infiltration mechanisms and quantities along the ridges and mountain slopes as compared to the washes.

4.2.3. Methods for Estimating Infiltration

Several methods may be used for estimating infiltration into the Yucca Mountain site. As discussed at length at the review meetings, most of these methods require a combination of theoretical modeling and experimental research. A brief summary of available methods is given below. These and other methods are discussed at length in a recent review article by Gee and Hillel (1988).

A. Water Balance Measurements

This approach is based on a local or regional water balance of the form

$$I = P - E \pm R \pm dS \tag{1}$$

where I is net infiltration, P is precipitation, E is evapotranspiration, R is runoff (can be a source or sink), and dS is the change in water storage in the surface soil/rock horizon. The reliability of the water balance approach depends on the accuracy with which the components P, E, R, and dS can be measured. Unfortunately, as noted in Section 4.1, measurement of P and E is generally not precise enough to allow confidence in the differencing of two numbers of nearly equal value. P and E are subject to measurement errors that can easily be an order of magnitude larger than the expected values for the net infiltration rate at Yucca Mountain. Estimates of P are seldom more precise than about ± 5%, whereas the error in E is usually not less than about 10% (Gee and Hillel, 1988). Evapotranspiration estimates at Yucca Mountain may be especially vulnerable to errors because of the sparse and irregular plant cover. Additional errors occur in estimating water storage based on neutron probe measurements. Given that P and E at Yucca Mountain are roughly 200 mm/year, the above measurement errors suggest that a water balance calculation for Yucca Mountain could lead to infiltration rate estimates that can be anywhere between 0 and about 30 mm/year or more. The accuracy of the water balance method, as with most other methods, is further complicated by the spatial (and temporal) variability of runoff and soil water storage. Thus, the PRT believes that methods other than (or in addition to) water balance methods must be employed. We also believe that the relatively extensive efforts currently used to measure the components P and E in Eq. (1), especially E, could be scaled down at the benefit of other methods for measuring infiltration rates.

B. Water Balance Simulations

Rather than directly measuring the P, E, R, and dS components, detailed simulations could be carried out to estimate the infiltration rate, I. Such simulations could be based on Richards equation with a sink term to account for plant root water uptake. Several simulation models exist in the literature and may be used for this purpose. As before, these models again rely on calculation procedures for estimating E by using of a variety of root water uptake models and surface evaporation equations. While the simulation approach may produce more reliable results than methods which are based on direct measurement of P and E, the same issues of accuracy in P and E arise. In addition, the method relies on accurate estimates of the unsaturated hydraulic conductivity (which is seldom known to within an order of magnitude), and presumes the validity of Richards' equation for water flow. A good example of the potential errors involved with this method is given by Narasimhan et al. (1988) who reported mass balance calculations for an arid site ($P \approx 220$ mm/year) in Wyoming.

C. Methods based on Darcy's law.

Deep percolation could also be estimated directly with Darcy's law by measuring the unsaturated hydraulic conductivity and the hydraulic gradient. Direct measurement of the hydraulic gradient may be very unreliable because of soil heterogeneity and instrumental limitations. Equally important, the unsaturated hydraulic conductivity generally cannot be estimated to within one order of magnitude, especially for the low (but spatially and temporally variable) flow rates at Yucca Mountain. Studies at the Hanford site (Enfield et al., 1983) and in New Mexico (Stephens and Knowlton, 1986; McCord and Stephens, 1987) support our feeling that the Darcy method can lead to very large errors in infiltration rate, I. In addition, the Darcy method is based on the classical Richards' equation, and hence has no provisions for estimating preferential flow through heterogeneous soils and fractured surface rocks. Small- and large-scale topographic effects, lateral flow, and spatial variability, likely lead to additional uncertainties.

Still, the Darcian approach could prove to be useful for estimating recharge when applied to flow through the more homogeneous Paintbrush nonwelded unit (PT_n). This unit contains relatively few fractures and may dampen the oscillatory flow regime in the surface soils and rocks. Assuming steady-state flow through this unit, the hydraulic gradient in PT_n likely may be assumed to be unity (although this assumption must be validated). Accurate measurement of the hydraulic conductivity in PT_n remains crucial to obtaining reliable estimates of the recharge rate using Darcy's law.

D. Lysimeter Measurements.

Lysimeters can be valuable tools for estimating the field water balance by permitting the direct measurement of E, dS, and possibly also deep drainage (i.e., I). This is especially true for weighing lysimeters that can give accurate estimates for evapotranspiration and deep drainage below the root zone. Examples of the use of lysimeters for assessing recharge (to within a fraction of a mm) in arid regions are given by Jones and Skaggs (1987) and Fayer et al. (1986) for the Hanford site. The PRT team acknowledges that the installation of operation of lysimeters can be costly, and that other disadvantages and limitations exist (i.e., the use of disturbed soil/rock media, elimination of lateral flow, and a need to impose an artificial boundary condition at the bottom of the lysimeter). Nevertheless, we believe that the use of lysimeters could materially enhance the quantitative understanding of the infiltration/recharge process. The same is true for large undisturbed soil or rock blocks which could be instrumented in the field in situ (either at Yucca Mountain or elsewhere) or brought into the laboratory. The PRT believes that studies involving these types of lysimeters and undisturbed soil/rock blocks should be given a relatively high priority.

E. Estimates based on tracer or dye experiments.

Chemically inert solutes (such as Cl and Br) or selected dyes may be used as tracers to determine water flow rates and/or preferential flow paths. Because of the low flow rates at Yucca Mountain, many years may be required to detect significant movement. The same is true for selected isotopes, including ^{3}H and ^{36}Cl which are being used by several investigators to assess long-term recharge. Unfortunately, most methods involving tracers are based on piston-flow concepts, ignore preferential flow, and only occasionally consider dispersion resulting from soil heterogeneity. The same is true for stable isotopes, such as ^{18}O and Deuterium, in more global assessments of recharge at the Yucca Mountain site. Still, the PRT feels that this work should continue. Wherever possible, the isotope transport studies should be aligned more closely with ongoing efforts to model water flow through Yucca Mountain.

Of the above methods, the PRT believes that a combination of detailed lysimeter flow/transport studies and tracer tests, augmented with process-oriented modeling, provide the best opportunity for estimating infiltration rates at Yucca Mountain. Lysimeters and in-situ or laboratory soil/rock blocks offer additional opportunities for prototype testing of instruments, measurement methodologies, methods of data analysis, as well as yield valuable data for model calibration and validation.

4.2.4 Data Requirements and Instrumental Needs

Most of the methods discussed above for estimating infiltration require estimates of the unsaturated hydraulic properties of soils and rocks. Similar data requirements apply to water flow predictions through the entire unsaturated zone of the Yucca Mountain site. Detailed discussion of data needs is thus postponed to Section 4.3.2 in the Section on Unsaturated Zone Water Flow. Similarly, discussion of instrumental needs is postponed to Section 4.3.3.

4.3 Unsaturated Zone Water Flow

In this section, we provide comments with respect unsaturated-zone water-flow processes. These comments build on the introductory presentation of the issues in Sections 3.1 and 3.2, the theoretical discussions in Section 3.4, and the discussions of infiltration in Section 4.2.

The section is divided into four subsections. In subsection 4.3.1, we summarize the assumptions underlying the current theoretical treatment of unsaturated flow at Yucca Mountain. In subsection 4.3.2, we summarize data requirements. In subsection 4.3.3, we examine instrumental needs. And in subsection 4.3.4 we make some suggestions with respect to data analysis.

4.3.1 Theories Applied to Yucca Mountain

The theories currently being applied to hydrologic conditions in the unsaturated zone at Yucca Mountain are based on two sets of assumptions: (1) mathematical assumptions and (2) site concepts. Each set of assumptions is briefly summarized below, where the mathematical assumptions have been generalized to those used in most models.

Mathematical Assumptions

1. capillary-bundle theory is valid (restricts model to fractures with apertures less than a few millimetres);
2. a dual-porosity equivalent continuum can represent the media (overlapping continua exist everywhere);
3. pressure heads in the fractures and in the adjacent porous medium are the same (rapid attainment of equilibrium);
4. Darcy's law is valid;
5. the matrix is rigid;
6. flow is isothermal; and
7. rock properties can be determined using empirical relationships derived for unconsolidated materials.

Site Concepts

1. densely welded tuffs are highly fractured;
2. nonwelded, vitric tuffs have few fractures (more specifically, the Paintbrush nonwelded unit may significantly attenuate the downward migration of infiltrating water);
3. nonwelded, zeolitized tuffs have few fractures (more specifically, the Calico Hills nonwelded unit may significantly attenuate the downward migration of infiltrating water and has chemical sorption potential); and
4. fractures act as capillary pressure barriers at all locations where fracture apertures exceed the mean pore size within the adjacent rock matrix; flow across fractures occurs only at contact areas.

It is worth comparing these site concepts with those presented in Section 3-2.

4.3.2 Data Requirements

The most basic data requirement revolves around the hydraulic properties of the fractured, porous rocks at the site. It is these properties that will allow modeling of the infiltration process described in Section 4.2, and it is these properties that will allow validation of the site concepts listed in the previous subsection.

The hydraulic properties include the water retention (or characteristic) function, $\theta(h)$, and the unsaturated hydraulic conductivity, K(h), where θ is the water content, h is the pressure head, and K is the hydraulic conductivity. While a large number of methods have been developed by soil physicists and hydrologists, current technology remains time-consuming, costly, and largely unproven. This is especially true for the hydraulic properties of spatially variable and layered field soils, rock matrices, and fractures. Consequently, research involving the unsaturated hydraulic properties of the very heterogeneous surface materials at Yucca Mountain, and of the fractured or stratified subsurface (welded and nonwelded) geologic units, must be innovative and at the forefront of current technology. Few, if any, examples in the literature exist to guide the experimental plan for measuring the hydraulic properties. This is especially true for the hydraulic properties of fractures at relatively high values of pressure head (e.g., $-50 < h < 0$ cm), and of the rock matrix at relatively low pressure heads (e.g., $-10^5 < h < -10^3$ cm). Nonstandard techniques and methods of analysis must be developed. From the peer review meetings, and associated literature, the PRT is impressed with the abundance of new ideas and devices put forth by the investigators to theoretically or experimentally quantify these properties. Because of the importance of the hydraulic properties in estimating flow through the mountain, current efforts must be continued in a collaborative manner between LBL, USGS (Las Vegas and Denver), SNL and PNL. Close cooperation with other groups (notably the University of Arizona), and the soil physics community (perhaps through membership in Regional Technical Committees) is encouraged. Continued innovative research is needed in view of the extreme variability of the hydraulic properties within and across the various geologic units of Yucca Mountain.

In addition to the data on hydraulic properties, there is a need for qualitative data to validate the assumptions listed in Section 4.3.1. For example, the conceptual model for the repository horizon, wherein moisture entering a fracture is quickly imbibed into the matrix due to hypothesized high tensions in the matrix, has not been thoroughly tested by means of field or laboratory experiments. The block experiments currently being conceived will provide data to address this concept. Tensions and moisture measurements in the field will provide additional information to help determine if the conceptualization is appropriate. The plan to observe tension over long periods in packed-off intervals appears promising and, hopefully, will provide some of the required data.

Other features only partially addressed to date are the potential effects of fracture coatings and entrapped air. Fracture coatings and entrapped air can effectively isolate the fracture from the matrix. Hence, it is possible that significant fracture flow could occur under some conditions. Fracture mapping in the exploratory shaft will help to define the extent of fracture coatings. The potential impacts of entrapped air (high residual air saturation) limiting imbibition into the matrix need to be evaluated experimentally.

The anisotropy of both fracture and matrix material needs to be addressed. It appears that no attempt has been made to define anisotropy in three dimensions. Flow directions and paths can be significantly influenced by the anisotropy of the fractures and matrix materials. It is not clear how the anisotropy of the system will be determined.

The potential impacts that the natural flow of air through Yucca Mountain will have on field experiments will have to be evaluated. Work should continue to determine if air flow is only a near-surface phenomenon, limited to formations above the Paintbrush tuff, or whether it extends into deeper formations. Physical data as well as isotope data should be collected and evaluated to determine if the Paintbrush is an infiltration attenuation boundary, delaying downward migration, allowing some water to be removed by air flow.

The spatial variability of hydrologic properties needs to be addressed to accurately assess the potential recharge flux through the repository. The planned program of using multiple boreholes will help define some aspects of spatial variability. Similarly, the presence or absence of perched water needs to be evaluated at Yucca Mountain. Then, because of the potential importance of the tufaceous beds of the Calico Hills in both retarding water and chemical migration, it is important to characterize this layer to insure its effectiveness. Finally, there is a need to evaluate the potential impacts of faults on the water flow paths.

4.3.3 Instrumental Needs

There is a need to assess the reliability of laboratory instrumentation for measuring the pressure head, h (or soil matric potential) over different ranges of h, including standard soil physics approaches (soil tensiometry, pressure plates, pressure transducers), the SPOC system, psychrometry methods, and centrifugal methods. The same is true for measurement of the water retention and hydraulic conductivity curves in general.

The PRT is concerned about the use of psychrometer methods for measuring the pressure head at head values greater than about -1,500 cm; other methods may be needed, or must be developed, for measurements in this range. Hence, the PRT believe that an in-depth comparison of alternative instrumental techniques is a high-priority task. The team is also concerned about the use of mercury intrusion methods for measuring the water retention characteristics of rocks. There appears to be little or no evidence in the literature to suggest that the mercury intrusion method gives reliable answers. Equally worrisome to the committee is the use of centrifuge methods for determining the hydraulic properties of soils and rocks. While the centrifuge method may provide useful results for water retention properties, its reliability for measuring hydraulic conductivity is largely unproven.

While generally impressed with the deep down-hole instrumentation proposed at the site, we do still harbor some concerns. These concerns are primarily related to the use of neutron moderation in fractured rock, the long term operation of thermocouple psychrometers in the lower matrix capillary pressures, the proposed soil gas sampling program, and the apparent lack of a strategy to obtain pore-liquid samples should they be encountered in the drilling program.

The PRt recognizes that at capillary pressures running 0.1 through 5.0 bars there is a substantial change in water content (by weight) from 15% to 3% . What needs to be recognized, however, is that the relative humidity changes very little over this range (from 99.992 to 99.632%). The substantial gains in the use of thermocouple psychrometers, while they appear impressive, have not been tested over time, at these configurations and at these depths.

The PRT is not comfortable with the use of large-diameter, unsealed, uncased holes for neutron moderation in fractured rocks. Large-diameter 17 1/2 inch boreholes as utilized at UZ-1 may result in instrument equilibrium problems and poor-quality data. Although future deep boreholes will probably not exceed 12 1/4 inch diameter, this size is substantially larger than the 2 inch diameter neutron probe. In deep holes, the large diameters are required to facilitate the use of the number of instruments that must be placed down the hole, but the successful use of neutron moderation in such holes has not yet been demonstrated. In shallower holes, where only neutron probes are used, casing sizes which are more compatible with neutron moderation should be used.

In addition, evidence indicates that soil moisture may increase above these instrument clusters. Any potential build up of soil moisture above the packers can result in the migration of fluids through fractures below the packers, thereby creating artificial conditions in the measurement clusters. Concern is raised relative to the movement of fluids through the fractures and down the uncased walls of the borehole. The movement of moisture along the borehole wall would give an unrealistic distribution of soil moisture when read by neutron moderation. Consideration should be given to techniques for insuring that moisture migration through the borehole will not interfere with measurements taking place within the instrument clusters. This approach could involve systems for removing water from accumulation areas in the borehole, or packer systems of sufficient length and frequency to preclude borehole water movement. Consideration should also be given to the potential use of selectively placed casing with annular seals to preclude movement along the casing.

The proposed technique for vapor sampling at depth does not allow for multiple utility of the sampling device. A new approach utilized in Japan, considers the application of the BAT system. The BAT system which was patented in Sweden and licensed to the Japanese government, utilizes a hermetically sealed glass sampling vial which is transferred from the surface to the sampling depth without the use of pumps. In effect, the potential for cross contamination does not exist and there is no possibility of loss of gases. In addition, the device offers the further advantage of allowing in-situ permeability testing or the ability to obtain pore-liquid samples in addition to vapor samples. The Swedish government maintains an office in Long Beach, California, under the name of BAT Envirotech.

On the basis of discussions over the course of the PRT review, it appears that no strategy exists for obtaining pore-liquid samples within the capillary pressure range of 0 to approximately 60 centibars of suction. The PRT is of the opinion that over the anticipated vertical profile of the deep monitoring wells, perched saturated zones and nearly-saturated formations will be encountered. To date, no strategy has been developed for utilizing suction lysimeters to obtain pore-liquid samples. Research conducted by Everett (1988), indicates that two out of the three pore-liquid samplers available internationally have serious design flaws. In addition, the sole remaining suction lysimeter, which utilizes a 1.8 micron aluminum oxide ceramic, may have a cation exchange capacity which makes it unattractive for radioisotope analysis. The PRT is aware that the Vitrification Laboratory at Catholic University in Washington, D.C., is under contract to develop porous glass suction lysimeters which should be considered as a part of the tension saturated monitoring strategy.

Recognizing the sensitivity of the site and the small variety of instruments to be used at the site, the PRT is concerned about the impact of the failure of one or more of the measuring devices. A back-up position should be developed in case one or more of the proposed monitoring technologies fail. This approach makes sense in light of the political sensitivity of the site.

4.3.4 Methods of Data Analysis

Despite the above caveats, the PRT was favorably impressed with the development and implementation of state-of-the-art instrumental methods and measurement devices for collecting a large number of rock and soils data, both in situ and in the laboratory. Given the investments in time and money to developing these measurement methods, the team believes that a commensurate effort is needed in the analysis of the observed data, especially for hydraulic property determinations. Methods of analysis must be used, or developed as needed, to extract the most information from the collected data. One such method that offers considerable potential is based on parameter optimization techniques as explained below.

A variety of methods currently exist for measuring the hydraulic conductivity properties of unsaturated soils and rocks. Most of these methods rely on some type of numerical or analytical approximation or linearization of Richards' equation so that the equation can be inverted to yield an explicit equation for the hydraulic conductivity in terms of measurable soil/rock variables. These variables include water contents and pressure heads when the instantaneous profile (drainage-flux) method is used for surface soils. A more flexible approach to solving the inverse problem is by using parameter estimation methods. Several studies have recently shown how these methods may be used to estimate the water retention and/or hydraulic conductivity functions of soils (see Kool et al., 1987, for a review). In these approaches, the direct flow problem may be formulated for any particular set of initial and boundary conditions, and solved with any appropriate analytical or numerical method. One way to implement the parameter estimation method is to assume certain constitutive functions for the hydraulic properties (e.g., those of Brooks & Corey, van Genuchten, or other functions), and then to estimate the unknown parameters in those functions by means of an optimization algorithm that minimizes a given objective function (e.g, the sum of the square deviations between observed and calculated pressure heads, water contents, water fluxes, or other attributes characterizing unsaturated flow). Several examples for water flow and solute transport are given by Kool et al. (1987) and Kool and Parker (1988). A related example is given by Peters et al. (1986) who attempted to reconstruct the hydraulic properties of a PT_n rock sample from imbibition experiments using repeated runs of the TOSPAC code. Mishra and Parker (1989) give several examples in which a number of hydraulic and transport parameters (notably solute dispersion parameters) were estimated simultaneously from transient flow/transport experiments.

