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PRELIMINARY DRAFT
INFORMATION ONLY

YUCCA MOUNTAIN PROJECT

A CONSENSUS PEER REVIEW OF PREDICTIONS OF SEEPAGE INTO THE DRIFTS OF A PROPOSED REPOSITORY AT YUCCA MOUNTAIN

Peer Review Team:	**Approvals**
Dr. Neil Chandler (Rock Mechanics/Rock Mass Response to Excavation)	______________________
Mr. Cliff C. Davison (Chair) (Fracture Flow and Transport)	______________________
Dr. Glendon Gee (Surface Flow Processes/Infiltration)	______________________
Dr. Paul LaPointe (Geostatistics/Fracture Flow Modeling)	______________________
Dr. Shlomo Neuman (Unsaturated Zone Flow and Fracture Flow/Transport)	______________________
	Signature / Date

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PREFACE

Scientific peer reviewers tend to be critical and look for flaws or gaps in the scientific work being reviewed. Thus most peer reviews tend to focus on weaknesses or deficiencies rather than draw attention to strengths and accomplishments. Because of this we have probably not presented a balanced view of the drift seepage work being conducted for the USDOE's Yucca Mountain Project (YMP).

We note that from a world wide perspective, and compared to other hydrologic situations, relatively little work has been done to develop a scientific understanding of the deep percolation of moisture through unsaturated rocks under arid climate conditions similar to those at Yucca Mountain. The YMP has been fostering leading-edge, scientific investigations of this topic for many years and many of the scientific staff involved in this work are considered experts in the field. We take this opportunity to commend the scientists working for the YMP who are trying to develop the understanding of the spatial distribution and rates that moisture will seep into the drifts of a repository at Yucca Mountain. We have been impressed with the overall technical and managerial capability of the LBNL and USGS teams working on the drift seepage topic for the YMP.

PRELIMINARY DRAFT
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EXECUTIVE SUMMARY

This report presents the discussion, conclusions and recommendations of a formal consensus peer review of the Yucca Mountain Project's (YMP) predictions of the spatial distribution and rate of moisture seepage into the drifts of a proposed repository at Yucca Mountain. The Management and Technical Support organization (MTS) for USDOE's Yucca Mountain Project Office (YMPO) initiated this peer review and asked the Drift Seepage Peer Review (DSPR) panel to evaluate the data, assumptions, conceptual models, methodologies and uncertainties associated with the YMP predictions of drift seepage into the USDOE's proposed repository at Yucca Mountain over long time frames. The scope of the review was limited to drift seepage under natural temperature conditions; the effects of waste-generated heat on drift seepage predictions were specifically not included in the review.

Our overall conclusion is that the YMP (largely through experimental and modeling work performed by scientific staff at Lawrence Berkeley National Laboratory (LBNL) and the United States Geological Survey (USGS)), has made significant progress toward understanding the factors, events and processes that will control the rate and spatial distribution of moisture seepage into the drifts of a repository at Yucca Mountain. However, there is currently a large amount of uncertainty associated with the quantitative estimates of the rate and spatial distribution of the seepage. This uncertainty has not been adequately quantified and more characterization, modeling and experimental work are needed to develop defensible estimates of the spatial distribution and rates of moisture seepage into the repository drifts.

We do not believe it is realistic that the YMP attempt to develop models that might be expected to "predict the current and future rates and locations of moisture seepage into the repository drifts at Yucca Mountain", especially for the long time frames required for PA analysis. Instead, we believe the YMP should develop models that can provide reliable statistical measures and bounds for estimating drift seepage rates and locations. Such models will need to rely on sound statistical descriptions of the upstream moisture boundary conditions (infiltration and percolation), downstream drift boundary conditions (including drift geometry and elements of the repository design that affect this boundary) and all of the features, events and processes that control moisture transfer and seepage into the repository drifts. We conclude that there is considerable room for improvement in this area of the YMP program not the least of which involves: developing a thorough plan for ongoing and future experimental and modeling work that is closely integrated with developments in the program areas of repository design and engineered barriers; conducting additional, comprehensive drift seepage measurements, tests and experiments in the ESF and the potential repository; and, obtaining additional site characterization information for a wide range of spatial scales (from a few tens of centimeters to many tens of meters), especially for the rocks of the repository horizon, that can be used to develop multiscale relationships of the geologic and hydraulic heterogeneity that controls moisture movement through the rocks at Yucca Mountain.

In conducting this future drift seepage modeling and characterization work we recommend that YMP should develop an overall plan and strategy that clearly describes and justifies the rationale, scope, and objectives of the ongoing and future drift seepage work. We have seen no evidence that such a plan exists and we believe such a plan would help to establish clear near-term and long-term objectives for the drift seepage work and would help to focus the available YMP resources on this topic. Further, we believe such a plan could provide a vehicle to consolidate the drift seepage resources and identify how the characterization, in-situ measurements, and modeling studies could be combined into fewer, but more comprehensive, drift seepage experiments that could benefit from thorough 3-D characterization and monitoring. We also urge the YMP to make sure the plan for future drift seepage characterization, modeling, and experiments is integrated with, and takes account of, the options that are being considered for the repository design and engineered barriers within the repository.