The PRT believes that these types of optimization methods may prove to be extremely useful for analyzing ongoing and planned laboratory imbibition experiments by the USGS (Denver and Las Vegas) to determine the unsaturated hydraulic properties of rocks and fractures. The methods provide an opportunity to extract as much information as possible from the experimental data. In particular, all transient observations of the pressure head, water content, and total water uptake by the sample (if measured), may be included in the objective function, rather than employing only time-consuming steady-state flow data. Of interest also is the application of parameter estimation methods to the imbibition of water into rock matrices with and without the surface coatings removed. This approach would give an estimate of the effects of surface coatings on the hydraulic properties of rock surfaces, and thus would help to validate the applicability of Richards' equation to flow into rock surfaces. Finally, parameter optimization methods should also be useful for improving the analysis of field experiments which use the instantaneous profile (drainage-flux), or other in situ methods, for estimating the unsaturated hydraulic conductivity.

4.4 Unsaturated Zone Gas Flow

Substantial gas flow has been observed in wells tapping the unsaturated fractured tuffs near the crest of Yucca Mountain. These flows are attributed to convective circulation through larger fractures arising from topographic relief, seasonal temperature variations, pressure changes, and density differences resulting from variations in gas composition. Air entering the mountain is drier than that will remove some of the water moving downward through the unsaturated zone.

This reduction in water flow moving downward by gas phase moisture capture emphasizes the importance of further regional gas-flow modeling. Though in the theoretical sense discussed in Section 3.4, such modeling should involve two-phase nonisothermal flow of fluids in heterogeneous fractured materials, it appears that simpler approximate modeling of gas flow through the mountain can lead to useful results (Kipp, 1987; Amter and Ross, 1990). Even though significant pressure, thermal, and vapor density effects exist, gas flow occurs primarily through larger fractures with minimal liquid phase effects in the fractures and essentially negligible matrix effects because of the relatively low gas pressure and temperature gradients involved in the fractures.

Additional effort should be given to providing appropriate gas flow models for analyzing the amount of vapor discharge from the mountain. Such modeling would enable careful scrutiny of the present estimated vapor discharge rates and complement the continuing field measurements (Thorstenson et al, 1989).

Particular care will be required in providing and applying appropriate gas models to obtain realistic flow results consistent with field observations. Providing realistic boundary conditions for the air pressure and to a lesser degree for the temperature may be a major modeling challenge. Whereas pressures and temperatures involve relatively small changes along the mountain boundaries, the seasonal changes with time may well introduce rather significant temporal variations. With the relatively small boundary variations, the pressure and temperature gradients under ambient conditions within the mountain should also be rather small so that any model calibration attempts will be difficult. Accordingly, simulations of conditions with wells penetrating the tuff formations likely will be most useful for testing model validity.

4.5 Saturated Zone Water Flow

The saturated zone beneath Yucca Mountain lies at a depth of 200 to 400 meters below the proposed repository horizon. This saturated zone is part of the

~~meters below the proposed repository~~ horizon. This ~~saturated zone is part of the~~ subregional ground-water flow system that extends from the south of Timber Mountain at the north to the Greenwater Range and Eagle Mountain at the south, and from the Funeral Mountains at the west to Jackass Flats at the east. Ground water within this subregional system flows in a southerly direction. The elevation of the potentiometric surface ranges from more than 1,100 m above sea level north of Yucca Mountain to about 600 m at Franklin Lake playa at the south end of the subbasin. Immediately south of Yucca Mountain, the potentiometric surface is very flat, at an elevation of about 730 m above sea level with a hydraulic gradient of about 0.0001. An area of steep hydraulic gradients, in the order of 0.15, occurs north and east of Yucca Mountain.

The subregional ground-water flow system is the ultimate receptor of water that may percolate through the proposed repository. It is a potential route by which radionuclides could be transported to the accessible environment. Present estimates of the travel time to the accessible environment, defined as a distance of 5 km from the site, are in the order of 150 years (see Section 5.2). Therefore, the saturated zone is not presently relied upon to provide protection against radionuclide transport to the accessible environment. The primary issues of concern with respect to the saturated zone are potential hydrologic changes that may occur as a result of tectonic activity, climatic changes and future ground-water development (Czarnecki, 1989).

The current model of the subregional flow system (Czarnecki, 1989) is a two-dimensional (areal) model based on an equivalent-porous-media conceptualization. Available hydraulic conductivity data have been used to develop the model and the model has been calibrated against available water-level data. Most of the wells from which the water-level data were obtained are open over large intervals and, therefore, the water levels represent composite heads. We note that there is evidence of vertical head gradients in the area; hence, the basic data is open to some question. The steep gradients north of Yucca Mountain are simulated by invoking a zone of low hydraulic conductivity in this area which acts as a barrier to flow and diverts the flow around the barrier and underneath the Yucca Mountain site. Discharge from the modeled area occurs by evapotranspiration at Franklin Lake playa. This conceptualization is different from that of previous models of the regional and subregional flow systems (Waddel, 1982; Czarnecki and Waddel, 1984; Rice, 1984; Czarnecki, 1985) which assumed discharge both at Franklin Lake playa and at Furnace Creek Ranch in Death Valley. This difference reflects the inclusion of recent data which indicate a potentiometric high at Greenwater Range west of Franklin Lake playa. The flow-system interpretation is still evolving.

The model was used to evaluate the potential effects of an increase in the hydraulic conductivity in the area of the steep gradient such as might result from tectonic activity (dam break scenario). This simulation indicated that there could be a 40-foot rise in the water table underneath the proposed repository site after 510 years.

According to Czarnecki, there are two main uncertainties associated with the modeling of the subregional flow system:

1. Does groundwater discharge split between Franklin Lake playa and Death Valley through a "window" at the Funeral Mountains?
2. What are the recharge paths by which groundwater beneath Yucca Mountain originates?

In the opinion of the PRT, the processes that control the movement of groundwater in the saturated zone are relatively well understood. Exceptions are the cause of the steep gradients north of the site and the uncertainty concerning the discharge areas.

The PRT is not convinced that the presence of this area of steep gradients is an important issue. It appears that the primary concern about the presence of the steep gradients is the potential alteration by tectonic activity of the conditions causing these steep gradients. The PRT believes that any tectonic activity capable of causing significant changes in the hydraulic properties of the subregional flow system would have more dire consequences for the site than a rise in the water table.

Czarnecki (1989) implies that eliminating the discharge at Death Valley results in a smaller quantity of flow beneath Yucca Mountain. The quantity of flow beneath Yucca Mountain is controlled by the transmissivity of the saturated zone and the hydraulic gradient at that location. If the transmissivities used in the subregional model are based on actual test data, and if recharge to the flow system upgradient of Yucca Mountain is adjusted during the calibration process to simulate the observed water levels, then the quantity of flow beneath the mountain should remain the same regardless of whether discharge from the system is only at Franklin Lake playa, or both at Franklin Lake Playa and Death Valley. We recognize that determining the recharge and the discharge from the system is a difficult task, not only for the subregional system at the Yucca Mountain site, but in general for most hydrogeologic systems. Determination of the transmissivity, or hydraulic conductivity, on the other hand is based on well established methodologies that provide fairly reliable estimates. The PRT recognizes that the great depth to the water table at this site poses a special challenge to hydrogeologic testing. However, we also believe that information on the hydraulic properties would be easier to obtain than attempting to determine recharge. If the flow beneath the mountain is based on transmissivities and hydraulic gradients, then the uncertainty concerning discharge areas becomes important only to the extent that it affects the flowpaths and travel times to the accessible environment.

The PRT does not believe that large-scale additional data collection is needed at this time. Priority should be given to data collection activities that would assist in refining the travel-time estimates (see Section 5.2). If updated estimates of travel time do not lead to revised travel-times on the order of 1000 years or more, then additional studies and data collection activities in the saturated zone would not be justified. The PRT suggests that a hypothesis-testing approach be used in establishing priorities for the groundwater data collection activities.

The present model of the flow system is based on a porous-medium conceptualization. The PRT believes that this is probably satisfactory for ground-water flow simulations. However, an attempt should be made to assess whether a double-porosity concept has any significant advantages. As will be discussed in Section 5.2, the double-porosity concept may be more suitable for transport simulations in a fractured medium.

The presence of vertical gradients indicates that the ground-water flow system in the vicinity of the site is three-dimensional. If recharge along Fortymile Wash causes significant downward gradients, then the flowpaths to the accessible environment would be longer than those based on the two-dimensional conceptualization. Therefore, if refined estimates of travel time based on two-dimensional flowpaths are less than but close to the required 1,000-year target, then the three-dimensionality of the system may need to be taken into consideration. Three-dimensional modeling of the regional or subregional flow system would require considerable additional data on depth-segregated hydraulic heads and conductivities.

5.0 TRAVEL TIME CONSIDERATIONS

5.1 Unsaturated Zone Travel Time

Present estimates of travel time through the unsaturated zone at Yucca Mountain are based on one-dimensional, vertical, steady-state, advective, unsaturated flow at unit gradient. Under these assumptions, the calculations require data on: (1) the thickness of each hydrogeologic unit along the assumed vertical flow paths, (2) the effective matrix porosity and the effective fracture porosity, (3) the saturated matrix hydraulic conductivity, (4) the Brooks-Corey exponent for relative matrix conductivity, and (5) the percolation flux between the disturbed zone and the water table (Lin and Tierney, 1986). Fractures are assumed to carry water only when the system becomes saturated. The saturated fracture conductivity is not required as input, because under a unit gradient, it is equal to the percolation flux, which is required as input.

The model is stochastic. The effective matrix porosity and the saturated matrix hydraulic conductivity are treated as random variables to take into account their spatial variability within each hydrogeologic unit.

In the calculations reported by Lin and Tierney (1986), a grid with grid blocks 250 ft. on a side was laid over the areal extent of the proposed Yucca Mountain repository, and one-dimensional calculations were made for the vertical column of rock corresponding to each grid block. For the upper limit of the estimated recharge flux, unsaturated-zone travel times exhibited a mean in excess of 40,000 years with a standard deviation of about 12,000 years. Less than 1% of the calculated travel times fell below 10,000 years. More recent calculations reported to the PRT by Kaplan suggest reduced travel times on the order of 16,000 years.

The PRT is encouraged by these results, but notes that the many assumptions underlying these preliminary estimates lead to a low level of confidence in their value at this time.

The use of a steady-state-flow approach is defended on the grounds that transient infiltration pulses are likely to be damped in the Paintbrush nonwelded tuff that overlies the repository. As note elsewhere in this report, this feature of the conceptual model of Yucca Mountain hydrology has yet to be confirmed in the field.

The use of a one-dimensional calculation is similarly open to question. There may well be horizontal flow routes in perched saturated zones along contacts at formation or interlayer boundaries. We agree with Lin and Tierney's (1986) assessment that "potential lateral flow and the concentration of flux down fault zones need to be investigated before the cumulative distribution function can be interpreted as representative of the fastest paths of likely radionuclide travel".

The PRT supports the probabilistic approach being followed by Sandia researchers. However, we encourage the research team to move toward a more realistic representation of the unsaturated-zone hydrology at Yucca Mountain; one that takes into account intralayer stratigraphic contrasts in hydraulic properties, transient water pulses, and three-dimensional flow mechanisms.

It is in the unsaturated-zone travel-time calculations that the need for integration between the performance-assessment teams and the site-characterization teams is greatest. Performance assessment against regulatory criteria must be carried out with models that reflect the latest field-measurement-based conceptual understanding of the hydrology at the site.

To this end, the research teams responsible for travel-time estimates must maintain a watching brief on research into gas-flow mechanisms at Yucca Mountain. The potential for gas-phase radionuclide transport cannot be divorced from the water-phase travel-time calculations.

5.2 Saturated Zone Travel Time

Present estimates of travel time to the accessible environment through the saturated zone are based on advective transport by ground water. The travel time has been calculated for a 5 km flow path, 4 km of which are through the tuffaceous beds of the Calico Hills and 1 km through the Topopah Spring Member of the Paintbrush Tuff. The hydraulic conductivities used in these calculations are based on the results of single-well tests, and the hydraulic gradients are based on observed water levels downgradient of the proposed repository site. Darcy velocities (specific discharge rates) calculated from these hydraulic conductivities and gradients we divided by calculated effective fracture porosities to determine particle velocities and estimate travel times. The estimated travel times are 50 years across 4 km of Calico Hills and 91 years across 1 km of Topopah Spring, or a total of 141 years across the 5 km to the accessible environment.

Because the processes that control the movement of groundwater in the saturated zone are well understood, calculations of travel time in the saturated zone are much easier to perform than those for the unsaturated zone. If the travel time through the saturated zone was larger than the 1,000 year requirement imposed by the U. S. Nuclear Regulatory Commission, the characterization of the site would be considerably simplified. Therefore, refining the estimates of travel time through the saturated zone should receive a high priority.

Whereas present estimates of travel time are based on field determinations of hydraulic conductivity and hydraulic gradients, the effective fracture porosities used in these estimates, 0.0004 for Calico Hills and 0.0028 for Topopah Spring, are not based on direct measurement. They have been calculated from fracture frequencies and apertures (personal communication with S. Sinnock, August 20, 1990). These calculated values of effective porosity appear to be very low and need to be verified in the field. In-situ effective porosities one order of magnitude larger than the calculated values are not beyond the realm of possibility. If such is the case, the travel time to the accessible environment could easily exceed the 1,000 year requirement. Given the potential consequences of larger saturated zone travel times, the PRT suggests that the planned tracer tests in the saturated zone be given a high priority.

It should be also noted that if travel time is interpreted as the arrival time of a given radionuclide concentration rather than that of a sharp advective front then matrix diffusion could play a very important role in delaying the arrival time and might result in much larger travel times. Interpretations of tracer tests conducted in the fractured Culebra dolomite at the Waste Isolation Pilot Plant (WIPP) site in New Mexico, using both double-porosity and single-porosity (porous medium) models (Reeves et al., 1987), indicate that travel times calculated using the double-porosity model are almost two orders of magnitude larger than those calculated using a single-porosity model with the fracture porosity. These interpretations further indicate that the best approximation to the double-porosity travel times is obtained by a single-porosity model using a fracture hydraulic conductivity and a combined fracture-plus-matrix porosity.

As stated earlier, the hydraulic conductivity values used in travel-time calculations are based on the results of field tests. The analyses of these tests need to be carefully reviewed to assure that these results are reliable. In particular, an evaluation must be made of whether the method used to analyze a given test is applicable to that specific type of test. For instance, the straight-line method of analysis assumes continuous injection at constant rate. Therefore, a review of the data from all injection tests should include an assessment of whether this condition was met during the tests. Similar reviews and evaluations, and if necessary re-analysis, of all the tests which form the basis of the hydraulic conductivity estimates would increase the confidence placed on these test results.

As the regional and subregional models of the saturated zone are refined, and particularly if three-dimensional models are developed, consideration should be given to incorporating into these models particle tracking routines to define flowpaths and calculate travel times.

Finally, travel times calculated on the basis of hydrogeologic data should be compared and made consistent with geochemical interpretations and isotopic age dating of groundwater in the vicinity of Yucca Mountain. The PRT supports the planned studies for Chlorine-36 analyses (Norris, 1989) and believes that they deserve a relatively high priority. Conversely, it must be recognized that isotopic age dating cannot be viewed as a stand-alone interpretive tool. Inconsistencies between isotopic ages and hydrogeologic travel times must be resolved.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Programmatic Issues

1. The PRT was impressed with the strong motivation of the hydrologic research teams in the Yucca Mountain Project and with the high scientific quality of the ongoing research programs and the published research record.
2. To fully capitalize on the research strengths of the individual research teams, there is a need for improved program integration and interagency communication in the Yucca Mountain Project.
3. It is imperative that the Yucca Mountain research teams gain access to suitable field sites on Yucca Mountain, or in similar terrain elsewhere, in order to carry out prototype studies required for equipment testing, concept hypothesis testing, field methodology development, and model validation.
4. In the opinion of the PRT, the quality-assurance procedures in the Yucca Mountain Project have become so over-formalized that they are creating unacceptable delays in the technical progress and a lowering of staff morale.
5. The PRT recommends a hypothesis-testing approach to site characterization whereby the calibration of hydrologic models is carried out with respect to integrated performance measures rather than a detailed matching of the state variables. The approach emphasizes the collection of field data for the purpose of reducing conceptual uncertainty through the testing of hypotheses, rather than for the reduction of parameter uncertainty per se.
6. The PRT is impressed with the development and implementation of state-of-the-art instrumental methods and measurement devices, especially with respect to deep downhole measurements of fluid pressures. The PRT offers strong support for the proposed deep borehole drilling program and recommends an early start for it. We have also identified several instrumental concerns. These are related to the use of neutron moderation in fractured rock, the long-term reliability of thermocouple psychrometers, the validity of mercury-intrusion and centrifuge methods in the laboratory measurement of hydraulic properties, and the strategies

for soil-gas and pore-liquid sampling at depth in the field. The PRT is also of the opinion that back-up strategies should be developed in case any of the proposed downhole monitoring technologies fail to perform as expected.

7. The PRT recommends that DOE streamline its publication review process so that technical reports are released or published within one year of preparation.
8. The PRT encourages the documentation, verification, and sharing of computer codes between research teams and across agency boundaries; we discourage the current trend toward model proliferation.
9. The PRT encourages closer coordination of construction activities and research activities on the Yucca mountain site. It is important that the influence of site construction on infiltration properties and drainage patterns be minimized.
10. The PRT encourages improvements in site housekeeping with respect to fluid spillage, borehole leakage, site security and well abandonment.

6.2 Technical Issues

11. The PRT did not identify any conceptual hydrologic paths of fluid flow through the unsaturated zone at Yucca Mountain that have not come under consideration as potential radionuclide migration routes by the various research teams.
12. The PRT is convinced that there is a source of water (both in the form of low-intensity, long-duration winter storms, and in the form of high-intensity storms), and a mechanism of infiltration (in the form of large-aperture surface fractures) that can introduce water to the ridges, slopes and upland areas of Yucca Mountain, in addition water that to infiltrates into the washes following rare runoff events. The PRT believes that a combination of lysimeter studies, tracer tests, and process-oriented modeling offers the best opportunity for estimating infiltration rates at Yucca Mountain.
13. One of the most critical features of the conceptual hydrologic model for Yucca Mountain is the postulated ability of nonwelded tuffs to attenuate and retard transient moisture pulses. We encourage early field experimentation in the Paintbrush nonwelded tuff and the nonwelded tuffs of the Calico Hills unit to

investigate the validity of this mechanism.

14. The most important conceptual issue at the Yucca Mountain site revolves around the hydrologic processes of matrix/fracture interaction. The PRT recognizes the difficulties in developing a single, coherent, and complete theoretical formulation capable of evaluating nonisothermal, multiphase fluid flow in a dual-porosity medium. The PRT is impressed with the emerging approximate theoretical approaches being developed within the Yucca Mountain project. However, it is imperative that there be continued evaluation of the assumptions that underlie these methods; in particular, the assumption of fluid-pressure equivalence across the matrix/fracture boundary, and the acceptance of the concept of overlapping continua. The PRT believes that it is unlikely that fractures will achieve sufficient separation or continuity to act as effective barriers to vertical infiltration.
15. The PRT believes that perched saturated zones will almost certainly be encountered during exploratory drilling at the site. Protocols should be in place for the sampling and testing of such zones. The presence of such zones should not, in and of themselves, disqualify the site from consideration for a nuclear waste repository.
16. The role of gas flow through Yucca Mountain deserves continued attention, especially with respect to its effects on moisture redistribution and potential radionuclide migration in the vapor phase.
17. The PRT supports proposed subsurface investigation of the hydraulic properties and hydrologic influence of fault zones on the Yucca Mountain site.
18. The PRT encourages the emerging development of stochastic modeling approaches in the Yucca Mountain Project. A stochastic component to modeling endeavors is required in order to meet the regulatory travel-time criterion, to carry out hypothesis testing, and to aid in assessing the worth of proposed data collection networks.
19. Inconsistencies between isotopic age dating of waters at depth and unsaturated groundwater travel times calculated with hydrogeologic models must be resolved.
20. Studies of two-phase fingering in traditional porous media have very little

little relevance to the Yucca Mountain Project. The PRT encourages an early transfer of research efforts on fingering from traditional porous media to fractured porous media.

21. The PRT supports research on the hydrologic influence of fracture coatings and fillings. However, it is possible that such coatings may be limited in their areal extent, and if so, they may not be of major importance. On the other hand, if ubiquitous, they could exert considerable influence on flow processes. Field investigation is in order.

22. The PRT recommends a re-examination of the saturated-zone groundwater travel-time calculations, especially with respect to the suitability of the hydraulic-conductivity and effective-porosity values used for this dual-porosity system. However, if updated estimates do not lead to revised travel times on the order of 1000 years or more, then additional studies and data collection activities in the saturated zone should be curtailed.

23. Reliable, direct, quantitative field measurements of evapotranspiration and groundwater discharge are probably not feasible in the Yucca Mountain climatological environment. The PRT recommends a low priority for these programs.

24. The PRT doubts that the release of water from the area of steep gradients north of the Yucca Mountain site due to tectonic activity is an important issue. We believe that any tectonic activity capable of causing significant changes in the hydraulic properties of rocks on a regional basis would have more dire consequences for the site than a rise in the water table.

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APPENDIX A

Peer Review Team

PEER REVIEW TEAM FOR UNSATURATED ZONE HYDROLOGY

1. Dr. R. Allan Freeze, Chairman
   R. Allan Freeze Engineering, Inc.
   3755 Nico Wynd Drive
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   British Columbia, Canada V4A5Z4
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2. Dr. Lorne G. Everett
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3. Mr. Gerald E. Grisak
   Vice President- Hydrogeology
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5. Mr. R. William Nelson
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6. Dr. Stavros S. Papadopulos
   President,
   S. S. Papadopulos & Assoc., Inc.
   Consulting Ground-water Hydrologists
   12250 Rockville Pike, Suite 290
   Rockville, Maryland 20852
   301-468-5760

7. Dr. M. Th. (Rien) van Genuchten
   U.S. Salinity Laboratory
   4500 Glenwood Drive
   Riverside, CA 92501
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ENCLOSURE 1

PEER REVIEW TEAM SELECTION RECORD

PEER REVIEW SUBJECT: Unsaturated Zone Hydrology at Yucca Mountain

Function	Representative
Chairman, ground-water hydrology	Dr. R. Allan Freeze
Vadose zone instrumentation and monitoring	Dr. Lorne G. Everett
Deep well instrumentation; nuclear waste hydrogeology	Mr. Gerald E. Grisak
Computer modeling of flow and transport	Dr. James W. Mercer
Unsaturated flow; nuclear waste disposal	Mr. R. William Nelson
Ground-water hydrology, well testing for permeability	Dr. Stavros S. Papadopulos
Theory of unsaturated flow and transport	Dr. M.T. van Genuchten

Based on review of the qualification documentation, these representatives cover the functions for this Review, and are acceptable as team members to accomplish the scope and purpose of this review.

Signed: R.A. Freeze
Peer Review Chairperson

APPENDIX B

Meeting Attendees

PEER REVIEW OF THE HYDROLOGY STUDIES OF THE UNSATURATED ZONE AT YUCCA MOUNTAIN

First Meeting - April 23-26, 1990

Full-Time Attendees

The Peer Review Team
Claudia Newbury, DOE Representative
Marvin Saines, Technical Secretary
Dwight Hoxie, USGS Observer
Everett Spinger, Los Alamos Observer
George Barr, Sandia Observer
Dwayne Chesnut, Lawrence Livermore Observer

Part-Time Attendees

Max Blanchard, DOE
Arch Girdley, DOE
Russ Dyer, DOE
Keith Kersch, SAIC
Steve Mattson, SAIC (Field Trip)
Barney Lewis, USGS (Field Trip)
Dave Beck, USGS (Field Trip)
Mike Chornack, USGS (Field Trip)

PEER REVIEW OF THE HYDROLOGY STUDIES OF THE UNSATURATED ZONE AT YUCCA MOUNTAIN

Second Meeting - June 4-8, 1990

List of Attendees*

June 4, 1990

Rick Whitfield, USGS
Larry Hayes, USGS
Joe Rousseau, USGS
Alan Flint, USGS
Carol Boughton, USGS
M.P. Chornack, USGS
Robert Craig, USGS
Charles A. Peters, USGS
Gary LeCain, USGS
Edward Kwicklis, USGS
Gary Severson, USGS
William Thordarson, USGS
June Fabryka-Martin, LANL
Robert S. Saunders, WEC
William E. Wilson, USGS
Everett Springer, LANL
John Cummings, SNL
Holly Dockery, SNL
Dwayne Chesnut, LLNL
Rick Spengler, USGS
Dwight Hoxie, USGS
Lorrie Flint, USGS
Paul Kaplan, SNL
R.W. Barnard, SNL
Keith Kersch, SAIC
Dan Gillies, USGS
Don Thorstenson, USGS
R.J. Glass, SNL
Barney Lewis, USGS
Bo Bodvarsson, LBL
Falah Thamir, USGS
Albert Yang, USGS
Tony Buono, USGS
U. Schimschal, USGS
Don Livingston, DOE
John Czarnecki, USGS
Ralph Peters, SNL
Chuck Savard, USGS
G.E. Barr, SNL
Joseph Wang, LBL
Jonathan D. Istok, Oregon State Univ.
Rob Trautz, USGS

* In addition to Peer Review Team, DOE Representative, and Technical Secretary

June 5, 1990

Dwayne Chesnut, LLNL
M.P. Chornack, USGS
Robert Craig, USGS
June Fabryka-Martin, LANL
Everett Springer, LANL
Robert S. Saunders, WEC
R.W. Spengler, USGS
Holly Dockery, SNL
George E. Barr, SNL
William Thordarson, USGS
Joe Rousseau, USGS
Chuck Savard, USGS
Lorrie Flint, USGS
Alan Flint, USGS
Gary LeCain, USGS
Falah Thamir, USGS
Gary Severson, USGS
Edward Kwicklis, USGS
Charles A. Peters, USGS
Don Thorstenson, USGS
Paul Kaplan, SNL
Dwight Hoxie, USGS
John Cummings, SNL
Albert Yang, USGS
Keith Kersch, SAIC
Rob Trautz, USGS
Bo Bodvarsson, LBL
Don Livingston, DOE
U. Schimschal, USGS
Tony Buono, USGS
Rick Whitfield, USGS
Carol J. Boughton, USGS
Dan Gillies, USGS
Barney Lewis, USGS

June 6, 1990

Paul Kaplan, SNL
Dwight Hoxie, USGS
Joseph Wang, LBL
Everett Springer, LANL
Chuck Savard, USGS
Carol Boughton, USGS
John Cummings, SNL
Falah Thamir, USGS
Dwayne A. Chesnut, LLNL
Joe Rousseau, USGS
Charles A. Peters, USGS
Dan Gillies, USGS
Gary LeCain, USGS
Keith Kersch, SAIC
Don Livingston, DOE
June Fabryka-Martin, LANL
Barney Lewis, USGS
M.P. Chornack, USGS
George E. Barr, SNL
Robert Craig, USGS
Alan Flint, USGS
Ralph Peters, SNL
William Thordarson, USGS
R.W. Barnard, SNL
Holly Dockery, SNL
Bo Bodvarsson, LBL
Tony Buono, USGS
Rick Whitfield, USGS
Gary Severson, USGS
John Nitao, LLNL
William E. Wilson, USGS
Albert Yang, USGS
Ed Kwicklis, USGS
Lorrie Flint, USGS
R.S. Saunders, WEC

June 8, 1990

Alan Flint, USGS
Tony Buono, USGS
Mike Chornack, USGS
Larry Hayes USGS
Bob Craig, USGS
Joe Rousseau, USGS
Don Thorstenson, USGS
Ken Richards, USGS
John Peck, SAIC
Steve Mattson, SAIC
Dan Blout, FNS
Jack Istak, Oregon State

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APPENDIX C

Documents Reviewed

READING LIST FOR FIRST MEETING OF HYDROLOGY PEER REVIEW TEAM, LAS VEGAS, APRIL 23-26, 1990

1. Volume 13 of "Radioactive Waste Management and Nuclear Fuel Cycle," pp 21-36, 51-92, and 121-145.

2. "Yucca Mountain Project Environmental Assessment," pp. 3-1 - 3-33.

READING LIST FOR SECOND MEETING OF HYDROLOGY PEER REVIEW TEAM
LAS VEGAS, JUNE 4-8, 1990

LOS ALAMOS

1. NORRIS, A.E., 1990, The Use of Chlorine Isotope Measurements to Trace Water Movements at Yucca Mountain, Proceed. of Nuclear Waste Isolation in the Unsaturated Zone, Focus '89, Amer. Nuclear Soc., 5 pages.

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2. KLAVETTER E.A. AND PETERS, R.R., 1986, Estimation of Hydrologic of an Unsaturated Fractured Rock Mass, Sandia Rept. SAND84-2642, 50 pages.

3. HELLER, P.R., 1985, Water Retention Characteristics and Hydraulic Conductivities for Tuffaceous Material from the Nevada Test Site - 1985 Samples, Sandia Keystone Document 6310-85-10, 40 pages.

4. PETERS, R.R. AND OTHERS, 1984, Fracture and Matrix Hydrologic Characteristicss of Tuffaceous Materials from Yucca Mountain, Nye County, Nevada, Sandia Rept. SAND84-1471, 64 pages and 6 append.

5. KLAVETTER, E.A. AND OTHERS, 1989, Experimental Plan for Investigating Water Movement Through Fractures, Sandia Rept. SAND84-0468, 48 pages and 4 append.

6. KLAVETTER, E.A. AND PETERS, R.R., 1986, Fluid Flow in a Fractured Rock Mass, Sandia Rept. SAND85-0855, 44 pages.

7. KLAVETTER, E.A. AND PETERS, R.R., 1987, An Evaluation of the Use of Mercury Porosimetry in Calculating Hydrologic Properties of Tuffs From Yucca Mountain, Nevada, Sandia Rept. SAND86-0286, 52 pages and 2 append.

8. PETERS, R.R. AND OTHERS, 1987, Measuring and Modeling Water Imbibation into Tuff, in Flow and Transport Through Unsaturated Fractured Rocks, Geophysical Monograph 42, 12 pages. [Note: This paper is also included in Reference No. 20.]

9. PETERS, R.R. AND KLAVETTER, E.A., 1988, A Continuum Model for Water Movement in an Unsaturated Fractured Rock Mass, Water Resources Research Vol. 24, No. 3, 13 pages.

10. LIN. Y.T. AND TIERNEY, M.S., 1986, Preliminary Estimates of Groundwater Travel Time and Radionuclide Transport at the Yucca Mountain Repository Site, Sandia Rept. SAND85-2701, 81 pages and 4 append.

11. DUDLEY, A.L. AND OTHERS, 1988, Total System Performance Assessment Code (TOSPAC) Volume 1: Physical and Mathematical Bases, Sandia Rept. SAND85-0002, 183 pages.

12. PETERS, R.R. AND OTHERS, 1986, The Effect of Percolation Rate on Water-

Travel Time in Deep, Partially Saturated Zones, Sandia Rept. SAND85-0854, 33 pages.

LAWRENCE LIVERMORE

13. NITAO, J.J. AND BUSCHECK, T.A., 1989, On the Movement of a Liquid Front in An Unsaturated, Fractured Porous Medium, Part I, LLNL Rept. UCID-2714, 44 pages.

14. NITAO, J.J., 1989, On the Movement of a Liquied Front in An Unsaturated, Fractured Porous Medium, Part II, LLNL Rept. UCID-21743, 26 pages.

15. RAMIREZ, A.L. AND OTHERS, Prototype Heater Test of the Environment Around a Simulated Waste Package, LLNL Rept. UCID-101693, 12 pages.

U.S. GEOLOGICAL SURVEY

16. DEPARTMENT OF ENERGY, 1988, Hydrology, Chapter 3, Site Characterization Plan, 241 pages. [Note: Read mainly the unsaturated zone sections.]

17. FLINT, ALAN, 1990, Characterization of the Unsaturated-Zone Infiltration, Draft Study Plan No. 8.3.1.2.2.1, 239 pages.

18. FLINT, ALAN, AND ROUSSEAU, JOE, 1988, Characterization of the Yucca Mountain Unsaturated-Zone Percolation: Surface-Based Studies, Draft Study Plan No. 8.3.1.2.2.3, 205 pages.

19. WEEKS, E.P., 1989, Characterization of the Yucca Mountain Unsaturated-Zone Gaseous Phase Movement, Draft Study Plan 8.3.1.2.2.6, 77 pages.

20. EVANS, D.D., AND NICHOLSON, T.J., 1987, Flow and Transport Through Unsaturated Fracture Rock, Amer. Geophys. Union Geophysical Monograph 42, 187 pages.

21. ROSS, C.S. AND SMITH, R.L., 1961, Ash Flow Tuffs: Their Origin, Geologic Relations, and Identification, U.S.G.S. Prof. Paper 366, 50 pages.

22. SMITH, R.L., 1960, Zones and Zonal Variations in Welded Ash Flows, U.S.G.S. Prof. Paper 354-F, 13 pages.

United States Department of the Interior

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WBS#: 1.2.3.1
QA: N/A

IN REPLY REFER TO:
May 18, 1990

Nick Saines
Technical & Management Support Services
Yucca Mountain Project
c/o SAIC
101 Convention Center Dr.
Suite 407
Las Vegas, Nevada 89109

Dear Mr. Saines:

In regards to the June 4-8 meeting of the Yucca Mountain Project Unsaturated-Zone Hydrology Peer Review Team, please add the following references to the PRT reading list.

Lewis, B., and others, 1988, Characterization of the Yucca Mountain Unsaturated-Zone Percolation, Exploratory-Shaft-Facility Study, Study Plan No. 8.3.1.2.2.4, R0.

Yang, I.C., 1990, Hydrochemical Characterization of the Unsaturated Zone, Draft Study Plan No. 8.3.1.2.2.7, R0.

Montazer, P., and Wilson, W., 1984, Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada: U.S. Geological Survey Water-Resources Investigations Report 84-4345, 55 p.

Thorstenson, D.C., Weeks, E.P., Haas, H., and Woodward, J.C., 1990, Physical and chemical characteristics of topographically affected airflow in an open borehole at Yucca Mountain, Nevada: In Proceedings of the Topical Meeting on Nuclear Waste Isolation in the UZ, Focus '89, American Nuclear Society, Inc.

Should you have questions regarding these references, please contact me at FTS 776-0546.

Sincerely,

Daniel C. Gillies

Daniel C. Gillies
Acting Chief, Nuclear Hydrology Program, YMPB

cc: W. Wilson
D. Hoxie
B. Lewis
LRC File 3.3.11

#210-A

APPENDIX D

List of Questions and Topics

LIST OF QUESTIONS AND TOPICS TO BE ADDRESSED BY YUCCA MOUNTAIN PRINCIPAL INVESTIGATORS AT SECOND MEETING OF PEER REVIEW TEAM, JUNE 4-8, 1990, LAS VEGAS, NV.

Prepared by Peer Review Team for Review of Unsaturated Zone Hydrology Work at Yucca Mountain.

Members of Peer Review Team

R. Allan Freeze, Chairman
Lorne G. Everett
Gerald E. Grisak
James W. Mercer
R. William Nelson
Stavros S. Papadopulos
M. Th. (Rien) van Genuchten

Introduction

Following a discussion of the issues presented in Table 1 of the Peer Review Plan (copy attached), the Peer Review Team (PRT) prepared the following list of questions and topics for the principal investigators.

The organization of the list reflects the PRT's differentiation between Processes (Sections A through H) and Calculation Methodologies (Sections I and J). The list also includes sections on Instrumentation Issues (Section K) and Modelling Philosophies (Section L). Lastly, there is a section on Site Housekeeping Issues (Section M).

The scope of the list of questions is circumscribed to some degree by the terms of reference of the Peer Review Plan. The PRT has been asked to emphasize: (1) flow, rather than transport, (2) unsaturated-zone processes, rather than saturated-zone processes, and (3) site characterization issues, rather than design or performance-assessment issues.

A. UNSATURATED-ZONE WATER-FLOW PROCESSES: MATRIX FLOW

1. How are the unsaturated hydraulic properties (the "characteristic curves" of water-content vs pressure-head, and hydraulic-conductivity vs pressure-head) being developed for the rock matrix of the various types of tuff?
   (a) What laboratory techniques are being used and what are their limitations?
   (b) What is the planned program for in-situ field determination of these properties?
   (c) How do either or both of the programs (lab and field) plan to address the issue of spatial variability of rock matrix properties?
   (d) Has the issue of residual saturation values received the particular attention it deserves? (i.e.: vapor phase effects, limiting hydraulic parameters.)

2. How will the water content and pressure head be determined in situ?
   (a) How will the rock disturbance caused by drillhole or shaft installation be taken into account?
   (b) What type of instrumentation will be used, and what are the limitations, operational ranges, and accuracies of such instrumentation?
   (c) Can neutron probes be used to measure absolute values of water content? If not, are relative values sufficient?

3. What methods, if any, will be used to back out unsaturated hydraulic properties of the rock matrix from observed in-situ measurements of water content and pressure head?

4. Are there any problems related to the lab or field measurement of unsaturated hydraulic properties or in-situ water contents and pressure heads in surficial alluvium deposits?