We note that YMP's drift seepage work so far has ignored the time-dependent, coupled effects (thermal, mechanical, chemical, hydrologic) of constructing and operating the repository. We believe this constitutes a significant gap in the YMP's current drift seepage work and we recommend future experimental and modelling work should include these aspects, as well as properly account for other long-term, time-dependent changes that could alter drift seepage during the postclosure period of performance analysis.

1. INTRODUCTION

1.1 OBJECTIVE OF THE PEER REVIEW

This peer review was initiated by the Management and Technical Support organization (MTS) for the U.S. Department of Energy's (DOE) Yucca Mountain Project Office (YMPO) to evaluate the data, assumptions, conceptual models, methodologies, estimates, and uncertainties of predicting drift seepage into the DOE's proposed high level nuclear waste repository at Yucca Mountain, Nevada over long time frames.

The Total System Performance Assessment-Viability Assessment of a Repository at Yucca Mountain (DOE 1998) showed that drift seepage is one of the few factors that can affect the long term estimates of radionuclide dose to a human receptor down gradient from the location of the proposed repository at Yucca Mountain by more than a factor of one hundred. Degradation of the waste package, dissolution of the waste, and migration of released radionuclides to the groundwater table are dependent on the estimated locations and amounts of drift seepage into the repository. Drift seepage is also a key factor contributing to the selection of metals for waste package design because it affects the corrosion characteristics.

The seepage of moisture into the drifts of a repository constructed above the groundwater table in the rocks at Yucca Mountain is directly related to the spatial and temporal distribution of moisture infiltration on the Mountain and the rate and location of the moisture percolation as it moves downward through the unsaturated zone to the groundwater table. The DOE's Expert Elicitation on the Unsaturated Zone Flow Model has previously considered the topics of moisture infiltration and percolation at Yucca Mountain (CRWMS M&O 1997).

Predictions of the rate and locations of moisture seepage into the drifts of the DOE's proposed nuclear waste repository at Yucca Mountain, Nevada are obtained from numerical modeling. The Drift Seepage Peer Review (DSPR) panel was asked to evaluate the basis and models used by the DOE's Yucca Mountain Project (YMP) to estimate the space-time distribution of moisture that will seep or drip into the repository drifts. The DSPR was asked to consider the drift seepage predictions under moisture infiltration and percolation conditions for the current (dry) and postulated future (wetter) climates, but was asked not to consider any potential impacts that thermal, thermomechanical, or geochemical alterations of the repository environment due to placement of the heat-generating nuclear waste in the drifts could have on predictions of drift seepage. While the DSPR attempted to restrict it's review to this mandate, it was difficult in some cases to refrain from commenting on the potential effects that the thermal load of the repository could have on estimates of drift seepage because it was judged that the effects could be significant and need to be accounted for in the drift seepage models. However our treatment of the topic of the thermal effects on drift seepage predictions has only been cursory, and the DSPR panel recommends that any future reviews of moisture movement and seepage into the repository at Yucca Mountain should consider the effects of the thermal load.

1.2 BACKGROUND

In order to understand the seepage of moisture into the repository drifts at Yucca Mountain there must be an understanding of the hydrologic processes and geologic features that control the infiltration and percolation of moisture within the mountain. Stated otherwise, there must be a reliable conceptual model of the hydrology of Yucca Mountain on both space and time scales that are relevant to understanding how moisture that is moving through the mountain will enter the repository drifts and emerge as evaporation or seepage. To assess this quantitatively, defensible models must be available that can be used to render quantitative estimates of where, when, and at what rates moisture will flow into the repository drifts. For repository performance assessment purposes these models must be able to represent the locations and rates that moisture will enter the repository under the dry climate conditions that exist at present, as well as under episodic periods of higher moisture flux or possible wetter climate conditions that might develop at Yucca Mountain over the next several hundred thousand years. Such models must account for the full range of possible conditions that could affect the spatial and temporal distribution of moisture evaporation and seepage into the repository drifts far into the future, or incorporate statistically meaningful assessments of the uncertainty about these conditions. In order to develop such quantitative models, conceptual models of the hydrology of the Yucca Mountain site must be translated into working mathematical-computational models that are capable of representing the space-time factors that will control the distribution of moisture movement into and within individual repository drifts.

The conceptual and mathematical-computational models which underlie the DOE's current analyses of the hydrology at Yucca Mountain are those embodied within the site-scale Unsaturated Zone (UZ) Flow and Transport Model (Bodvarsson and Wu, 1998), that has been developed and is continuously being improved by Lawrence Berkeley National Laboratory (LBNL). Because LBNL's site scale UZ model has a descretization grid of 100 - 200 m it does not have the necessary space-time resolution to allow a detailed quantitative analyses of seepage into individual repository drifts at the repository horizon. This is overcome to some degree by adopting a binary, dual permeability representation of the site scale moisture flow through the fractured rocks at Yucca Mountain. Many key parameters of this dual permeability model, such as the fracture-matrix transfer coefficient, and unsaturated properties of the corresponding fracture continuum, have been estimated primarily on the basis of one-dimensional and partial model calibrations, which render them highly uncertain.