B. UNSATURATED-ZONE WATER-FLOW PROCESSES: FRACTURE FLOW

1. How will surface and subsurface geologic data on fractures (frequency, aperature, length, continuity, connectivity, etc.) be incorporated in the evaluation of fracture flow?

2. Are there any differences between cooling and tectonic fractures which would result in different hydrologic characteristics?

3. What surface and/or borehole geophysical techniques will be used to evaluate fracture patterns and their relationship to geologic structure?

4. How are the unsaturated hydraulic properties being developed for the fracture networks in the various types of tuff?

   (a) Are there any laboratory techniques under consideration?

   (b) What is the planned program for in-situ field determination of these properties? Will measurements be carried out for different types of tuff at various depths?

   (c) How do either or both of these programs (lab and field) plan to address the issue of spatial variability of rock fracture hydraulic properties?

C. UNSATURATED-ZONE WATER-FLOW PROCESS: MATRIX/FRACTURE INTERACTIONS

1. What studies are planned to assess whether coatings and mineralization observed on fracture faces may produce hydraulic properties at the face that differ from matrix hydraulic properties? If such differences exist, could they significantly influence the unsaturated transfer of water across matrix/fracture boundaries?

2. In particular, is the issue of hydrophobicity of fracture faces being addressed? Could it arise under the influence of drying due to gas-phase flow in the fractures?

3. What are the implications of fracture-face mineralization or hydrophobicity on the mercury intrusion method of developing water retention curves?

4. If cross-fracture flow is limited to areas of matrix contact, how will the effective contact area be determined or estimated in-situ, given the difficulties of accessing undisturbed fractures from subsurface openings?

D. UNSATURATED-ZONE WATER-FLOW PROCESSES: GENERATION OF SATURATED FLOW

1. What are the natural conditions (ie. during the period prior to repository emplacement) that could result in the generation of zones of saturated flow within the unsaturated zone (fracture barriers, capillary barriers, layered stratigraphy, three-dimensional heterogeneities, etc)?

2. Have any model simulations been carried out to evaluate the necessary and sufficient conditions required to create saturated flow in any of these cases, or to investigate their sensitivity to rock hydraulic properties?

3. Are there any field or laboratory experiments planned to investigate these issues?

4. If it is possible that saturated flow conditions may be generated by any of these mechanisms, what are the implications with respect to rapid, fracture-dominated downward flow toward the water table?

5. Does the sporadic nature of rainfall and the high intensity of the rainfall rates in this arid environment enhance the likelihood of generating saturated flow at depth at capillary or fracture barriers (see also Section F)?

6. Is there any documentation summarizing the anecdotal evidence of saturated flow (eg. water inflow in neutron hole N-2, televiewed seepage in drillholes, flow of drilling water from G-1 to UZ-1, seepage in G-tunnel, etc)? Is there any evidence of recent springs in the vicinity of Yucca Mountain?

E. UNSATURATED-ZONE WATER-FLOW PROCESSES: PREFERENTIAL FLOW PATHS

1. What saturated/unsaturated conditions or flow processes in the unsaturated zone might lead to the generation of preferential flow paths?

   (a) Instabilities and fingering at boundaries between tuff layers with different hydraulic properties?

   (b) Hydrophobicity and water repellancy (see C.2)?

(c) Connectivity generated by intersections of capillary barriers and vertical fractures (see D.4)?

F. SURFACE-WATER INFILTRATION PROCESSES

1. What are the mechanisms of infiltration on: (i) upland rock surfaces, and (ii) alluvium-filled washes, and what is their relative importance to the water balance of the area?

2. Will infiltration rates be estimated both by direct measurements during rainstorm events, and by indirect water balance or modeling calculations?

3. With respect to direct measurements during rainfall events:

   (a) What measurements are being used or comtemplated (i) on upland rock surfaces, and (ii) in alluvial washes?

   (b) What type of measurement network is being planned to estimate the spatial variability of infiltration during rainfall events?

4. With respect to indirect modeling:

   (a) What models or water balance equations are being used or contemplated for estimation of long-term and short-term infiltration into rock surfaces and alluvial washes?

   (b) What calculations or modelling exercises will be used to assess spatial variability in infiltration due to (i) large-scale heterogeneity in rock type, and (ii) topographic variability in rainfall rates?

5. Is there any possibility of short-circuiting of the infiltration that occurs on the upslope portions of Yucca Mountain? Could there be discharge of the infiltrated water out of the mountain sideslopes above the repository horizon due to (i) water-phase transport, or (ii) gas-phase transport (see Section G)?

6. Are field experiments planned to measure the response of water-content profiles to natural and/or experimentally-induced infiltration events? Can such experiments be used to estimate the depth (if any) at which the water-content transient induced by surface infiltration events becomes negligible? Do bedded or nonwelded tuffs act to attenuate transient infiltration effects?

7. What studies will be carried out to determine the potential effects of roadways, transects, pads, and other repository construction activities on the uniformity of infiltration?

G. UNSATURATED-ZONE GAS-PHASE-FLOW PROCESSES

1. What is the quantitative significance of gas-phase water-vapor transport to the Yucca Mountain water balance?

(a) What are the boundary conditions for air, water vapor, and water flow in the mountain?

(b) Is air and water-vapor flux through the mountain limited to fractures?

(c) Is air and water-vapor flux limited to the upper part of the mountain?

(d) Is it possible to transport colloidal particles in the vapor phase?

2. What is the theoretical basis of gas-phase air-and-water-vapor-flow modeling (transfer coefficients, driving forces, etc.)? Will such modeling be carried out (i) in a multiphase formulation? (ii) for non-isothermal conditions?

3. How will the lab and field gas-phase data base be developed with respect to hydraulic properties of the matrix and fractures, and with respect to in-situ water-vapor conditions? (This question is the gas-phase equivalent to questions A.1, A.2, and B.4).

4. Is the wintertime exhaust of air from Yucca Mountain a long-term condition? What are the implications of the seasonal timing of air flow at the mountain surface relative to precipitation and infiltration in fractures?

H. UNSATURATED-ZONE FLOW PROCESSES: FLUID PROPERTIES

1. Are the nonhomogeneous fluid properties of gas and water (density, viscosity, surface tension, material wetting properties, etc.) that result from the dependency of these properties on temperature, pressure, and concentration of dissolved solids and gases, of quantitative significance in developing the gas-phase and water-phase flow directions and flux values in the unsaturated zone at Yucca Mountain?

2. If so, how are these dependencies accommodated in:

(a) theoretical model analyses?
(b) field and laboratory measurements?

I. UNSATURATED-ZONE TRAVEL-TIME CALCULATION METHODOLOGY

1. How is travel time defined? What are the technical implications of this definition?

2. Can travel-time calculations be made using one-dimensional flow tubes, or is a two-or-three-dimensional analysis needed?

3. What is the theoretical basis for the models used to make travel time calculations, (i) for models used in the past, and(ii) for models contemplated for the future? What data are used in these models? What boundary conditions are used in these models?

4. Do the travel-time calculations take into account transient pulses due to infiltration events or are they steady-state analyses?

5. Do the travel time calculations take into account the potential existence of preferential flow paths (Section E) and gas-phase vapor transfer (Section G)?

6. How is uncertainty addressed in the calculations:

   (a) with respect to model conceptualization?

   (b) with respect to hydraulic properties and their spatial variability?

7. How are the models calibrated and validated?

8. Have any modifications been made to planned field studies on the basis of modelled travel time calculations?

9. Are unsaturated-zone travel time estimates made thus far consistent with isotope age dating of water at Yucca Mountain?

10. Are unsaturated-zone travel time estimates made thus far consistent with water balance calculations performed for Yucca Mountain?

J. SATURATED-ZONE TRAVEL-TIME CALCULATION METHODOLOGY

1. What methods are being used for travel-time calculations in the saturated zone? Do they involve only numerical and/or analytical modeling? Or do they also include tracer experiments? For the modeling:

   (a) Is the analysis one-, two-, or three-dimensional?

   (b) Is the model based on a porous-media or fracture-flow conceptualization?

   (c) What is the basis for the transmissivities, storativities, and effective porosity values used in the model?

   (d) What are the boundary conditions used?

   (e) What recharge distribution is used?

3. What are the uncertainties associated with the saturated-zone travel-time calculations, and what is the level of confidence in the current estimates?

4. How are the models calibrated and validated?

5. Have any modifications been made to planned field studies on the basis of modelled saturated-zone travel-time calculations?

6. Are saturated-zone travel time estimates made thus far consistent with isotope age dating of groundwater at Yucca Mountain?

K. INSTRUMENTATION ISSUES

1. With respect to the deep downhole measurement of water content, pressure head, and water flux with such instruments as heat dissipation sensors, thermocouple psychrometers, transducerized tensiometers, neutron probes, BAT suction lysimeters, etc.

   (a) What are the installation requirements for such instruments in deep holes in tuff?

   (b) What is the accuracy and precision of such instruments in deep holes in tuff?

   (c) What are the effects of temperature and pressure variations on the measurements with such instruments?

2. What indirect field measurement or instrumentation techniques are being used to derive information on the hydraulic nature and conditions of the unsaturated zone (eg. cross-hole geotomography, surface/airborne remote sensing).

L. MODELING PHILOSOPHY

1. Is the modeling philosophy on the Yucca Mountain project one of (i) using models to provide best estimates of travel time and other regulatory criteria, or one of (ii) using models to identify conceptual inconsistencies, provide indications of bounding values, and identify parameter values that constitute the necessary and sufficient conditions to ensure acceptable site behavior? Would the second philosophy lead to field-data requirements that could be more-directly or more-easily measured than the full suite of site characterization data required by the first philosophy? If such a hypothesis-testing approach to modeling were used, what would be the implications for the field measurement program at Yucca Mountain?

M. SITE HOUSEKEEPING ISSUES

1. It appears that roads, pads, borrow pits and other disturbances at test sites and construction locations at Yucca Mountain may be changing drainage patterns, damming valleys, and creating the potential for ponding of infiltration events. Aren't these site disturbances liable to influence field hydrologic measurements and interpretations?

2. It appears that there has been hydraulic fluid spillage at drill sites. Can this be more closely controlled?

3. There may be a need for more careful surface sealing and cap locking of wells so that down-casing water infiltration cannot occur, and so that adequate well protection against vandalism is ensured during periods of non-use. What are the current sealing and well-protection protocols?

4. What are the current well abandonment procedures?

5. Will it be possible in the future to size casings more closely to the requirements of anticipated downhole instrumentation?

APPENDIX E

Summary of Peer Review Meetings

PEER REVIEW OF THE HYDROLOGY STUDIES OF THE UNSATURATED ZONE AT YUCCA MOUNTAIN

First Meeting - April 23-26, 1990

Summary

Day 1

The meeting was conducted in accordance with the Hydrology Peer Review Plan. The Director of the Regulatory and Site Evaluation Division of the Department of Energy in Las Vegas, Max Blanchard, discussed the purpose of the peer review, the regulatory climate, and the roles of the various Participants. The purpose of the peer review is to determine whether or not the plans for characterization of the unsaturated zone at Yucca Mountain are adequate. A key parameter is ground water travel time in the unsaturated zone. Since the evidence suggests that travel time in the saturated zone to the accessible environment may be relatively rapid, the project must rely on slow travel time in the unsaturated zone to comply with NRC requirements.

Following Mr. Blanchard's talk, the individual members of the Peer Review Team made presentations on topics assigned to them by the Chairman, Dr. Allan Freeze. The topics were chosen on the basis of the member's expertise, as related to unsaturated zone hydrology:

Dr. van Genuchten: Physics of unsaturated flow
Dr. Papadopulos: Fracture systems in volcanic rock, especially at Yucca Mountain
Mr. Grisak: Instrumentation and measurement in deep boreholes
Dr. Everett: Vadose (unsaturated) zone instrumentation
Dr. Mercer: Reliability and uncertainty in modeling with sparse data
Mr. Nelson: Evaluation methods for subsurface contamination migration

Day 2

On April 24 the Peer Review Team was taken on a field trip to Yucca Mountain led by Mike Chornack and Dwight Hoxie (USGS) and Steve Mattson (SAIC) in which salient features of the geology and hydrogeology were observed and discussed.

Day 3

The following day the issues listed in Table 1 of the Peer Review Plan were discussed by the Peer Review Team in order to develop a conceptual understanding of unsaturated zone hydrology. Included in the discussion were the following topics: matrix and fracture flow, capillary and fracture boundaries, gaseous and water vapor flow, and ground-water travel time. During the discussions questions for the Principal Investigators (PIs) began to emerge and were recorded.

Day 4

On April 26 the draft list of questions for the PIs was completed. In the afternoon a draft list of probable PIs to invite to make presentations at the second meeting, based on the questions, was developed with input from the Participant observers at the meeting. The observers were:

George Barr - Sandia
Everett Springer - Los Alamos
Dwayne Chesnut - Lawrence Livermore
Dwight Hoxie - USGS

The second meeting was set for June 4-8. In preparation for the meeting Dr. Freeze will provide the final questions by May 11. The Team will be sent copies of publications selected by the Participants on May 11. On May 25 any additional questions based on the readings will be sent to the PIs.

PEER REVIEW OF THE HYDROLOGY STUDIES OF THE UNSATURATED ZONE AT YUCCA MOUNTAIN

Second Meeting - June 4-8, 1990

Summary

The second meeting of the Hydrology Peer Review Team was held on June 4-8, 1990 at the St. Tropez resort in Las Vegas.

Day 1

After welcoming remarks, Claudia Newbury of the Department of Energy, Las Vegas identified the Participant Observers: Dwayne Chestnut of Lawrence Livermore National Laboratory; Dwight Hoxie, U.S. Geological Survey (USGS); Everett Springer, Los Alamos National Laboratory; and George Barr, Sandia National Laboratory. She then introduced Allan Freeze, the Chairman of the Peer Review Team, who in turn introduced the peer review team members. He assigned each one of the team as rapporteur for a particular topic as follows: Site "housekeeping" - Lorne Everett; deep borehole instrumentation - Gerry Grisak; matrix hydrologic properties - Rien van Genuchten; infiltration - Steve Papadopulos; regional groundwater flow - Jim Mercer; anisotropy - Bill Nelson. Dr. Freeze laid out the ground rules for the presentations which allowed questioning and interaction with the peer review team during, as well as after, the presentations.

John Czarnecki (USGS) made a presentation on the regional groundwater flow system, including flow system geometry, potentiometric surface, groundwater flow, recharge and discharge.

Rick Spengler (USGS) discussed the geologic and drogeologic framework of Yucca Mountain in his talk on the geologic aniso opy of the site unsaturated zone.

Barney Lewis (USGS) presented a comprehensive overview of the unsaturated zone hydrology program with over 30 viewgraphs of organization charts and activity objectives.

Alan Flint (USGS) began his presentation with a discussion of the meteorology program, particularly precipitation studies. Relating precipitation to infiltration, he moved on to the infiltration studies. He then explained the three components of the infiltration studies: characterization of surficial materials, evaluation of natural infiltration, and evaluation of artificial infiltration.

After lunch Alan Flint presented his discussion of matrix hydrologic properties. He referred to Section 3 of Study Plan 8.3.1.2.2.3, "Characterization of the Yucca Mountain Unsaturated Zone Percolation, Surface-Based Studies."

Joe Rousseau (USGS) followed Alan Flint with a detailed discussion of deep borehole drilling and instrumentation. He referred to the same study plan mention by Alan Flint (8.3.1.2.2.3). He described the plans for 19 vertical boreholes (17 hydro-instrumented and two VSP-instrumented) for a total footage of about 32,000 feet. The maximum planned depth is about 2,500 feet.

The last presentation of the day, on "site housekeeping," was by Merrick Whitfield (USGS). He addressed the question "Could site activities such as construction of roads, drilling pads and borrow pits affect hydrologic measurements such as infiltration?" Other topics included well construction and abandonment.

Day 2

Mike Chornack (USGS) explained fracturing and fracture systems in the rocks at Yucca Mountain. Following the structural geology he discussed evidence for fracture flow such as movement of drilling fluid between boreholes and rapid rises in water levels after precipitation events.

Carol Boughton (USGS) discussed exploration effects testing in the Exploratory Shaft Facility, referring to Study Plan Activity 8.3.1.2.2.4.5. She also discussed the plans for studies of fluid flow and chemical transport through variably-saturated single fractures (8.3.1.2.2.4.1); bulk permeability testing in the Exploratory Shaft Facility (8.3.1.2.2.4.3) and related percolation testing.

Robert Trautz (USGS) discussed the determination of unsaturated zone permeability and storativity using in situ gas injection tests at Apache Leap, Arizona.

Joe Rousseau (USGS) returned to discuss development of software for, and various types of testing in, multiple boreholes. Testing included air permeability, water injection, VSP, and tracer testing.

June Fabryka-Martin (Los Alamos) reported on work done mostly by Ted Norris (who has been transferred) on Chlorine 36 measurements in the unsaturated zone at Yucca Mountain. She discussed the Chlorine 36 evidence for deep fracture flow.

After lunch Al Yang (USGS) presented the results of his work so far with gaseous and aqueous phase isotopes, mostly the latter. He discussed the implications of his tritium analyses, which indicated bomb (high) tritium at depth, suggesting fracture flow. He also explained the application of his work to infiltration and recharge studies.

Don Thorstenson (USGS) discussed his work and Ed Weeks' on the chemistry and physics of the blowing borehole at the top of Yucca Mountain, its relation to stratigraphy and fracture versus matrix flow.

Robert Glass (Sandia) presented a video tape on laboratory experiments dealing with flow in partially saturated rock.

Day 3

Joseph Wang (Lawrence Berkeley Laboratory) discussed "Concepts and Parameters for Flow in Fractured, Porous Media (small scale)," referring to the work of many researchers. He explained the use of medical tomography in looking inside rocks at fluids in fractures, instead of inside the skull at fluid in the brain.

Ralph Peters (Sandia) discussed a continuum model for water movement in an unsaturated rock mass. The objectives of the model are to simulate water movement in a partially saturated rock mass, i.e. to simultaneously simulate water flow in fractures and in the matrix.

Ed Kwicklis (USGS) presented objectives and technical issues of SCP Study 8.3.1.2.2.8, "Fluid Flow in Unsaturated Fractured Rock." His presentation included variable aperture fracture models, fracture-stress permeability models, fracture network models, double porosity models, channel models, stochastic continuum models, and model validation.

Dwight Hoxie (USGS) expressed the need for integrating and synthesizing the various studies of the unsaturated zone. This is the objective of the site scale modeling study plan. This work includes conceptual model development, simulation of the natural system, and stochastic modeling and uncertainty analyses.

G. (Bo) Bodvarsson (Lawrence-Berkeley Laboratory) followed-up on Dwight Hoxie's talk by mentioning the cooperative USGS-LBL studies, including seismic tomography and profiling, fracture modeling of the saturated zone, and conceptual and numerical models of the unsaturated zone. He concentrated on site-scale modeling efforts, and reviewed two-dimensional numerical models, fracture/matrix models, fracture and fault studies, and code development.

After lunch Tom Buscheck (Lawrence Livermore) made a presentation of his work with John Nitao on "Modeling Unsaturated Hydrothermal Flow in the Near Field Environment." His view graphs illustrated studies of the thermal response and movement of moisture in the waste package environment. John Nitao, also of LLNL, then discussed their work on fracture/matrix flow interactions.

Paul Kaplan (Sandia) made a presentation describing performance assessment studies relating to unsaturated zone ground water travel time. As indicated in 10 CFR 60.113 (a)(2) the ground water travel time to the accessible environment must be more than 1000 years. He discussed a one-dimensional steady state flux of 0.5 mm/yr with a travel time of 16,000 years. In this model the probability that the travel time to the saturated zone is less than 1,000 years is 20 percent due to fracture flow.

George Barr (Sandia) presented a talk on saturated zone travel time studies. He included the results of pumping tests and slug tests in developing permeabilities. Dividing by calculated effective fracture porosities of .0004 and .0028 for the Calico Hills and Topopah Springs, respectively, estimated velocities of 80 m/yr and 11 m/yr were calculated .

Day 4

The Peer Review Team met to evaluate presentations.

Day 5

In the morning, analysis of the presentations was continued by the team and the preliminary findings were finalized. At 2:00 PM Allan Freeze presented the preliminary findings. He said that the team did not identify any conceptual hydrologic paths of water flow through the unsaturated zone that have not already come under consideration by the Yucca Mountain Project research teams. Included was a list of seven points of conceptual understanding and five subjects not as yet understood by the researchers. Preliminary conlusions and recommendations were outlined in his talk. Questions and answers followed the presentation.

APPENDIX F

Regulatory Framework

SUMMARY OF REGULATIONS PERTAINING TO HYDROLOGY

ANALYSES FOR FAVORABLE AND POTENTIALLY ADVERSE CONDITIONS

The favorable and potentially adverse conditions that the site can have that may effect the ability to isolate waste are specified in 10 CFR 60.122 (b) and (c). A summary of the conditions that pertain to hydrology is presented below.

FAVORABLE CONDITIONS

The regulations list eight favorable conditions that, if present in the site could enhance the ability of the site to meet performance objectives. It (10 CFR 60.122 (a)) states that the favorable conditions that are present should combine with the engineered barrier system to provide reasonable assurance that the performance objectives relating to isolation of waste will be met. Thus, the site does not necessarily need to have all of the favorable conditions. The Safety Analysis Report is required (in 10 CFR 60.21 (c)(1)(ii)(B)) to contain: "analyses to determine the degree to which each of the favorable and potentially adverse conditions, if present, has been characterized, and the extent to which it contributes to or detracts from isolation". The favorable conditions that pertain to hydrology are summarized as follows:

Favorable condition number 1:

> "The nature and rates of tectonic, hydrogeologic, geochemical and geomorphic processes (or any of such processes) operating within the geologic setting during the Quaternary Period, when projected, would not affect or would favorably affect the ability of the geologic repository to isolate the waste."

Some aspects (cyclic precipitation and the tectonic setting, for example), however, could be disruptive if they were to continue into the future. Both faulting and volcanic activity were present within the Quaternary and could adversely affect the hydrologic system if they were continued into the future.

Favorable condition number 7:

> "Pre-waste-emplacement travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment that substantially exceeds 1,000 yr."

This is one of the most important performance assessment issues. This condition is addressed in 10 CFR 60.113 (a)(2), as well as under 10 CFR 60.122(a) (Favorable Conditions). In 10 CFR 60.113 (a)(2) there is a provision that allows the NRC to change this ground water travel time.

Favorable condition number 8:

> "For disposal in the unsaturated zone, hydrogeologic conditions that provide-
> (i) Low moisture and nearly constant moisture flux in the host rock and in the overlying and underlying hydrogeologic units;

(ii) A water table sufficiently below the underground facility such that fully saturated voids contiguous with the water table do not encounter the underground facility;
(iii) A laterally extensive low-permeability hydrogeologic unit above the host rock that would inhibit the downward movement of water or divert downward moving water to a location beyond the limits of the underground facility;
(iv) A host rock that provides for free drainage; or,
(v) A climatic regime in which the average annual historic precipitation is a small percentage of the average annual potential evapotranspiration."

The above Favorable Condition provides that any one of five alternatives can be met to satisfy it.

POTENTIALLY ADVERSE CONDITIONS:

There are 24 potentially adverse conditions (PACs) identified by 10 CFR 60.122(c). This regulation states that these conditions are potentially adverse if they are characteristic of the controlled area or may affect isolation within the controlled area.

Potentially Adverse Condition number 1:

"Potential for flooding of the underground facility, whether resulting from the occupancy and modification of floodplains or from the failure of existing or planned man-made surface water impoundments."

Potentially Adverse Condition number 2:

"Potential for foreseeable human activity to adversely affect the ground-water flow system, such as ground-water withdrawal, extensive irrigation, subsurface injection of fluids, underground pumped storage, military activity or construction of large scale surface water impoundments."

Potentially Adverse Condition number 3:

"Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such magnitude that large-scale surface water impoundments could be created that could change the regional ground-water flow system and thereby adversely affect the performance of the geologic repository."

Potentially Adverse Condition number 4:

"Structural deformation, such as uplift, subsidence, folding or faulting, that may adversely affect the regional ground-water flow system."

Potentially Adverse Condition Number 5:

"Potential for changes in hydrologic conditions that would affect the migration of radionuclides to the accessible environment, such as changes in hydraulic gradient, average interstitial velocity, storage coefficient, hydraulic conductivity, natural recharge, potentiometric levels, and discharge points."

Potentially Adverse Condition Number 6:

"Potential for changes in hydrologic conditions resulting from reasonably forseeable climatic changes."

Potentially Adverse Condition Number 7:

"Ground-water conditions in the host rock, including chemical composition, high ionic strength, or ranges of Eh-pH, that could increase the solubility or chemical reactivity of the engineered barrier system."

Potentially Adverse Condition Number 9:

"Ground-water conditions in the host rock that are not reducing."

The proposed repository is planned to be located in the unsaturated zone of Yucca Mountain, consequently oxygen is expected to be present, and the ground-water conditions are not expected to be reducing. Thus, this PAC is expected to be present. The impact of oxidizing ground-waters on performance is expected to be slight.

Potentially Adverse Condition Number 16:

"Evidence of extreme erosion during the Quaternary Period."

Potentially Adverse Condition Number 20:

"Rock or ground-water conditions that would require complex engineering measures in the design and construction of the underground facility or in the sealing of boreholes and shafts."

Potentially Adverse Condition Number 22:

"Potential for the water table to rise sufficiently so as to cause saturation of an underground facility located in the unsaturated zone."

Potentially Adverse Condition Number 23:

"Potential for existing or future perched water bodies that may saturate portions of the underground facility or provide a faster flow path from an underground facility located in the unsaturated zone to the accessible environment."

Potentially Adverse Condition Number 24:

"Potential for the movement of radionuclides in a gaseous state through air filled pore spaces of an unsaturated geologic medium to the accessible environment."

GROUND WATER PROTECTION REQUIREMENTS

Ground water protection requirements are specified in 40 CFR 191.16 (a) and (b), which states the maximum allowable contamination of special sources of ground water after 1,000 years of undesturbed performance. This regulation recognizes the uncertainties associated with making projections for 1,000 years, so it asks for reasonable expectation that these requirements can be met. Definition of some of the terms is provided in 40 CFR 191.12. According to these definitions, we may not have any special sources of ground water (irreplaceable sources of drinking water within 5 km of the controlled area that supply water to thousands of persons).

S E C T I O N 2

Reponses of the Participants to Conclusions and Recommendations in the Peer Review Record Memorandum Report

Prepared by DOE

February, 1991

RESPONSES OF THE PARTICIPANTS TO CONCLUSIONS AND RECOMMENDATIONS IN THE HYDROLOGY PEER REVIEW RECORD MEMORANDUM

February 20, 1991

Note: Numbers refer to Section 6.0, Conclusions and Recommendations, of the Hydrology Peer Review Record Memorandum, September, 1990

6.1 Programmatic Issues

6.1.1 The PRT was impressed with the strong motivation of the hydrologic research teams in the Yucca Mountain Project and with the high scientific quality of the on-going research programs and the published research record.

The agreements between the DOE, SNL, LLNL, and the USGS have provided this Project with some of the best scientists and research facilities available today. The scientists on this Project are to be commended for their dedication and motivation in the face of budgetary cutbacks and regulatory requirements that severely constrain their time and ability to do research.

6.1.2 To fully capitalize on the research strengths of the individual research teams, there is a need for improved program integration and interagency communication in the Yucca Mountain Project.

The need for improved program integration and interagency communication has long been recognized by DOE, Project participants, the NWTRB, and many other entities. That it has been universally recognized is in no way intended to trivialize this conclusion, but to indicate that a solution is elusive. Not only is there difficulty in achieving better integration, it is hard to reach consensus on what program integration is. Some see it as a function to be accomplished solely through formal planning, budgeting, and scheduling. To some degree, these are necessary, but hardly sufficient.

Program integration must also create an environment in which researchers from different disciplines in the same organization, as well as in other organizations, work together synergistically to synthesize sometimes novel solutions to technical problems. The efforts of individual researchers are vital, because creative problem-solving often is a singular activity. However, in order to make timely contributions to developing an overall understanding of Yucca Mountain that is both scientifically defensible and complete enough to support a license application, these individuals must have ready access to, and awareness of, related research. Formal interface controls, although required, are not enough.

As noted by the PRT in Sections 2.1 and 2.2 of the PRRM, technical meetings on Project topics are a valuable and perhaps under-utilized vehicle for promoting inter-agency communication. Attendance at the PRT meeting and at CASY meetings, as noted, shows the enthusiastic response of Project researchers to opportunities for technical exchange with their colleagues. The PRT suggested using CASY as a basis to build broad interagency participation. The Project will encourage the USGS to continue the workshops which have been conducted under CASY auspices.

In Section 2.1, the PRT also recommended the creation of an interagency technical overview team responsible for periodic review of data and conceptual models to recommend changes in data collection activities, hypothesis testing, etc. They could also help facilitate interagency exchange of information, data, and models. This idea was recommended to the Project Office by John Czarnecki of the USGS, before the CASY meeting in Denver (September 13-14, 1990). Chris Fridrich of the DOE-YMPO is currently forming a permanent Hydrology Integration Task Force which could perform the functions envisioned by the PRT for the technical overview team. The first meeting of this group was held on January 31, 1991. The Task Force will initially concentrate on the saturated zone but will interface with the unsaturated zone investigators. This task force will be given a charter to review and recommend courses of action to the DOE for integration of the hydrology program. The Project Office will appoint a member of the DOE staff as hydrology program lead to direct implementation of the Hydrology Integration Task Force recommendations as appropriate within the context of the total program.

6.1.3 It is imperative that the Yucca Mountain research teams gain access to suitable field sites on Yucca Mountain, or in similar terrain elsewhere, in order to carry out prototype studies required for equipment testing, concept hypothesis testing, field methodology development, and model validation.

We agree strongly that researchers need access as soon as possible to field sites suitable for prototype studies, concept testing, methodology development, and model validation. Such studies are vital for all the activities (prototype studies, etc.) listed by the PRT. Unfortunately, under current budgetary constraints, it is unlikely that such studies can be re-initiated anytime soon, even if a facility were made available. Prototype testing has continued at locations outside of Nevada, in particular, at Apache Leap, Arizona and in Utah (prototyping dry drilling technology). Project management agrees with the PRT and Participants that a location such as G-Tunnel is beneficial for prototype work prior to construction of the ESF. However, the funding for such a facility would depend on contributions from Participant's current funding. While such an arrangement is not likely to occur in the near future, the Project will continue to work toward resolution of this problem.

6.1.4 In the opinion of the PRT, the quality-assurance procedures in the Yucca Mountain Project have become so over-formalized that they are creating unacceptable delays in the technical progress and a lowering of staff morale.

The Project QA is aware that over-prescriptive, excessively detailed procedures have been developed. This may be largely the product of QA personnel who were highly experienced in QA for nuclear power plants, but inexperienced in application of QA to scientific investigations. Another factor may be a lack of an established, integrated procedure infrastructure.

The Project is currently holding workshops between scientific/technical management and Quality Assurance management to simplify and streamline Project procedures to make maximum use of the established scientific methods, thus eliminating excessive detail.

6.1.5 The PRT recommends a hypothesis-testing approach to site characterization whereby the calibration of hydrologic models is carried out with respect to integrated performance measure rather than a detailed matching of the state variables. The approach emphasizes the collection of field data for the purpose of reducing conceptual uncertainty through the testing of hypotheses, rather than for the reduction of parameter uncertainty per se.

The Peer Review Team's recommendation of a hypothesis-testing approach to site characterization addresses a recognized gap in the present program. The Site Characterization Program consists of both traditional characterization (parameter uncertainty reduction) and hypothesis-testing (conceptual uncertainty reduction) approaches directed ultimately at resolving performance issues (through performance measures). However, it is not clear that sufficient attention has been paid to formulating hypotheses related to performance of the site. Thus, the Project may not be placing enough importance on using performance measures for the site to determine that the tests being performed are those most critical to the functioning of the potential repository system.

One possible aspect of Site Characterization consists of the systematic gathering of measurements of parameters that are generally agreed to be of importance. These data provide the technical background for evaluation of the site. For example, we will make little improvement in our conceptual understanding of the site without a more complete description of the hydraulic conductivity of the numerous volcanic units at the site. Virtually any hypothesis test will require such data. Most of the site characterization hydrologic modeling that is planned at Yucca Mountain is intended to test specific hypotheses concerning hydrologic processes and concepts within the unsaturated zone (SCP Activities 8.3.1.2.2.8 and 8.3.1.2.2.9).

Of principal concern, for example, is the qualitative representation and simulation of moisture flow in variably saturated fractures. Consequent to this effort is an evaluation of the hypothesis that Darcian continuum-flow models are applicable in fractured, variably saturated, welded tuff. Simulation of the present state of the hydrologic system will be performed to calibrate system models. These simulations will test the validity of the hypothesis that the present system is in steady-state quasi-equilibrium. These sorts of hypothesis tests are similar to those proposed in Section 3.3 of the Peer Review Team's discussion: vapor transport across fractures, surface infiltration, and attenuation of moisture flow across non-welded tuffs.

Performance Assessment likewise has a dual role. One part consists of addressing hypotheses about the validity of critical site models, in cooperation with the modeling efforts of the Site Characterization Program. The second form consists of testing hypotheses with respect to performance, given the current state of certainty about the relevant models. It is this sort of hypothesis testing which will ultimately resolve SCP Issues, and which the Peer Review Team's comment addresses. The modeling capabilities developed for these two sorts of hypotheses will be different, and the types of site characterization data they need may well be different. In addition, it is this sort of hypothesis testing that will determine which hypothesis of the first kind are important to test because they will affect performance of the site. The "features"-oriented aspects of site characterization may have been laid out with only the first type of hypothesis testing in mind.

The Yucca Mountain Project recognizes that the effort to bring this second type of hypothesis testing into the interaction between performance assessment and site characterization will require extensive consideration of the basis for both activities. It may require a kind of conceptual "reprogramming" of the attitudes of analysts and data-gatherers alike. Without it, however, the resolution of technical performance issues, and ultimately of the formal systematic issues of the SCP, will be difficult, if not impossible.

6.1.6 The PRT is impressed with the development and implementation of state-of-the-art instrumental methods and measurement devices, especially with respect to deep downhole measurements of fluid pressures. The PRT offers strong support for the proposed deep borehole drilling program and recommends an early start for it. We have also identified several instrumental concerns. These are related to the use of neutron moderation in fractured rock, the long-term reliability of thermocouple psychrometers, the validity of mercury-intrusion and centrifuge methods in the laboratory measurement of hydraulic properties, and the strategies for soil-gas and pore-liquid sampling at depth in the field. The PRT is also of the opinion that back-up strategies should be developed in case any of the proposed downhole monitoring technologies fail to perform as expected.

Neutron moderation

It is recognized that neutron moderation is unable to detect pulses of water through fractures. The neutron hole monitoring program was designed and is suited to study the change in moisture storage within the surrounding media. Where there are likely locations for fracture flow, attempts are being made to understand these through other means, such as at N-2 where there is a recording rain gage at the surface and a recording moisture sensor at the bottom of the borehole. Other attempts to understand flow in fractures will be undertaken in artificial infiltration studies (cross hole gamma, TDR, tracer tests, geotomography, etc.) and in laboratory block and core tests.

Mercury intrusion

We believe that it has been illustrated by several YMP studies (e.g. Flint and Flint, 1990; Peters et al., 1987) as well as from perusal of the theory (Amyx et al., 1960; Purcell, 1949) that mercury intrusion may be inappropriate for moisture retention determination on tuffaceous materials. The primary assumption involved in this method is the conversion from the measured pore size distribution to moisture retention. In addition, lower flow tuffs have extremely small pores for entry of a nonwetting fluid (therefore requiring very high pressures for intrusion, up to 30,000 psi) and calculations using contact angle can only incorporate "ball park" assumptions for associated mineralogy, which are not appropriate for this medium. Mercury intrusion is also a destructive method that renders the sample useless for further testing and requires small chips for samples, which are unrepresentative unless many samples are tested. The Institute of Gas Technology has developed mercury intrusion methods using small core samples, which have eliminated some of these concerns. Recent studies by Shell Oil Company (Yuan and Swanson, 1989) strive for a more accurate pore size distribution measurement by maintaining a constant rate of mercury input into the sample while monitoring the pressure changes. Mercury intrusion is not without its merits as a tool to obtain porosity quickly. It is believed that there is much room left for additional prototype testing on this method because its advantages may outweigh its concerns.

Centrifuge method

Based on prototype testing conducted to date, we believe the centrifuge method has been shown to be a viable method for characterization of moisture retention. It currently appears to have limitations in nonwelded tuffs as shown by inconsistencies in measurements taken at the wet end of the moisture retention curve. It has, however, been shown to match several other methods at suction less than -2 bars (Flint and Flint, 1990) and shows possibilities for use in hysteretic measurements. Further testing needs to be done on this method to illustrate repeatability and to validate the measurement of hysteresis. All of these suggested methods require additional prototype testing to determine usefulness in the measurement of moisture retention on welded tuffs.

Long-term reliability of thermocouple psychrometers

The long-term reliability of the thermocouple psychrometers and other sensors that will be used in the deep UZ borehole instrumentation and monitoring program, have been of paramount concern to those involved in designing and developing appropriate instrumentation schemes for long-term monitoring. Strategies have been, and are being, developed to deal with the problem of a downhole sensor failure. In the case of the thermocouple psychrometer, the back-up strategies include the following:

1. Instrumentation design calls for duplication of the sensor at all levels of monitoring. These backup sensors provide for recovery of measurements in the event of the complete failure of the primary sensor. Primary sensors will be excited and read once every five hours. Over a five-year period, this represents about 9,000 duty cycles. Because thermocouple psychrometers interact directly (i.e. actively) with the environment they are sensing, sensor drift and degradation of the welded (wet bulb) junction is anticipated. The backup sensor will be cycled intermittently over the monitoring period to verify the primary sensor's reading. This sensor, used in a verification mode, will be cycled approximately 100 times over a five-year period. In the case of a complete failure of the primary sensor, the backup will be used in it place.