Other LBNL modelers, have developed local drift-scale seepage models that provide much more detailed descriptions of the hydrologic conditions controlling moisture movement in the close vicinity of the repository drifts at Yucca Mountain than is currently done with the site-scale UZ flow model. These higher-resolution, drift-scale seepage models (Tsang et al. 1998) use a grid size of 30 - 50 cm to represent the spatial variability in hydrologic properties and receive their hydrologic inputs, in the form of deterministic water pressures and/or percolation rates, from LBNL's much cruder, deterministic site-scale UZ flow model. For the drift scale modeling, this deterministic moisture flow input is routed to and/or around the drifts through a nonuniform porous continuum that is used to represent the heterogeneous fractured rock environment in the close vicinity of the repository drifts. Multiple realizations of the nonuniform porous continuum are generated via a geostatistically-based Monte Carlo process by viewing the logarithm of saturated rock permeability as a statistically homogeneous (stationary) random field with a given variance and spatial autocorrelation scale. The corresponding "stochastic continuum" can be rendered anisotropic by ascribing to it different spatial correlation scales in the vertical and horizontal directions. It can incorporate two scales of heterogeneity by including two distinct spatial correlation scales in any given direction. As each random realization of the stochastic continuum is, in theory, equally likely, there are no grounds for selecting one of them to represent actual conditions of seepage into a drift. Instead, numerous realizations are modeled and the results are averaged to obtain a single "most likely" description of drift seepage. Whereas individual realizations may (if resolution is high enough) provide "realistic looking" images of seepage around and into drifts, these images are not unique. When these images are averaged, a unique result emerges which may constitute an optimum prediction. Because the averaged image is relatively smooth however, it does not in general have a realistic appearance.

The extent to which the combined models of moisture infiltration, percolation and seepage can predict the rate and location that moisture will enter the drifts of a repository at Yucca Mountain depends on the reliability and validity of the underlying conceptual-mathematical models for moisture infiltration, percolation and drift seepage at the mountain, how these models are linked, and on the amount and quality of the geologic and hydrologic data that is used in the models. Our review covers all these topics.

2. DRIFT SEEPAGE PEER REVIEW PROCESS

The Drift Seepage Peer Review (DSPR) was initiated by Dr. Bimal Mukhopadhyay of the Management and Technical Support Organization (MTS) for DOE's Yucca Mountain Project Office. The review officially began by appointing a chairperson (Mr. Cliff Davison, Atomic Energy of Canada Limited, fracture flow and solute transport) and establishing a technical contact in Las Vegas (Dr. Ronald Linden of MTS) for the DSPR panel.

Based on the statement of work prepared by the MTS, the DSPR panel chair developed a peer review plan entitled "Plan for a Consensus Peer Review of YMP Predictions of Drift Seepage into the Proposed Repository at Yucca Mountain" (Appendix 1) in accordance with Section 5.6 of YMPO Quality Management Procedure QAP 2.5, Rev.1, ICN 0: Performance of a Consensus Peer Review. The following people were subsequently selected to serve on the DSPR panel:

- Dr. Shlomo Neuman (University of Arizona)
    - Unsaturated zone and fracture flow/transport modeling

- Dr. Glendon Gee (PNL, Richland, Washington)
    - Surface flow processes/infiltration

- Dr. Paul LaPointe (Golder Associates, Seattle, Washington)
    - Geostatistics/fracture flow modeling

- Dr. Neil Chandler (Atomic Energy of Canada Limited, Whiteshell Labs/ URL)
    - Geomechanics/rock mass response to excavation

Copies of the major, most recent YMP drift seepage reports were distributed to members of the DSPR panel in 1998 November. These are listed in Appendix 2, along with other documents related to drift seepage at Yucca Mountain which were sent to the DSPR panel during the course of this review.

The DSPR panel met in Las Vegas January 11-13, 1999 with the Principal Investigators (PI's) responsible for the experimental and modeling aspects of the YMP's drift seepage work. Appendix 3 contains the agenda and list of speakers for 1999 January DSPR meetings. On the second day of the meeting, the DSPR panel members were given a field tour of the DOE's Experimental Studies Facility (ESF) at Yucca Mountain to see the conditions that affect seepage into the drifts, to visit the locations of the past and ongoing YMP seepage experiments and tests, and to hear discussions from the drift seepage PI's of plans and suggestions for future drift seepage measurements, tests and experiments in the ESF.

2.1 PEER REVIEW TASKS

The purpose of this peer review was to evaluate the data, assumptions, conceptual models, methodologies and uncertainties associated with the Yucca Mountain Project's (YMP) predictions of drift seepage into the proposed repository at Yucca Mountain over long time frames. The scope was limited to drift seepage predictions under natural temperature conditions. Predictions of the effects of waste-generated heat on drift seepage were specifically not included in this review.

The DSPR panel had the following tasks:

- define conditions which control moisture seepage into repository drifts at Yucca Mountain
- review the most recent YMP synthesis reports on drift seepage and moisture monitoring tests conducted in niches and alcoves of the ESF at Yucca Mountain
- examine the representativeness of using the inverse modeling technique to obtain the continuum fracture characteristics from a calibrated flow model at the mountain scale for modeling drift seepage
- examine the representativeness of using the continuum fracture network model versus a discrete fracture model for estimating drift seepage
- examine the adequacy and representativeness of the seepage testing approach and field test locations (both present and planned)
- examine the adequacy of interpretation and incorporation of experimentally acquired seepage data into the 3-D UZ Flow Model
- examine the nature and extent of uncertainties produced by changing from the 30 m grid for surface modeling (infiltration model) to the 100-200 m grid for the 3-D UZ Flow Model (percolation flux model) to the very small 0.5 m grid for the drift scale model (seepage model)
- evaluate the current YMP seepage estimates into the repository drifts at Yucca Mountain considering:
    - data on rock heterogeneity
    - interpretations of site hydrogeologic features
    - knowledge of the present and projected future ranges of percolation flux at the repository horizon
    - data and interpretations of matrix and fracture moisture content
    - understanding of partially saturated matrix and fracture characteristics
    - knowledge of the effects of capillary barriers surrounding mined repository openings
    - relevancy of conceptual models
    - appropriateness of assumptions
    - promising or alternative modeling techniques

- state the degree of confidence the Panel has in:
  1) the test results obtained from the experimental drift seepage program in the ESF; and,
  2) the predictions of repository drift seepage obtained from the YMP numerical modeling efforts.

The individual members of Drift Seepage Peer Review panel considered all these tasks throughout the course of the review, although they also focused their attention on drift seepage topics closely associated with their respective areas of scientific expertise and experience:

- Neil Chandler: near field effects of excavation on drift seepage observations and seepage models, geomechanical considerations in predicting drift seepage.
- Cliff Davison: site and drift scale models of fluid flow through the fractured rock at Yucca Mountain, spatial characterization of the hierarchy of fracturing in the rock and representing the fracture geometry and other fracture flow characteristics that effect moisture flow and drift seepage at the different modeling scales.
- Glendon Gee: moisture infiltration and percolation at the mountain scale*, the location and adequacy of the previous and future seepage experiments in the ESF, impacts of advective drying on drift seepage observations and experiments.
- Paul LaPointe: numerical modeling of fluid flow through fractured rocks, scale effects, geostatistical approaches, model formulation, model verification, model validation and model feasibility.
- Shlomo Neuman: moisture infiltration and percolation through Yucca Mountain*, scaling (including micro scale) considerations in modeling moisture percolation, seepage and dripping, flow focusing and fingering, preferential and episodic paths for fluid flow, the effects of hydrodynamics and hysteresis on fluid flow through fractured rock.

* Glendon Gee and Shlomo Neuman were members of a previous expert panel that was established for the DOE's Unsaturated Zone Flow Model Expert Elicitation Project (CRWMS M&O 1997). Shlomo Neuman was also a member of the DOE's Saturated Zone Expert Elicitation Project.

The individual review reports which were submitted by the DSPR panel members were used by the panel chair to create the various drafts of this report which were subsequently reviewed, revised and reorganized by all panel members into this final version. The DSPR panel met in Las Vegas on 1999 August 18-19 to discuss the final report and agree on its content.

3. DRIFT SEEPAGE ISSUES FOR REVIEW

Estimates and predictions of where and how much moisture enters and seeps into the drifts of a repository at Yucca Mountain are controlled to a very large extent by estimates of the rate and space-time distribution of moisture moving through the rocks of the repository horizon as it travels downwards to the water table. This, in turn, is controlled by the way the moisture is modeled to enter the surface of the mountain (infiltration) and then how it is modeled to flow downward through the unsaturated, fractured rocks at the mountain (percolation). Before dealing with some of the near-field issues related to modeling and predicting the location and rate of moisture movement into the proposed repository drifts, the DSPR panel first examined the basis and models being used by the YMP to describe the infiltration and percolation of moisture at Yucca Mountain.

3.1 INFILTRATION

Net infiltration is water entering the land surface that is not removed by evaporation from soil and plant surfaces (i.e., evapotranspiration). Over extended periods of time, net infiltration is equivalent to recharge (i.e., water passing through the vadose zone that subsequently enters the underlying water table). A number of conceptual models have been developed in the past 15 years to describe net infiltration (recharge) rates at Yucca Mountain (Flint et al. 1999). A conclusion from the report of the Unsaturated Zone Flow Model Expert Elicitation Project was that "net infiltration is the fundamental control on the overall water balance for the UZ flow system under ambient conditions" (CRWMS M&O 1997). Because moisture percolation through Yucca Mountain is considered to be essentially vertical, the UZ expert panel concluded (although it was not unanimous) that "net infiltration is equivalent to percolation flux at the potential repository horizon".

We acknowledge that some very good work has been done by the YMP in the development and evolution of a conceptual and numerical model for the net infiltration of moisture into the rocks at the Yucca Mountain site, as summarized in the report "Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada" (Flint et al. 1999). The infiltration model, calibrated to changes in moisture content at neutron boreholes, is used to predict the spatial distribution and rates of infiltration at the site under the current dry and expected future wetter climate conditions. The region of greatest expected infiltration, based largely on a model that relates infiltration to the thickness of soil cover, is at the crest of the mountain, directly above the "footprint" of the proposed repository. The USGS report (USGS 1996) notes that under the current climate conditions at Yucca Mountain, the spatial variability of the moisture infiltration rate over the repository area may be from 0 mm/yr for some of the area to in excess of 15 mm/yr for others directly beneath the crest of the mountain. The estimated average rate of current infiltration (dry climate) averages over the entire area of the repository footprint is 7.7 mm/yr. (In later discussions we have used about 10 mm/yr as the overall estimate of the current rate of moisture infiltration into the mountain over the repository area). The average infiltration rate predicted for postulated long-term average climate conditions (wetter) is estimated by the YMP to be 42 mm/yr for the area of the repository and the spatial variability is predicted to range from about 5 mm/yr for a few locations of the repository to up to 85 mm/yr for other locations.