2. Design modifications to the thermocouple psychrometer have been implemented by the USGS that allows the voltage across the well bulb to be measured while the psychrometer is being excited. The actual output or measurement of water potential is taken following excitation. Monitoring of voltage during excitation may provide a means to monitor changes in the resistance of the wet

bulb with time, and thus can be used to provide an independent diagnostic to monitor sensor drift. This feature of the design was exercised during the "G" Tunnel prototype drillhole instrumentation program. The results of this work are still under evaluation; however, preliminary findings suggest that there is a strong correlation between changes in resistance of the wet bulb over time and measured output voltages following current excitation that can be used to correct for the effects of long-term sensor drift.

3. A gas-sampling scheme has been developed which will be used to withdraw nearly vapor-saturated rock gases from borehole instrumentation sites where thermocouple psychrometers are located. A measured mass-flow of dry gas (N_2) is introduced into a "U" tube arrangement to dilute and lower the dew point temperature of a source gas withdrawn under vacuum from the instrument station cavity. In this manner, the source gas' water vapor content is conserved as the mixed gas moves from warmer temperatures at depth to cooler temperatures at the surface. At the surface the dew point temperature of the mixed gas, the mass flow of the dry carrier gas, and the mass flow of the mixed gas are measured. These measurements are used to verify psychrometric readings. This scheme has been successfully tested in a laboratory under temperature gradients that are much more severe than those that will be encountered in an instrumented borehole. This method has proven satisfactory in laboratory testing to calculate equivalent water potentials to within one bar of their true value. The scheme requires that liquid/vapor phase equilibrium exist within the instrument station cavity. This scheme provides a long-term backup to the psychrometers, but can only be implemented one or two times per year.

4. Each borehole will be stemmed using a hollow central support tube. the internal diameter of this tube is sufficient to accommodate a neutron moisture meter probe or a small thief sampler. The thief sampler can be used to sample rock gases directly through remotely actuated access points located along the length of the hollow support tube and adjacent to the downhole instrument stations. A thief sampler is being designed that utilizes many of the sampling design features incorporated into the design of the BAT lysimeter. This scheme of measurement/sampling provides a 4th level of backup that will be used, as needed, throughout the planned monitoring period.

Backup strategies 3 and 4 do not provide facility for high frequency monitoring. They do, however, provide an independent means of verifying the accuracy or authenticity of the downhole thermocouple psychrometers. Although it is planned to cycle the primary sensors once every five hours, it is anticipated that this duty cycle can be relaxed after a period of monitoring sufficient to confirm reequilibration of liquid water potential as measured in the vapor phase. Reducing the duty cycle of the primary sensor will increase long term reliability and will be done as soon as it can be demonstrated that higher frequency measurements are not needed.

6.1.7 The PRT recommends that DOE streamline its publication review process so that technical reports are released or published within one year of preparation.

The streamlining of the publication review process has already begun, with delegation of responsibility for technical review to the Participant

Organization under their own internal QA programs, with only a policy review at YMPO. Whether or not the one-year target is consistently being met for release or publication of technical reports can only be documented through the Project's document tracking system. However, the Project Office is currently releasing manuscripts to the ANS for next spring's International High Level Radioactive Waste meeting in days to weeks after receipt.

The Project Office procedure for review and approval is currently under revision to further streamline the Project review process. Participant's internal review processes are varied in their requirements, some internal policies may delay final publication. The Project is committed to completing its review and approval in two to three weeks unless major technical questions arise.

6.1.8 The PRT encourages the documentation, verification, and sharing of computer codes between research teams and across agency boundaries; we discourage the current trend toward model proliferation.

The Yucca Mountain Project acknowledges the need to avoid a proliferation of codes with overlapping capabilities and encourages transfer and sharing of codes. For example the ground-water flow code TOUGH is used, with modifications, by Lawrence Berkeley laboratories, the U.S.G.S., Lawrence Livermore National Laboratory, Pacific Northwest Laboratory, and others.

The Project also recognizes a need for an appropriate repertoire of codes based on different models, assumptions, and idealizations. The Project is currently evaluating current code needs. There may be some reduction in the number of codes in use in the future. These changes represent the natural evolution of codes with developing computer and conceptual model sophistication.

Many of the hydrologic flow and transport codes currently in use predate the Project, and thus have not been a drain on Project resources. Rather, codes such as TOUGH and its progeny represent an opportunity for the radioactive waste management community to benefit from extensive code development efforts that were undertaken for other programs. Other codes, such as NORIA, LLUVIA, and PORFLO represent different numerical and modeling approaches, and implement different capabilities with distinct advantages for performing certain kinds of calculations.

This specialization of codes to certain types of calculations gives the appearance of over-proliferation, but is needed when dealing with computationally intensive problems like those involving fluid and contaminant transport in variably saturated, multi-phase systems, where non-linear relationships are the rule. A range of tools with some overlap in capabilities is needed also in order to perform code benchmarking exercises needed to meet software verification requirements and to perform independent review of model validation exercises.

It is highly likely that, as computer capabilities advance, and models are refined, some tools will be merged, or new, more comprehensive codes will be developed as successors to the present codes. SCP Activity 8.3.1.2.2.9.2 specifically considers the selection, testing, and adaptation of model-based computer codes to simulate moisture storage and flow in variably saturated hydrogeologic systems. At present, however, the Project considers the range of codes now in use to be reasonably optimal.

6.1.9 The PRT encourages closer coordination of construction activities and research activities on the Yucca Mountain site. It is important that the influence of site construction on infiltration properties and drainage patterns be minimized.

This potential for interference has been recognized for several years. It is common practice for design engineers to contact principal investigators to determine if planned construction activities will interfere with proposed experiments.

The Project Geographic Information System (GIS) contains the locations of proposed and existing surface-disturbing activities and research sites. It is expected to produce accurate maps of work in progress as site characterization progresses. In addition, the Project Office has purchased Interactive Volume Modeling, a 3-D modeling package from Dynamic Graphics, which will assist managers in determining any potential test interferences before work starts, so that the tests may be modified accordingly.

Site coordination and interference of activities have been a prime concern to many of the investigators, and efforts to coordinate all activities for optimum production and protection of research is ongoing.

6.1.10 the PRT encourages improvements in site housekeeping with respect to fluid spillage, borehole leakage, site security and well abandonment.

The Project agrees that there have been "housekeeping" problems and potential borehole security problems in the past. With the advent of formal site characterization, access to and operations at the site are becoming increasingly controlled.

The Department of Energy's Administrative Procedure (AP-6.13) entitled "Authorization for Use of Regulated Hazardous Substances and Materials" assigns responsibility and established a process for the identification of requirements for their use in Yucca Mountain Site Characterization Project activities. A document entitled "Hazardous Materials Management and Handling Program (HMMHP) is currently being written which will provide detailed guidance and information concerning regulations applicable to project participants for handling spills of hazardous substances and other materials, which include oil and hydraulic fluids. All individuals working on this project are subject to the Resource Conservation Recovery Act which states that an individual responsible for a spill can be fined. In order to assure that all responsible investigators are aware and in compliance with this law, AP-6.13 requires each participating organization to have a designated Hazardous Materials Coordinator (HMC) with an alternate. This individual is responsible for providing training to investigators in his or her organization.

All spills must be reported immediately to the EPA contact located on the NTS for clean-up instructions. For small spills (less than 1 gallon) the EPA official may allow the participant to dig up the contaminated soil and rock and temporarily dispose of it in a marked 55-gallon drum which is later removed to a permanent disposal site. For larger spills, EPA will send out a team to oversee the removal of the contaminated material to a permanent designated area. The quick removal of future spills will reduce the potential for spreading of contaminants. Water pumped out of boreholes for hydrologic testing will be removed from the site by pipeline or tanker truck.

Borehole leakage around casings and grout has not been a problem in the past and is not anticipated to be a future problem. Hydrologic data obtained by periodic monitoring of water levels and neutron logging of cased and grouted boreholes have shown no evidence of surficial leakage into existing boreholes located on various types of terrain and geologic material. Grouting of casing in an arid environment where ponding of water around the casing is infrequent is very successful. Boreholes planned to be drilled in washes will be given extra protection by building earthen embankments to divert runoff away from the well casing, except where the purpose of the hole is to monitor infiltration beneath the channel.

Site security at the NTS has also not been as much of a problem as in non-restricted areas. However, as a precaution, all future boreholes will be provided with locking caps or shelter houses to prevent vandalism and loss of borehole data.

A strategy document dealing with sealing exploratory boreholes is currently being prepared by Sandia National Laboratories as part of the Yucca Mountain Project Respository Sealing Program. This document represents the first step in the development of requirements for sealing boreholes. It will include: a description of the exploratory boreholes (existing and proposed); air and water flow performance evaluations of the borehole seals; structural analyses of open boreholes and emplacement of cementitious seals; and the feasibility of reconditioning boreholes and the emplacement of the seals. If a repository is not developed at Yucca Mountain, the exploratory boreholes will be sealed to satisfy the State of Nevada well abandonment regulations.

6.2 Technical Issues

6.2.11 The PRT did not identify any conceptual hydrologic paths of fluid flow through the unsaturated zone at Yucca Mountain that have not come under consideration as potential radionuclide migration routes by the various research teams.

The Site Characterization Plan set forth by the Yucca Mountain Project in December, 1988 was the comprehensive basis on which the hydrology program was developed. The Project Participants are to be commended for their thoroughness in identifying, considering, and developing investigations to assess all potential fluid flow paths.

6.2.12 The PRT is convinced that there is a source of water (both in the form of low-intensity, long-duration winter storms, and in the form of high-intensity storms), and a mechanism of infiltration (in the form of large-aperture surface fractures) that can introduce water to the ridges, slopes and upland areas of Yucca Mountain, in addition to water that infiltrates into the washes following rare runoff events. The PRT believes that a combination of lysimeter studies, tracer tests, and process-oriented modeling offers the best opportunity for estimating infiltration rates at Yucca Mountain.

Most of the recommendations by the PRT (tracer tests and process-oriented modeling) are planned for use in estimations of infiltration rates. For example, soil profiles of anthropogenic Chlorine-36 from atmosphere testing of nuclear devices are to be measured by LANL in order to estimate infiltration rates for the last 30 years and to identify zones of rapid water movement, such as along fractures, in deeper samples.

It is believed, however, that lysimetry is an inappropriate method for this environment and objective. An example of an appropriate use of lysimetry is illustrated by G. W. Gee at Pacific Northwest Laboratory, which involved a disturbed, not skeletal or bouldery, soil whose total depth was encompassed within the lysimeters. At Yucca Mountain the material under investigation is either deep alluvium, very high in rock fragment content (in the flats or channels) or shallow alluvium underlain by bedrock (on the sideslopes). (Evapotranspiration from bedrock or very shallow soils cannot be measured using lysimetry.) Once disturbed, the material will not conduct water in a representative manner.

There is also no current understanding of the depth of investigation necessary to characterize upward and downward movement of water in the alluvium. There is surely no justification for assuming that anything that comes out the bottom of a lysimeter is recharge, nor is there any way to incorporate bedrock into a lysimeter. In addition, at Yucca Mountain the topography and subsurface flow patterns pose additional problems for the use of lysimetry. It is estimated that less than 20 percent of the land surface above the repository block is alluvium. This alluvium is located in narrow washes, which are characterized by the lateral flow of subsurface water down the channel and is not measurable by a lysimeter. Also, steep topography makes installation of a lysimeter very difficult. There are, however, some locations that are not representative of the repository block, where use of a lysimeter is more feasible. Because it is highly regarded as an effective measurement tool under some conditions, it is intended for use as a possible validation tool for other more versatile evapotranspiration measurement systems (see comment 6.2.23). Lysimetry for the use of precipitation collection is very expensive with respect to the extensive recording rain and snow gage network being planned for the region.

6.2.13 One of the most critical features of the conceptual hydrologic model for Yucca Mountain is the postulated ability of nonwelded tuffs to attenuate and retard transient moisture pulses. We encourage early field experimentation in the Paintbrush nonwelded tuff and the nonwelded tuffs of the Calico Hills unit to investigate the validity of this mechanism.

The importance of the nonwelded tuffs is acknowledged by the researchers and is reflected in the study plans. Early investigations, however, are constrained by drilling schedules and must be limited to surface studies. In some cases, (such as natural infiltration studies) nonwelded properties are often only inferred, or are measured indirectly. In the case of outcrop studies, core are obtained and physical and flow properties and state variables can be determined. Studies using samples from outcrops are underway to investigate one- and two-dimensional spatial relationships of various hydrologic and physical properties while other studies are investigating sample handling methodology and the effects of degrees of drying on zeolites, pore geometry, and flow parameters. The presence of zeolites in the Calico Hills, and to a lesser extent in the members of the Paintbrush Tuff, introduces a greater challenge to the representative measurements of in situ hydrologic properties. It is also recognized that zeolites, along with the more malleable and less fractured nature of the nonwelded units, may enhance the dampening effect on moisture pulses. Once boreholes are drilled and core from depth are obtained, thorough analysis of the core will be conducted and down hole monitoring of saturation and water potential in the nonwelded units will be undertaken.

The DOE will consider initiating early investigations of the PTn (Paintbrush Tuff nonwelded unit) and the Tpt (Topopah Spring nonwelded unit) to evalute their potential to attenuate moisture pulses.

A risk/benefit analysis of methods of obtaining data from the Calico Hills unit was performed by the DOE pursuant to an objection by the NRC to the Consultation Draft Site Characterization Plan. The risk/benefit analysis of alternative strategies for characterizing the Calico Hills unit concluded that, on the basis of the potential impacts estimated for any or all of the facilities considered, and on postclosure aqueous releases from the total system, there is no reason not to extensively explore the Calico Hills unit by means of underground excavation below the proposed repository.

6.2.14 The most important conceptual issue at the Yucca Mountain site revolves around the hydrologic processes of matrix/fracture interaction. The PRT recognizes the difficulties in developing a single, coherent, and complete theoretical formulation capable of evaluating nonisothermal, multiphase fluid flow in a dual-porosity medium. The PRT is impressed with the emerging approximate theoretical approaches being developed within the Yucca Mountain project. However, it is imperative that there be continued evaluation of the assumptions that underlie these methods; in particular, the assumption of fluid-pressure equivalence across the matrix/fracture boundary, and the acceptance of the concept of overlapping continua. The PRT believes that it is unlikely that fractures will achieve sufficient separation or continuity to act as effective barriers to vertical infiltration.

The Project and its Participants agree with the PRT about the importance of understanding matrix/fracture interactions at Yucca Mountain, and the need to continuously evaluate the assumptions that underlie the approximate methods that are being developed.

Most of the work addressing this area are being conducted by the USGS and LBL, and by LLNL. Current plans for the work at the USGS and LBL include:

1. Evaluation of the approximate semi-analytical methods developed by Zimmerman et al. (1990),

2. Evaluation of the fluid pressure equilibration between fracture and matrix blocks through the use of detailed numerical simulations, and

3. Evaluation of the effect of fracture contact area on the ability of fractures to function as barriers to vertical liquid flow.

LLNL's work in this area originally arose from their work in Waste Package Design, which in turn required the development of predictions of the environmental conditions surrounding the waste packages as a function of their spatial locations and the time after emplacement. LLNL is also responsible for Near Field Performance Assessment, including the development of a source term predictive capability.

An important component of this environmental and performance predictive capability is the Near Field Hydrology program, to be conducted under the Study Plan 8.3.4.2.4.2 (in revision and comment resolution). Great progress has been made in refining conceptual understanding and calculational ability through planning, conducting and analyzing the results of the prototype heater test in G-Tunnel to simulate some aspects of the effects due to the horizontal emplacement of a waste package in host rock similar to the horizon being considered for a possible repository at Yucca Mountain. This has required a continual and rapid interplay of lab work, field investigation, and "numerical experiments" with computer and analytic models - precisely the role for proto-typing described in Section 2.3 of the Hydrology Peer Review Record Memorandum - with a low level of QA.

Flow surrounding waste packages will be a complex transient process requiring proper treatment of simultaneous flow of heat, liquid water, water vapor, and air for time periods on the order of tens to hundreds of years after placement, over distances of tens of meters. It is within this "altered zone" or "near field" region that the use of conventional models is most severely challenged, particularly in regard to how fracture/matrix interaction is handled.

Tom Buscheck and John Nitao have been rapidly developing new approaches to the fracture/matrix interaction problem, and some of their work was presented at the June PRT meeting in Las Vegas. Theory and "numerical experiments" (application of computer codes) combined have begun to define the conditions (i.e., the combination of fracture properties, matrix properties, and flux) under which the assumption of fluid-pressure equivalence across the matrix/fracture boundary represents a reasonably good approximation to the actual distribution of flow between a connected fracture network and the porous matrix within which it is embedded. This assumption of pressure equivalence leads to an "equivalent continuum" representation of fractured porous media which can be strictly correct only under steady-state flow conditions (including the no-flow condition of a system in capillary-gravity-equilibrium), <u>when there is no net mass transfer</u> between the fractures and the matrix. Buscheck's results show numerous combinations of parameters for idealized fracture systems under which the equivalent continuum approximation fails in comparison with treating the fractures as discrete elements. This is believed to be especially significant in the following situations requiring transient flow analysis:

1. Flow generated by the thermal pulse from waste emplacement.

2. Effect of drilling fluid lost by inadvertently drilling into the repository at some time in the future.

3. Episodic, as opposed to averaged, infiltration.

The consequences of all of these events must be evaluated with a discrete treatment of fractures to correctly analyze the resulting radionuclide release and near field transports. Item 1 also requires consideration of gas flow as well, and accordingly will be the subject of continuing investigation at LLNL.

The Project will continue to re-evaluate the conceptual understanding regarding matrix/fracture interaction as more field data become available and in light of new theoretical results.

6.2.15 The PRT believes that perched saturated zones will almost certainly be encountered during exploratory drilling at the site. Protocols should be in place for the sampling and testing of such zones. The presence of such zones should not, in and of themselves, disqualify the site from consideration for a nuclear waste repository.

Protocols for testing and sampling of perched water are, in fact, included in the study plans for both surface-based and ESF exploration of percolation in the unsaturated zone.

Two types of perched zones are believed to be possible at Yucca Mountain. Near-surface perched zones may develop where water is temporarily impounded in fractures (single fractures or fracture sets). This type of perched water zone most likely is a transient phenomenon and does not add to net infiltration at Yucca Mountain. In addition, deep perched water zones may develop at lithologic contacts and fault contacts where there are appreciable contrasts in permeability.

Near-surface perched water has been observed at Yucca Mountain during the drilling of, and after completion of, some neutron access boreholes. The Project recognizes that larger infiltration fluxes in the past could result in deep perched zones. Future drilling operations are planned to be conducted such that perched water, if present, will be detected, tested and sampled.

6.2.16 The role of gas flow through Yucca Mountain deserves continued attention, especially with respect to its effects on moisture redistribution and potential radionuclide migration in the vapor phase.

The Project agrees with the PRT's assessment of the important role of gas flow through Yucca Mountain. This will continue to receive considerable attention, with respect to both moisture redistribution and vapor-phase radionuclide migration, in the Site Characterization, Design (Waste Package and Repository), and Performance Assessment programs. The gaseous phase circulation is being investigated by Ed Weeks and others in on-going study 8.3.1.2.2.6. Study Plan 8.3.1.2.2.7, being conducted by Al Yang and others, includes gaseous phase chemical investigations.

6.2.17 The PRT supports proposed subsurface investigation of the hydraulic properties and hydrologic influence of fault zones on the Yucca Mountain site.

As the PRT has noted and supported, the Project plans investigations of influence of fault zones on the hydrology of the Yucca Mountain site. In their Site Characterization Analysis (of the SCP), the NRC recommended more extensive studies of the role of faults in the saturated-zone flow system. In its response, the Project committed to a continuing, long-term evaluation of the role of faults in the saturated and unsaturated zones. The evaluation is based, in part, on the rate of developing confidence in the demonstrable performance of the primary, unsaturated-zone barrier to fluid flow and radionuclide migration. As such, the DOE is examining ways of ensuring that fault zones are evaluated fully.

These ways include the currently ongoing assessment of alternatives for construction and testing in the ESF; the currently planned assessments of fault zones in the ESF, which involve long drifts planned to intercept known fault zones and examine potential fault zones; and a horizontal borehole planned to examine characteristics of the Solitario Canyon fault.

6.2.18 The PRT encourages the emerging development of stochastic modeling approaches in the Yucca Mountain Project. A stochastic component to modeling endeavors is required in order to meet the regulatory travel-time criterion, to carry out hypothesis testing, and to aid in assessing the worth of proposed data collection networks.

The Yucca Mountain Project concurs with the Peer Review Team's recommendation to continue use of stochastic modeling approaches for ground water travel-time calculations, for hypothesis testing, and for examining the worth of proposed data networks.

The stochastic approach to ground water travel-time calculations is defined in the Sandia work plan and the Work Breakdown Structure dictionary description for the ground water travel-time task. The current task leader has presented a framework and calculations demonstrating this approach to several technical meetings both inside and outside the Department of Energy (Kaplan, 1990). The approach has also been presented to the Nuclear Waste Technical Review Board and in a technical exchange with the Nuclear Regulatory Commission, with the object of determining whether a probabilistic calculation will be accepted by the regulator responsible for evaluating a license application.

The probabilistic framework provides a robust approach to hypothesis testing.

Recommendation 6.1.5 addresses this issue in more detail, and the Project's plans to apply stochastic methods to test alternate hypotheses are described in detail in the response to that comment. Stochastic decision analysis methods are also being applied to determine the value of information to be derived from site testing. Both the Calico Hills Risk/Benefit Analysis and Testing Priorities Task Forces have implemented these methods.

The Project has long recognized the appropriateness of these methods in making hydrogeologic decisions within a regulatory framework. However, there remains some uncertainty about how to develop a clear and widely comprehended means of using these techniques to present a coherent evaluation for decision makers.

As a first step the Project plans to hold a workshop on hydrologic decision analysis in the near future. The targeted group will be the Performance Assessment and site modelers.

6.2.19 Inconsistencies between isotopic age dating of waters at depth and unsaturated groundwater travel times calculated with hydrogeologic models must be resolved.

The calculated Carbon-14 age of unsaturated-zone water from UE-25 UZ #4 at a depth of 96-100 m is about 1,000 ±100 years. Water from UE-25 UZ #5 at the 103-105 m depth interval, had a calculated Carbon-14 age of about 4,900 ±500 years. For this limited data set, the 5-fold difference of ages indeed indicates preferential flow paths in the upper part of the unsaturated zone. This work was done under Study Plan 8.3.1.2.2.7, "Hydrochemical Characterization of the Unsaturated Zone."

Chlorine-36 data from UZ-1 indicated post bomb pulse water at a depth of 500 feet. Study Plan 8.3.1.2.2.2, "Water Movement Tracer Tests Using Chloride and Chlorine-36 Measurements Of Percolation at Yucca Mountain," is currently being revised to address the need to resolve inconsistencies between isotopic age dating of waters at depth and ground-water travel times calculated with hydrogeologic models. The revision is scheduled for completion by April, 1991.

As the PRT Record Memorandum states (Sec. 5.1), Lin and Tierney acknowledged that "potential lateral flow and the concentration of flux down fault zones need to be investigated before the cumulative distribution function can be interpreted as representative of the fastest path of likely radionuclide travel", and more recent calculations by Kaplan result in substantially reduced travel times. These facts indicate that the GWTT models are still evolving and, increasingly, are reflecting hydrogeologic realities. However, modeling cannot advance with confidence until data collection and experiments produce constraints and calibration guidance. We share the PRT's opinion that modeling ultimately must be consistent with field observations. Both informal communications and formal interfaces will help ensure this ultimate consistency.

6.2.20 Studies of two-phase fingering in traditional porous media have very little relevance to the Yucca Mountain Project. The PRT encourages an early transfer of research efforts on fingering from traditional porous media to

fractured porous media.

In support of conceptual model development and validation, a research program has been developed at Sandia National Laboratory for the Yucca Mountain Project to investigate mechanisms and processes which govern flow and transport through unsaturated, fractured rock (Glass, 1990). The research program integrates fundamental physical experimentation with conceptual model formulation and mathematical modeling. Our approach follows five basic steps:

1) Identify processes governing water flow and radionuclide transport through fractured porous media;

2) Develop basic scientific understanding of these processes through fundamental conceptual and mathematical modeling, controlled experimentation, and model validation (invalidation) exercises at both the laboratory and field scales;

3) Bound various processes in terms of system parameters such as initial conditions, boundary conditions, and distribution of properties in both time and space;

4) Provide informational needs for site characterization so that the probability of occurrence for each process can be assessed and appropriate model parameters measured; and

5) Integrate models for important (high probability of occurrence) water flow and radionuclide transport processes into performance assessment models.

Gravity-driven water fingering in unsaturated porous media and fractures

Most conceptual models assume that infiltration flows are essentially stable with any irregularity in the flow field caused by spatial variability in hydraulic properties, initial conditions, or boundary conditions. Yet, gravity-driven instability of an infiltration flow or "wetting front instability" can cause the flat wetting front moving downward through an unsaturated porous medium to break into fingers which move vertically, bypassing a large portion of the vadose zone. Wetting front instability within porous media has been demonstrated in both laboratory and field settings and has been shown to have a dramatic effect on water and solute transport (Hill and Parlange, 1972; Starr et al., 1978; Glass et al., 1988a, 1988b, 1989a). The development of a two-zone moisture content field consisting of high moisture content finger cores surrounded by lower moisture content fringe regions and the persistence of this structure from infiltration cycle to infiltration cycle has been demonstrated and explained with a simple theory based on hysteresis in the moisture characteristic relations (Glass et al., 1989b). The dependence of finger properties on system parameters for initially dry, coarse, nearly uniform sand has been determined through dimensional analysis and experimentation (Glass et al., 1989c, 1989d). Stability criteria and relations for finger width or diameter have been formulated through linear stability analysis and compared to experimental data showing remarkably good agreement for homogeneous media where the analysis applies (Glass et al., 1989d).

Generalization of these non-Yucca Mountain supported theoretical and experimental studies suggests many situations for flow in "traditional" porous media, such as an increase in conductivity with depth, unsaturated infiltration from a boundary held at less than saturation, and redistribution following an infiltration event, can cause a wetting front to become unstable and form persistent fingers. In addition, and very importantly for Yucca Mountain, generalization suggests similar situations for flow in non-horizontal fractures will also be unstable. Because all of these situations occur at Yucca Mountain, the process of wetting front instability must be understood and bounded so that its probability of occurrence can be credibly determined. Thus, within the context of SNL's research program supporting conceptual model development and validation for the YMP, SNL is considering gravity driven fingering in both porous media and fractures as part of a five stage approach: identify, understand, bound, assess probability of occurrence, and integrate into performance assessment models if found to be important (see Glass, 1990).

With respect to gravity driven fingering in unsaturated fractures, the brief presentation on the subject of instability given to the PRT by Glass caused the PRT to recognize and single out gravity driven fingering in fractures "as an example of a research project that requires upgrading" (pg. 10, Peer Review Record Memorandum). We completely agree with this acknowledgment. Two years ago, Glass recognized the probable importance of fingering in controlling flow in large fractures in the extreme of very low permeability matrix, such as in highly welded, or zeolitized tuff, or for matrix which is near saturation. For these situations the effect of the matrix on flow and transport through a conducting fracture is of second order and thus flow within the fracture will dominate. A series of demonstration laboratory experiments showed the existence of gravity driven fingering in analogue fractures. Since that time SNL has been developing the capability to attack the problem in earnest.

This development has included:

1) The development of flow and transport models for individual fractures (Thompson, 1990);

2) the development of models to determine wetted region structure within unsaturated fractures influenced by gravity (Glass and Yarrington, 1989);

3) the development of techniques to measure aperture structure in fractures and create casts of naturally occurring fractures for experimentation;

4) the development of an experimental approach to systematically explore fingering in unsaturated fractures; and

5) the development of the required experimental apparatus and techniques to support experimentation.

Unfortunately SNL was not given the time to present this development directly to the PRT during the presentation. However, a detailed discussion of SNL's research effort in unsaturated fracture flow and transport, of which gravity driven fingering is a small part, can be found in Glass and Tidwell (1990). We should note that all of the model and experimental development has taken place with the general understanding of flow and transport in unsaturated fractures and fracture/matrix interaction in mind.

Our research program is also considering gravity driven fingering in general porous media composed of unconsolidated sand. The PRT has encouraged an "early transfer of research efforts on fingering from traditional porous media to fractured porous media" and have stated that "studies of two-phase fingering in traditional porous media have very little relevance to the Yucca Mountain Project." Our fingering research in fractures and sands is being conducted concurrently using identical experimental techniques. While sand is a "traditional" porous media, we consider sand in a thin slab chamber to be an analogue to a fracture. With this in mind, many effects of system parameters can be explored more easily in sand than in fractures. In fact, the hydraulic properties of fractures have "traditionally" been considered similar to those of coarse sand. For these reasons alone we must reject the PRT's statement that these studies are irrelevant to the Yucca Mountain Project. (It is easy to understand why the PRT missed these points considering the forced brevity of Glass's presentation.) There are however, other reasons of relevance to the model conceptual development and validation task for research in understanding and bounding the fingering process in "traditional" unsaturated porous media.

A series of experiments to investigate the effects of these factors is currently underway in a meter-scale slab chamber using optical techniques to follow the evolution of the moisture content fields in silica sands. The grain size distribution of the sand and thus the pore size distribution of the media are being varied systematically. Similitude theory applied to finger properties is used to design the grain size distributions. Several preliminary experiments in horizontally microlayered sand systems suggest that fingers widen and perhaps are suppressed as the amplitude and spatial frequency of the property oscillation between layers increase. A series of experiments where microlayering is systematically varied are planned as are experiments where the effects of contact angle and initial moisture content will be systematically explored.

Over the next two years the importance of gravity driven fingering for groundwater travel-times and radionuclide transport at Yucca Mountain will be determined through current modeling and laboratory based experimental efforts. This phenomena is being addressed as only a subset of SNL's effort in conceptual model development and validation.

6.2.21 The PRT supports research on the hydrologic influence of fracture coatings and fillings. However, it is possible that such coatings may be limited in their areal extent, and if so, they may not be of major importance. On the other hand, if ubiquitous, they could exert considerable influence on flow processes. Field investigation is in order.

We agree that fracture coatings may be important to flow processes, particularly to rates of imbibition from fractures into the rock matrix. The determination of the distribution, identity, physical characteristics, and geochemical characteristics of mineral species within fractures and fracture coatings is an ongoing activity within the geochemistry program of the Yucca

Mountain Project. Intense examination is planned during drilling and exploratory shaft excavation. The planned activity is described in the SCP in Section 8.3.1.3.2.1.3 -- Fracture mineralogy. Previously published work on this topic include three papers by Carlos and others (see References).

6.2.22 The PRT recommends a re-examination of the saturated-zone groundwater travel-time calculations, especially with respect to the suitability of the hydraulic-conductivity and effective-porosity values used for this dual-porosity system. However, if updated estimates do not lead to revised travel times on the order of 1,000 years or more, then additional studies and data collection activities in the saturated zone should be curtailed.

This item contains two separate recommendations, one for re-evaluation of GWTT and a second for curtailing further studies based on the results of the first. The first recommendation addresses re-examination of the saturated zone (SZ) GWTT. Staff basically agree with this recommendation since they are continually reassessing the interpretation of the SZ as data are available. We recognize that the initial calculations used inconsistent data--namely an "effective" value for (hydraulic conductivity) from a well test with combined fracture/matrix flow and a fracture porosity rather than an effective porosity. Several workers (e.g., Czarnecki et al., USGS; Barr, SNL) are presently re-examining interpretations of the saturated zone travel times. Dual porosity calculations have not yet been started by project workers--a matter which does need to be rectified.

For the second recommendation, we disagree that studies of the SZ should be curtailed if GWTT is much less than 1000 years. Saturated-zone studies address other issues in addition to GWTT. In particular, the concerns are where releases might be expected to appear and how the saturated-flow system might be altered by climate change or by catastrophic events. The PRT expressed the opinion that release of the high gradient area is unimportant for catastrophic events. This may indeed be the case, however there are clear technical arguments for caution in making a premature determination. Development of alternative models (see 6.2.24) for the high-gradient region in the SZ reopens the issue of behavior of the SZ in response to catastropphic events. Lastly, the SZ studies involve resolution of inconsistencies in interpretation of flow through the mountain. For example, isotopic results (Benson et al., USGS-OFR-83-854) suggests low SZ flow velocities - the mountain is an isolated backwater - while current inferences concerning the high gradient area suggest more rapid flow.

Updated estimates based on more complete analyses of the saturated zone may indeed establish flow times >1000 years to the accessible environment and that matrix diffusion may add 1 or 2 orders of magnitude to that expectation. These analyses, particularly those hypothesizing dual porosity, require more data (e.g. tracer tests) and more careful reduction of existing data. These analyses will be pursued as time and funding permit.

The PRT's comments here and in the discussion of Section 5.2 are well taken with respect to ground-water travel time. However, in terms of the cumulative radionuclide releases to the accessible environment over 10,000 years, it is not apparent that the contributions of the saturated-zone flowpaths will be trivial.

Furthermore, an understanding of the saturated-zone is essential in estimating its response to tectonism and to climate change.

6.2.23 Reliable, direct, quantitative field measurements of evapotranspiration and groundwater discharge are probably not feasible in the Yucca Mountain climatological environment. The PRT recommends a low priority for these programs.

The total water balance is not the basis by which calculations of infiltration rates are planned to be made at Yucca Mountain. This is only one approach to help define the processes and mechanisms involved in the upper flux system. Each of the components of the water balance equation (along with their associated errors) will be necessary, however, for the process-oriented modeling that will be used for calculations of rates. Each of the field instruments planned for measurement of evapotranspiration (ET) has it limitations. It is recognized that these measurements are often difficult in arid environments but they do work after a rain storm when relative humidity is high; measurement of ET at that time is very important in understanding the processes. For example, if it rains 2" in a channel and 1" ET is measured over the next 3 days, while in the alluvial fan downstream it also rained 2" but 3" of ET was measured, translocation of subsurface water is suggested. If after a 1" storm it takes 3 days to measure 1" of ET versus 3 weeks, it suggests there was little time of contact for moist alluvium to transmit water into the slower conducting bedrock. Prototype tests and preliminary data have shown that, while the measurement of ET in this environment is far from being exact, it is likely to be a useful tool to aid in understanding mechanisms and processes and that under certain conditions and using several methods, values of ET with acceptable errors will be successfully generated for input into models calculating infiltration rates.

With respect to discharge measurements at Franklin Lake Playa (Alkali Flat), we agree that high precision in measuring evapotranspiration is probably not attainable, but it does not follow that the effort should be assigned a low priority for several reasons:

(1) Directly determining flux and flow velocities beneath the controlled area is similarly imprecise -- and perhaps more so -- because of the difficulty of characterizing the near-zero hydraulic gradient and the distribution of actual flow paths (see response to 6.2.24). Even if tracer testing and associated modeling are successful, there will remain the question of whether the results at a relatively few sites are sufficiently representative.

(2) Determining recharge throughout the area contributing to the saturated-zone flux is the least feasible of the alternatives.

(3) In a strict regulatory sense, the radionuclide discharge outside of the controlled area is the fundamental site-suitability criterion; the 1,000-year GWTT performance objective is one of several proxies that may indicate the likelihood of achieving the fundamental criterion. However, an understanding of regional flow, including the partitioning of discharge between Franklin Lake and Death Valley, is inherent in a broader interpretation of the regulations. And,

(4) The saturated zone at both regional and site scales is very important to assessments of the hydrology, and thus to the impacts on waste isolation of climate change and future tectonism.

We are aware, of course, that the difficulty of measuring evapotranspirative discharge is added to that of partitioning flow-system discharge across the width of the system to estimate the flux beneath the site itself. We retain the position that multiple approaches -- including geochemical and isotopic techniques -- are necessary to attain the needed confidence in characterization results.

It should also be noted that the DOE has a Test and Evaluation Plan (DOE, 1990; YMP/90-22) in place, and this document governs the Project actions for data gathering and evaluation. If it should be determined that a test is not gathering any new information, this procedure allows for that test to be discontinued.

6.2.24 The PRT doubts that the release of water from the area of steep gradients north of the Yucca Mountain site due to tectonic activity is an important issue. We believe that any tectonic activity capable of causing significant changes in the hydraulic properties of rocks on a regional basis would have more dire consequences for the site than a rise in the water table.

Interestingly, opinions as to the significance of the large hydraulic gradient -- and particularly the possible effects of tectonism on the gradient -- range widely among review panels according to their expertise. In contrast to the UZ/PRT's comment, tectonics experts and geotechnical engineers generally minimize the significance of postclosure tectonism except as it may cause large changes in the hydrologic system.

With respect to the water-table altitude, the magnitude of rise beneath the repository can be considered in three stages:

(1) Rise to beneath the emplacement zone (<200 m). The effect would be to shorten the generally downward flow paths through the unsaturated zone, with an attendant decrease of travel time and associated retardation. In the saturated zone itself, gradients would necessarily increase, thereby increasing the transport velocity to the accessible environment.