The information suggests that the net infiltration of moisture into Yucca Mountain varies with large frequencies and amplitudes in space-time. However, the near-surface processes which lead to the infiltration of moisture into Yucca Mountain are very complex and difficult to quantify so the details of this variability remain highly uncertain despite the excellent work which has been done on this topic by Alan Flint and others at the USGS. Initially, the infiltration models were estimates based on measured saturation and hydraulic conductivities of the matrix materials, with little or no consideration given to water movement in the fractures. More recently, the models combine estimates of water balance from known variations in precipitation, with spatial distributions of shallow surface soils and estimates of the dual hydraulic characteristics of the underlying fractured tuff materials, with observations of water pulses (from neutron logging) associated with El Nino (high precipitation) events. This information has been coupled with estimates of water flux, based on thermal profile data, to generate moisture recharge maps for large areas of Yucca Mountain including the repository area (Flint et al. 1999). Estimates of net infiltration for areas directly above the planned location of the proposed repository range from less than 0.5 mm/yr to more than 40 mm/yr, and localized recharge zones exceeding 100 mm/yr are estimated to develop under elevated precipitation scenarios. However, the area of Yucca Mountain where the greatest infiltration is modeled to occur has very few if any field measurements of moisture saturation or hydraulic conductivities. Even at the measurement sites the assessments of net infiltration are suspect because the distance between neutron monitoring boreholes is often larger than that needed to understand shallow moisture flow conditions during and after storm events.

We are concerned that there has been no analysis to quantify the uncertainty in the estimated moisture infiltration rates. Since there are so many variables and the flux rates are relatively low, the uncertainties are generally considered to be in excess of a factor of 5 or more. While the cross-borehole studies that are currently being planned in the ESF may give some information regarding the percolation flux at the ESF, they will cover only a tiny fraction of the planned repository area and will not intersect the regions of the mountain with the highest estimated recharge. Verification of the spatial and temporal variability in moisture recharge rates above the footprint of the repository with such sparse data may not be possible.

Future climate scenarios with postulated elevated (pluvial) precipitation conditions cause estimates of net moisture infiltration (recharge) at Yucca Mountain to increase by as much as an order of magnitude above present day (dry climate) estimates. Percolation fluxes ranging to values greater than 90 mm/yr, with an average long term value for the overall area of the repository of 42 mm/yr, were presented as possibilities in the future climate scenario developed by LBNL for Yucca Mountain (Bodvarsson and Wu 1998).

We echo some of the concerns raised by members of the recent UZ Flow Model Expert Elicitation Project (CRWMS M&O 1997) that moisture infiltration remains one of the least understood hydrologic processes at Yucca Mountain. We are not aware of any examples (neither in fractured nor in porous terrains; neither in humid nor in arid environments) where such measurements and models have ever been verified to yield reliable estimates of net infiltration on a scale comparable with that of Yucca Mountain, and with the space-time resolution that seems to be needed to ultimately estimate the distribution and rates of moisture seepage into the proposed repository drifts at Yucca Mountain. We are concerned that neither the models nor the data used to generate net infiltration maps across the surface of Yucca Mountain are yet to the stage that they can be fully relied upon to provide credible estimates of temporally averaged net rates at which moisture currently enters (and is expected to enter under future wetter climate conditions) the surface of the mountain, or of the spatial distribution. In particular, we are uncomfortable with the premise, which underlies the model that is currently being used to generate the infiltration maps, that net infiltration rates are higher along hilltops and the mountain crest than along washes at Yucca Mountain. We concur with statements made by the UZ Expert Elicitation Project (CRWMS M&O 1997) that there is inadequate treatment of surface runoff and shallow lateral flow in the current moisture infiltration models of Yucca Mountain and these processes could discredit this premise.

The apparent downward propagation of elevated moisture signals observed in some neutron monitoring boreholes during and after storm events has been interpreted by the YMP as an indication of downward flow and has been used to estimate vertical net infiltration. It is possible however that such signals reflect lateral, not only vertical movement of moisture.

The possibility that lateral moisture flow can direct the moisture infiltration along the bedrock-alluvium contact at Yucca Mountain is supported by the finding of bomb-pulse ^{36}Cl in the pore waters at the base of the alluvium in borehole UZ-16, but not within the alluvium. Shallow lateral subsurface flow may also take place along hill slopes due to a phenomenon similar to that which causes a thatched roof to divert rainwater laterally away from the underlying structure. No such lateral flows are considered in the models that have been used by the USGS to generate the published net infiltration maps for Yucca Mountain. Not only has near-surface flow been assumed to be everywhere vertical for the purpose of preparing these infiltration maps, but the calculated rates of infiltration into the rock are based on permeabilities that have often not been measured, but have been derived theoretically on the basis of a statistical treatment of fracture geometry data such as densities and apertures. It is well established that such estimates of permeability lack a firm basis in theory and experiment (Neuman 1987) and are therefore generally unreliable.