(2) Rise into the repository zone (200-500 m). The effects would include eliminating the unsaturated flow paths, further increasing -- relative to (1) -- saturated-zone velocities, and changes in the physical and chemical environments of the waste packages.

(3) Rise to above surface-channel altitudes within the controlled area (>500 m). The effects include those of (2) but also shrinking the distance to the accessible environment.

Most conceptual models of the cause for the large hydraulic gradient include variations in the areal distribution of zones of differing transmissivity and, to date, the effects have been evaluated for various scenarios for increasing the permeability in zones of current low permeability. Modeling indicates that water-table rises beneath the repository would probably be minor, tens of meters at the most with current recharge rates, which is consistent with the UZ/PRT's observation.

However, two models -- both recently defined -- allow for a south-southeastward migration of the gradient itself. The first, offered by K.F. Fox, Jr. and his colleagues, attributes the apparent greater transmissivity (evidenced by small gradients) to the southeast and south of the large-gradient zone to refreshing of fracture permeability in the upper plate of a detachment system, moving generally westward but rotating such that displacement increases to the south. Assuming that the healing of fracture permeability occurs at a rate that is significant relative to the 10,000-year isolation period, the current areal distribution of transmissivity depends on continued upper-plate deformation.

The second model, offered by W. W. Dudley, Jr., is similar but involves the third dimension -- downward diversion of the generally southward saturated-zone flow into the underlying Paleozoic carbonate rocks in the vicinity of the steep gradient, leaving only a small flux (and, hence, small gradients) in the volcanic rocks beneath the south-southeast of the repository. In this model, the downward flow could coincide with the northern and western limits of significant fracture refreshing -- as in Fox's model -- or with generally southward thinning, to a threshold thickness, of the Eleana argillite that overlies the northward-dipping Paleozoic carbonates; a combination of the two is also likely.

These models share a dependency on maintaining the presently large permeability south of (and/or) beneath the belt of the current large gradient. Should fracture healing by persistent geochemical processes, igneous intrusion, or a change in the state of stress occur, the elevated water table might migrate southward. Given its current altitude at the northern limit of the gradient (>1,100 m), part or all of the repository could be submerged. At the present time, we do not understand the probable rates of the fracture-healing processes sufficiently well to declare the possibility of repository submergence to be trivial.

The DOE will consider the possibility of convening a panel composed of hydrologic and tectonics experts to evaluate the potential effects of tectonic processes on the site hydrology.

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S E C T I O N 3

Evaluation of the DOE Responses to the Peer Review Record Memorandum Report and Recommendations

Prepared by Allan Freeze and the Peer Review Team

April, 1991

EVALUATION OF DOE RESPONSES TO THE PEER REVIEW RECORD MEMORANDUM

Prepared for the

U.S. DEPARTMENT OF ENERGY

by the

PEER REVIEW TEAM

on

UNSATURATED ZONE HYDROLOGY

at

YUCCA MOUNTAIN, NEVADA

April, 1991

INTRODUCTION

The Unsaturated Zone Hydrology Peer Review Team (PRT) was established by the Regulatory and Site Evaluation Division of the Yucca Mountain Project office of the U.S. Department of Energy (DOE) in March, 1990. Following meetings of the PRT in Las Vegas in April and June, 1990, a Peer Review Record Memorandum (PRRM) was submitted to DOE in September, 1990. A document outlining the Responses of the Participants to the Conclusions and Recommendations of the PRRM was delivered to the PRT on February 28, 1991. It was accompanied by a List of DOE Action Items based on the recommendations of the PRRM and the responses of the participants to these recommendations.

This document provides an evaluation by the PRT of the DOE responses (and action items) that have emerged from DOE consideration of the recommendations and conclusions of the PRRM. In general, the PRT did not find the DOE responses contentious, and in most cases, a straightforward resolution of the issues has been reached. In the few cases where disagreement still exists, we judge the DOE Action Items to be a suitable resolution to the state of disagreement. The PRT feels that the review process is now complete, and it is the wish of the PRT members that this document bring the PRT deliberations to closure.

The evaluation that follows is presented in a point-by-point format, where the numbers refer to Section 6.0, Conclusions and Recommendations, of the PRRM. This is the same format used by DOE in the document outlining the Responses of the Participants.

EVALUATION OF RESPONSES

6.3 Programmatic Issues

6.1.1 The PRT was impressed with the strong motivation of the hydrologic research teams in the Yucca Mountain Project and with the high scientific quality of the on-going research programs and the published research record.

The PRT agrees with the DOE response to this conclusion.

6.1.2 To fully capitalize on the research strengths of the individual research teams, there is a need for improved program integration and interagency communication in the Yucca Mountain Project.

The PRT concurs with the analysis presented by DOE in response to this recommendation. We support the encouragement of CASY workshops (Action Item 1) and the formation of a Hydrology Integration Task Force (Action Item 2).

6.1.3 It is imperative that the Yucca Mountain research teams gain access to suitable field sites on Yucca Mountain, or in similar terrain elsewhere, in order to carry out prototype studies required for equipment testing, concept hypothesis testing, field methodology development, and model validation.

This recommendation is considered by the PRT to be the most important of all the recommendations made in the PRRM. Access to field sites, preferably on Yucca Mountain, is urgently needed for hypothesis testing of unsaturated-flow processes. If quality-assurance issues are causing the delays in field access, bureaucratic steps are needed to facilitate progress. If the Yucca Mountain permitting situation is preventing access to Yucca Mountain, the PRT recommends that access to other sites be enhanced. If current funding is holding up access, the PRT recommends that diversion of funds from other cost centers be investigated. If this is not currently possible, than arguments need to be made within DOE that the research budget is unecessarily contrained. Confirmation or adaptation of current theories of unsaturated flow to site-specific problems in fractured tuff is one of the basic issues that will control the potential acceptability of Yucca Mountain as a repository site. The PRT strongly supports Action Item 3.

6.1.4 In the opinion of the PRT, the quality-assurance procedures in the Yucca Mountain Project have become so over-formalized that they are creating unacceptable delays in the technical progress and a lowering of staff morale.

The PRT strongly supports Action Item 4.

6.1.5 The PRT recommends a hypothesis-testing approach to site characterization whereby the calibration of hydrologic models is carried out with respect to integrated performance measures rather than a detailed matching of the state variables. The approach emphasizes the collection of field data for the purpose of reducing the conceptual uncertainty through the testing of hypotheses, rather than for the reduction of parameter uncertainty per se.

The PRT concurs with the analysis presented by DOE in response to this recommendation.

6.1.6 The PRT is impressed with the development and implementation of state-of-the-art instrumental methods and measurement devices, especially with respect to deep downhole measurements of fluid pressures. The PRT offers strong support for the proposed deep borehole drilling program and recommends an early start for it. We have also identified several instrumental concerns. These are related to the use of neutron moderation in fractured rock, the long-term reliability of thermocouple psychrometers, the validity of mercury-intrusion and centrifuge methods in the laboratory measurement of hydraulic properties, and the strategies for soil-gas and pore-liquid sampling at depth in the field. The PRT is also of the opinion that back-up

strategies should be developed in case any of the proposed downhole monitoring technologies fail to perform as expected.

The PRT agrees with the DOE response to those aspects of this recommendation that deal with neutron moderation, mercury intrusion, and the centrifuge method.

With respect to the long-term reliability of the thermocouple psychometers that will be used in the deep UZ borehole instrumentation and monitoring program, the proposed duplication of the psychrometers, the intermittent cycling of the backup, and the design modifications for drift diagnosis, adequately address the long-term reliability issue. The U-tube gas sampling and vapor-content measurments provide a suitable approximate verification of the psychrometer readings. The thief sampler proposed as an additional fallback leaves the PRT confident that the borehole instrumentation and measurement program is properly addressed. Continued vigilance with respect to the limitations of current instruments, as well as appreication for alternative opportunities in instrumentation, is essential.

6.1.7 The PRT recommends that DOE streamline its publication review process so that technical reports are released or published within one year of preparation.

The PRT is pleased to learn of DOE initiatives in this regard, and supports Action Item 5.

6.1.8 The PRT encourages the documentation, verification, and sharing of computer codes between research teams and across agency boundaries; we discourage the current trend toward model proliferation.

The PRT accepts the arguments presented in the DOE response to this recommendation, and supports Action Item 6.

6.1.9 The PRT encourages closer coordination of construction activities and research activities on the Yucca Mountain site. It is important that the influence of site construction on infiltration properties and drainage patterns be minimized.

The PRT encourages continued vigilance and supports continued development of the GIS-based control mechanisms.

6.1.10 The PRT encourages improvements in site housekeeping with respect to fluid spillage, borehole leakage, site security and well abandonment.

The PRT encourages continued vigilance, and acknowledges Action Item 7.

6.2 Technical Issues

6.2.11 The PRT did not identify any conceptual hydrologic paths of fluid flow through the unsaturated zone at Yucca Mountain that have not come under consideration as potential radionuclide migration routes by the various research teams.

The PRT agrees with the DOE response to this conclusion.

6.2.12 The PRT is convinced that there is a source of water (both in the form of low-intensity, long-duration winter storms, and in the form of high-intensity storms), and a mechanism of infiltration (in the form of large-aperture surface fractures) that can introduce water to the ridges, slopes and upland areas of Yucca Mountain, in addition to water that infiltrates into the washes following rare runoff events. The PRT believes that a combination of lysimeter studies, tracer tests, and process-oriented modeling offers the best opportunity for estimating infiltration rates at Yucca Mountain.

The PRT acknowledges the limitations of lysimetry in measuring infiltration over the very heterogeneous surface of Yucca Mountain. Nevertheless, the PRT maintains that lysimeters can be helpful tools for delineating infiltration mechanisms and for model calibration and validation studies. In our opinion, lysimeters do not have to be perfectly representative of any particular location on Yucca Mountain; "disturbed" lysimeters may well be good enough, as long as they contain structured materials that are reasonably representative of the surface horizons. We note that lysimeters also provide a manageable medium for prototype testing of instruments, measurement methodologies, and methods of data analysis.

In contradistinction to the classic weighing lysimeters discussed above, the PRT also wishes to draw attention to the availability of high-pressure/vacuum downhole lysimeters, which may be applicable to the assessment of perched conditions at depth. Recent EPA research on porous glass should overcome earlier limitations associated with porous teflon and aluminum oxide ceramics, thus removing any hesitation on the use of high-pressure/vacuum downhole lysimetry.

6.2.13 One of the most critical features of the conceptual hydrologic model for Yucca Mountain is the postulated ability of nonwelded tuffs to attenuate and retard transient moisture pulses. We encourage early field experimentation in the Paintbrush nonwelded tuff and the nonwelded tuffs of the Calico Hills unit to investigate the validity of this mechanism.

The response to this recommendation, and Action Item 8, promise early investigation of the non-welded tuffs of the Paintbrush and Calico Hills units. If this investigation will be limited to surface studies, samples from outcrops, and core analysis, as implied in the response, it will not satisfy the PRRM recommendation. Similarly, if "early" means early in a still-distant site-characterization program, it will not satisfy the PRRM recommendation. The PRRM recommendation was meant to emphasize the need for on-site, in-situ, underground experimentation in the Paintbrush and the Calico Hills, in the next year or so. This recommendation is coupled to recommendation 6.1.3 in that it reflects the strong PRT view that in-situ confirmation of hydrologic mechanisms favorable to site acceptability ought to be the highest-priority technical issue in the program.

The PRT is in agreement with the conclusion of the risk/benefit analysis that there is no reason not to extensively explore the Calico Hills unit by means of underground excavation below the proposed repository.

6.2.14 The most important conceptual issue at the Yucca Mountain site revolves around the hydrologic processes of matrix/fracture interaction. the PRT recognizes the difficulties in developing a single, coherent, and complete theoretical formulation capable of evaluating nonisothermal, multiphase fluid flow in a dual-porosity medium. The PRT is impressed with the emerging approximate theoretical approaches being developed within the Yucca Mountain project. However, it is imperative that there be continued evaluation of the assumptions that underlie these methods; in particular, the assumption of fluid-pressure equivalence across the matrix/fracture boundary, and the acceptance of the concept of overlapping continua. The PRT believes that it is unlikely that fractures will achieve sufficient separation or continuity to act as effective barriers to vertical infiltration.

The PRT is in agreement with most of the analysis presented by DOE in response to this recommendation, and strongly supports Action Item 9.

We note, however, that evaluation of the assumptions underlying the theories of matrix-fracture interactions cannot be achieved with numerical experiments based on the application of computer codes. Sensitivity analyses with computer codes will identify the necessary and sufficient conditions for certain mechanisms to be active, given the assumptions underlying the theories encoded in the computer models. The PRT is espousing continued investigation of the underlying assumptions, and this must be accomplished through experimental or in-situ field validation.

6.2.15 The PRT believes that perched saturated zones will almost certainly be encountered during exploratory drilling at the site. Protocols should be in place for the sampling and testing of such zones. The presence of such zones should not, in and of themselves, disqualify the site from consideration for a nuclear waste repository.

The PRT concurs with DOE plans in this regard, and supports Action Item 10.

In addition to typical groundwater sampling techniques, which could be applied under perched conditions, the PRT suggests consideration be given to the use of the BAT system should tension-saturated conditions occur in the vadose zone.

The third paragraph of the response to this conclusion seems to imply that deep perched zones could not develop without larger infiltration fluxes in the past. The PRT does not concur with this interpretation. The PRT believes that deep perched zones could develop under current infiltration rates.

6.2.16 The role of gas flow through Yucca Mountain deserves continued attention, especially with respect to its effects on moisture redistribution and potential radionuclide migration in the vapor phase.

The PRT concurs with DOE plans in this regard.

6.2.17 The PRT supports proposed subsurface investigation of the hydraulic properties and hydrologic influence of fault zones on the Yucca Mountain site.

The PRT concurs with DOE plans in this regard, and supports Action Item 11.

6.2.18 The PRT encourages the emerging development of stochastic modeling approaches in the Yucca Mountain Project. A stochastic component to modeling endeavors is required in order to meet the regulatory travel-time criterion, to carry out hypothesis testing, and to aid in assessing the worth of proposed data collection networks.

The PRT agrees with the DOE response to this conclusion, and supports Action Item 12.

6.2.19 Inconsistencies between isotopic age dating of waters at depth and unsaturated groundwater travel times calculated with hydrogeologic models must be resolved.

The PRT agrees with the DOE response to this recommendation.

6.2.20 Studies of two-phase fingering in traditional porous media have very little relevance to the Yucca Mountain Project. The PRT encourages an early transfer of research efforts on fingering from traditional porous media to fractured porous media.

The PRT agrees with the potential importance of wetting front instability. There is no question in the minds of the PRT reviewers that the fingering research is of high scientific quality. In particular, the PRT was impressed with the optical scanning techniques developed. In addition, we were unaware that some of the porous-media instability research reported to us was not funded through the Yucca Mountain Project. The PRT acknowledges that time constraints may have resulted in an overemphasis on the porous media work rather than the more recent research on fingering in fractures.

However, the PRT still questions the role of porous-media fingering experiments except perhaps in methodology development. Contrary to the position stated in the DOE response, the PRT is convinced that "sand in a thin slab chamber" is not a suitable analogue to a fracture, except in the very limited instance of a "hydraulically equivalent resistance" under saturated, laminar-flow circumstances. We believe that the development of fingers in discrete systems of channelled planar fractures in rock is quite different than in sand. Recognizing the importance of preliminary methodology development in sand, and without wishing to unduly disrupt the orderly 5-step research procedure outlined in the DOE response, the PRT reaffirms its recommendation that research efforts on fingering move toward an emphasis on fractured media in due course.

6.2.21 The PRT supports research on the hydrologic influence of fracture coatings and fillings. However, it is possible that such coatings may be limited in their areal extent, and if so, they may not be of major importance. On the other hand, if ubiquitous, they could exert considerable influence on flow processes. Field investigation is in order.

The PRT concurs with DOE plans in this regard. Once again, earlier in-situ investigation on Yucca Mountain would benefit the program.

6.2.22 The PRT recommends a re-examination of the saturated-zone groundwater travel-time calculations, especially with respect to the suitability of the hydraulic-conductivity and effective-porosity values used for this dual-porosity system. However, if updated estimates do not lead to revised travel times on the order of 1,000 years or more, then additional studies and data collection activities in the saturated zone should be curtailed.

The PRT strongly supports Action Item 13. These calculations should be given a high priority. If current funding is holding up progress, as is implied in the response, diversion of funds from other cost centers should be investigated. Site acceptability may depend heavily on saturated groundwater travel time. It seems likely that consideration of dual porosity effects and matrix diffusion will increase estimates of travel time. If so, interest in the saturated zone should not flag. If travel times less than 1000 years emerge, the PRT continues to believe that some curtailment of the saturated-zone effort would be in order. We are, however, influenced by the arguments presented in the response in this regard, and we agree that issues other than groundwater travel time deserve consideration in any such curtailment.

6.2.23 Reliable, direct, quantitative field measurements of evapotranspiration and groundwater discharge are probably not feasible in the Yucca Mountain climatological environment. The PRT recommends a low priority for these programs.

The PRT concurs with the first paragraph of the DOE response. The PRT also concurs with the later paragraphs of the DOE response insofar as they emphasize the difficulties inherent in trying to estimate the partitioning of regional groundwater fluxes between the various potential discharge points. The PRT agrees that multiple approaches, including flow-system modeling, geochemical and isotopic techniques, and field measurement are in order. It continues to be our opinion, however, that field measurements of hydrogeologic parameters are more likely to aid in saturated-zone model calibration than are measurements of evapotranspiration and groundwater discharge in discharge areas of the flow system.

The PRT encourages researchers in the Yucca Mountain project to develop "significance" tests to assess the continuation or discontinuation of data gathering efforts. With this approach, tests and/or data are compared to objective criteria to determine if the tests or data are significant. For example, if the tests or data can be used to confirm (or reject) all (or part) of a hypothesis related to a performance measure, then the tests or data are significant. This type of data-worth assessment is integral to the PRT's recommendation for a hypothesis-testing approach to site characterization (see item 6-1-5).

6.2.24 The PRT doubts that the release of water from the area of steep gradients north of the Yucca Mountain site due to tectonic activity is an important issue. We believe that any tectonic activity capable of causing significant changes in the hydraulic properties of rocks on a regional basis would have more dire consequences for the site than a rise in the water table.

The PRT concurs with the arguments presented by DOE in response to this conclusion. In the PRRM, we may have given the impression that we do not think a large rise in the water table would be detrimental to the site. Such is not the case; we agree with the implications of a large water table rise as listed in this response. Rather, it is our view that such a large rise in the water table due to tectonic activity is unlikely, and that the steep hydraulic gradient to the north of the site is not in itself indicative of any particular likelihood of rising water tables. Nevertheless, we are aware of the wide spectrum of views that exists about the potential coupling of tectonic and hydrologic processes. The PRT concurs with Action Item 14, wherein DOE proposes to base its actions on the recommendations of a specially-constituted NAS panel on this topic.