Many other important sources of error and uncertainty affect the current model used to estimate net infiltration rates at Yucca Mountain including: low space-time resolution of storm events; relatively poor understanding of, and ability to quantify, processes which control water uptake by plants from soils and fractures; poor definition of the processes and material properties (such as spatial variations in near-surface bedrock permeability) which focus moisture infiltration into fast flow paths; and the transient nature of infiltration processes, including the effects of hysteresis. In particular there appears to have been no effort to determine the effect of funnel flow through fractures on net infiltration. Geologic characterization has shown that horsetail patterns of fracturing occur in the surface rocks at Yucca Mountain and these suggest funnel-type fracture networks exist. However, this information seems to have been ignored in developing the current moisture infiltration model.

The areas where net infiltration has been predicted do not, in general, correspond to areas where actual infiltration measurements have been made and where surface sediments have been characterized. The lack of direct measurements makes it very difficult to verify the YMP's net infiltration models. The planned cross-drift seepage studies in the ESF may be helpful in providing some verification data, however, the areal extent of the drift is very limited relative to the planned layout of the repository. None of the present or proposed study effort includes any assessment of moisture percolation beneath the areas of the mountain expected to have the greatest infiltration. Obtaining water flux data from beneath such locations of the highest estimated infiltration rates should be a top priority in future characterization efforts.

Although the discussions on infiltration contained in the report on the UZ Flow Model Expert Elicitation Project (CRWMS M&O 1997), in the USGS report (USGS 1996) and in Flint (1999) provide us with some confidence that a good model for moisture infiltration can be developed for Yucca Mountain, we conclude that the infiltration model as it is currently presented is not entirely defensible. We agree with some members of the UZ flow model expert elicitation that the current model may overestimate infiltration percentages at the crest of Yucca Mountain and underestimate them at lower elevations. It is our view that the YMP should quantify the uncertainty in the current models used to predict the spatial distribution and rates of moisture infiltration for the mountain, particularly for the crest of the mountain directly above the planned location of the repository where infiltration is expected to be the greatest. The evidence suggests that the current overall amount of net moisture infiltration into Yucca Mountain cannot be predicted to within a half order of magnitude. Scenarios involving elevated precipitation (either as episodic events or during a possible future wetter climate) increase the estimates of net infiltration into the mountain and also increase the uncertainty in these estimates.

We support a suggestion made by D.B. Stephens of the UZ Flow Model Expert Elicitation Project (CRWMS M&O 1997) to thoroughly instrument and study at least one small drainage basin at Yucca Mountain. Such a study would examine infiltration processes on a sufficiently small spatial scale, over a sufficiently long time period, to provide information about both spatially distributed and relatively slow, as well as focused and comparatively fast, rates of net infiltration at and near the soil surface. The study might rely (among others) on rain gauges, detailed mapping of fractures (beneath the alluvium at some locations), nests of piezometers in the alluvium and bedrock, and detailed mapping of the depth to bedrock. Measurements could be made of surface flow during storm events and subsurface flow along the bedrock-alluvium contact using trenches, surface runoff gages and weirs, buried pan or wick-type lysimeters, and TDR or capacitance probes. Part of the watershed should ideally overlie the ESF and the planned location of the waste emplacement rooms of the repository, where other instrumentation (such as tensiometers, neutron probes, and heat dissipation sensors) are monitored and pore water is sampled for geochemistry. A goal of the watershed study would be to develop a complete water balance for this local watershed, over a number of years, to assess the amounts and spatial (as well as temporal) distribution of infiltration in the watershed. Information thus gained would provide support for YMP's modeling of moisture infiltration at Yucca Mountain.

S.P. Neuman of the UZ Flow Model Expert Elicitation Project proposed an approach to asses long-term average deep percolation through Yucca Mountain by focusing on matrix-dominated flow within the Paintbrush nonwelded (PTn) unit that lies between the TCw and TSw (CRWMS M&O 1997). He showed how one could use pressure, saturation and relative permeability data in boreholes to calculate vertical flux through the PTn by means of Darcy's law (CRWMS M&O 1997). We also recommend that serious consideration be given to this proposal. This would provide an independent confirmation of the estimates of long-term average moisture infiltration and deep percolation derived by other means. It is recognized that there are relatively large uncertainties in such an approach (often as much as an order of magnitude error in flux estimates). However, within the limitations of the present methodologies this approach may be more reliable than the less direct methods that have been used so far, such as water budget (ET estimations), chloride mass balance analysis, or estimates from geothermal gradients (thermal profiling).

Continuation of the USGS surface infiltration studies at Alcove 1 in the ESF to evaluate the effect of ponded infiltration on drift seepage should add some credibility to the infiltration assessment and estimated percolation rates. In addition, the planned study in the ESF cross-drift to measure moisture seepage into a niche in the ESF from a controlled infiltration of water from an overlying niche in the E-W Cross Drift should also provide valuable information regarding the impact of possible elevated infiltration rates on drift seepage.

3.2 PERCOLATION

The topic of moisture percolation through the unsaturated rocks at Yucca Mountain has also been carefully examined for the YMP by the recent UZ flow model expert elicitation panel

(CRWMS M&O 1997). Most of the experts noted that because percolation is mainly vertical the percolation flux should be directly related to the infiltration flux. However, the spatial distribution of the percolation at the depth of the proposed repository will be affected by lateral moisture flow at the top of the PTn and funneling or focusing of the moisture flow through fractures or high permeability pathways in the rock units above the repository, including fractures or other flow channels penetrating the PTn. For the most part, the PTn is expected to act as a buffer to downward moisture percolation, with matrix flow predominating.

The effect is that the YMP's current moisture percolation models assume that the PTn dampens out the effects of episodic infiltration events (infrequent high intensity storms) and thus there is steady moisture percolation through the underlying TSw that reflects the long-term average of infiltration (i.e., no episodic flux).

The rate and location of moisture percolation through the UZ at Yucca Mountain has not been measured directly. The estimates of the spatially averaged, current rates of moisture percolation flux at the depth of the repository horizon (about 300 m below the crest of Yucca Mountain), without any direct measurements of fluid volume, appear to be constrained between 2 and 50 mm/yr with the average flux over the area of the repository footprint estimated to be about 10 mm/yr (Bodvarsson and Wu, 1998). Because vertical moisture flow predominates the models to the depth of the repository, the estimated percolation rates and their spatial distribution at the repository horizon are virtually identical to the estimated rates and spatial distribution of the moisture infiltration over the surface of Yucca Mountain.

There now appears to be general consensus throughout the YMP that the moisture percolation through the unsaturated zone at Yucca Mountain is bi-modal or multimodel; that is, it is divided into slow flow and fast flow components (DOE 1998). The time required for water to travel from surface to the repository horizon if it percolates only through slow pathways in the intact rock matrix is expected to be hundreds of thousands of years. However, there is evidence from isotopic studies of the pore water in the rocks at Yucca Mountain, that some of the moisture percolates through interconnected networks of fractures or other channels that allows the moisture to travel to repository depths in thousands of years and some of the moisture appears to move through very fast pathways that allows moisture to percolate from the surface of the mountain to the depth of the repository in less than 100 years.

Although a great deal of discussion surrounds the estimates of the moisture travel time through Yucca Mountain from surface to the depth of the repository horizon, the time required for this flow is largely irrelevant for predictions of drift seepage. Moisture flux at the repository horizon, and not velocity, is one of the primary factors that affects estimates of the locations and rates that moisture will enter into the repository drifts. However, the distribution of slow, fast, and very fast percolation pathways has significant implications with respect to estimating the spatial and temporal distribution of moisture flux at the repository horizon and thus on drift seepage predictions.

The YMP has not yet developed good estimates of the fast and very fast flow path fluxes under the current infiltration/percolation conditions that exist at Yucca Mountain. We strongly urge the YMP to try to quantify the spatial distribution and rate of moisture percolation flux moving through the fast pathways at the repository horizon in Yucca Mountain under current climate conditions. We see this as key to developing credible predictions of the rates and locations of moisture seepage that will enter the repository drifts in the future under dry climate conditions similar to those of today, as well under possible wetter climates or in response to episodic periods of greater infiltration.

Since the matrix permeability of TCw (Tiva Canyon welded) and TSw (Topopah Spring welded) rock samples is known from laboratory measurements to be lower by several orders of magnitude than the permeability of fractures and faults, and there is a pervasive hierarchical network of fracture through the TCw and TSw, it is safe to conclude that moisture percolation through these units is dominated by fractures. Field observations of outcrops of the TCw reveal many fractures that are filled with secondary minerals, however these minerals do not seem to impede in any major way the ability of the fractures and faults to conduct moisture across the TCw. The TCw appears to be so permeable that once infiltrating water migrates below the root zone, it moves with relative ease downward through the fractures and faults in the TCw. Because the matrix of the TCw is at relatively high ambient water saturation at depth, there is little opportunity for water to move into it; thus most of the percolating water moves exclusively through fractures and faults in the TCw. The same is expected to happen within the TSw.

Unfortunately, there is very little information available from Yucca Mountain to evaluate directly the modes, rates and directions of moisture percolation through the complete hierarchy of fractures and faults or other pathways of elevated hydraulic conductivity through the mountain. Furthermore we believe it will never be possible to collect sufficient information about these pathways to precisely predict the number, location, and hydraulic properties of these flow paths within the TCw and TSw units with the resolution required for deterministic drift seepage predictions. Because of this difficulty, one recommendation of the UZ Expert Elicitation Project was to focus more work on obtaining the data needed to understand and quantify the vertical, matrix-dominated flow through the relatively unfractured Paintbrush nonwelded unit (PTn) that lies between the fractured TCw and TSw units (CRWMS M&O 1997). This proposal appears to have been ignored so far by the YMP and we believe it should be pursued.

That much of the moisture percolation through the PTn occurs through the intact (unfractured) rock matrix derives from the following facts: the matrix has comparatively high porosity and permeability; saturation within the PTn matrix is sufficiently low to cause water from fractures and faults to strongly imbibe into the matrix, thereby tending to attenuate moisture flow within the fractures; the fracture density within the PTn is relatively low; faults within the PTn are relatively narrow and few have been identified; and, the unit has shown a pronounced capability to attenuate the propagation of pneumatic pressure signals across it. Yet the discovery of bomb pulse isotopes (^{3}H and ^{36}Cl) in waters at the base of the PTn and from the ESF tunnel (Fabryka-Martin et al. 1998) implies that at least some of the moisture which percolates through the PTn must do so at relatively high velocities through fast pathways or channels. Since bomb-pulse isotopes have also been found within the moisture in the PTn matrix, this rapid flow may not be confined to only fractures or faults in the PTn but probably also occurs (at least in part) through the intact matrix.

The current estimates of mean moisture flow rates and percolation velocities through the PTn matrix are insufficient to account for these observations of bomb-pulse isotopic signatures in the matrix waters of the PTn. The only way to account for these signatures is to postulate preferential moisture flow through relatively narrow channels associated with locally elevated hydraulic conductivities. Contrary to prevailing belief, these channels need not be confined to only fractures or faults. It is possible (in principle) for preferential moisture flow channels to develop within the PTn matrix due to: (a) focused infiltration which concentrates percolating water along narrow flow paths that enter the PTn; (b) buildup of saturation along these flow paths which may persist due to hysteresis, as shown experimentally in recent work by DiCarlo et al. (1999), so that antecedent paths act as channels of elevated hydraulic conductivity during subsequent infiltration/percolation events; (c) spatial variations in matrix permeability; and (d) instability and fingering due to contrasts in material properties between the PTn and the overlying TCw unit (Chen, Taniguchi, and Neuman 1995).

Such preferential fast flow channels may either persist or adjust themselves dynamically to variably changing conditions of moisture infiltration at the surface. Regardless of whether distinct preferential flow channels develop within fractures, faults or the matrix of the PTn, we expect the rock volume they occupy is so small as to render the probability of adequately observing and characterizing them in the field exceedingly low. Nevertheless the bomb pulse isotope information suggests these fast pathways may allow significant volumes of percolating moisture to penetrate the PTn at high flux rates and they should be accounted for in the overall moisture percolation model for Yucca Mountain.

In addition, it is highly probable that the percolation fluxes could be higher than expected in the areas of the mountain beneath the location where the highest rates of moisture infiltration are expected to occur. Estimates of the percolation rates for these areas of the mountain cannot be made by extrapolating from the sites that have been characterized so far, that unfortunately are not located in zones of estimated highest percolation. Ponded infiltration studies in the ESF or E-W Cross Drift should be performed to obtain some of the needed information on the moisture percolation through the PTn to the underlying welded tuff units.

It is important to recognize that the existence of fast flow paths for moisture percolation does not imply that the openings along these paths (whether in fractures, faults, or the matrix) must be saturated with water, only that the corresponding moisture saturation within them is large compared to the bulk of the associated fractures, faults or matrix. The existence of such fast flow paths in the rocks at the depth of the repository therefore does not imply that there should necessarily be visible moisture seeps where they are exposed in the ESF tunnels or the drifts, though the formation of such visible seeps is possible. As described in the infiltration model (USGS 1996), the fast flow paths for moisture percolation are more likely to exist where there is both shallow soil cover and fractures or faults that interconnect through the PTn, although as we pointed out previously, some fast flow paths may exist where no fractures are present and horsetail fracture patterns may funnel the infiltration through the fracture networks.

Moisture percolation through the proposed repository unit, the TSw, will be largely through the pervasive hierarchy of fracture and fault networks in the TSw and therefore is expected to be relatively un-slowed. As we mentioned earlier, the areal extent and spatial distribution of these pathways and the volume of moisture moving through them has received only educated estimates by the YMP so far in the material we reviewed. Some estimates suggest that the areal extent of these fast percolation pathways should be of the order of 5% of the total area of the repository horizon, but the moisture flux through some of them could be high (one expert estimate is as high as 200 mm/yr) if lateral flow occurs at the top of the PTn and the percolation is subsequently funneled through the PTn within the channel pathways required for the fast flow. Other estimates suggest the flux rate through the fast paths could also be low, with one modeling effort suggesting that the flux in these fast flow paths is only of the order of 5 mm/yr. During the 1999 January presentations to the DSPR Panel, a verbal estimate of the fast flow component of the percolation flux at Yucca Mountain was 1% (A. Flint). Thus, in our view, there is currently considerable uncertainty in the estimates of the amount of moisture and the rate of percolation flux that is transmitted through the fast paths in the unsaturated zone at Yucca Mountain to the depth of the proposed repository. We would also expect that some portion of the fast pathway percolation flux through the mountain should reflect the episodic nature of rainfall, snowmelt and infiltration at Yucca Mountain. We recommend the YMP should attempt to reduce this uncertainty by developing a better understanding of the geologic and hydrologic characteristics of these fast pathways, particularly in the rock units being targeted for the potential repository horizon.

The spatial distribution of fast pathways for moisture percolation estimated from ^{36}Cl data taken from samples collected along the main ESF tunnel (Fabryka-Martin et al. 1998) suggests there is some correlation between the fast pathways and the location of major fractures and faults in the rocks of the repository horizon. It must be pointed out that we have only seen the results of the sampling for ^{36}Cl from the ESF which only borders the east side of the proposed repository horizon. Sampling has been performed in the E-W Cross Drift but the results were not available to us.

However the relationship of the pattern of ^{36}Cl to geologic conditions in Yucca Mountain is still not well understood, largely because little attention appears to have been paid so far by the YMP to characterizing the complete hierarchy of fractures and faults that cut through the rock units of the repository horizon. While some very large fault zones have been identified at Yucca Mountain and incorporated into the moisture percolation models (i.e., those generally having trace lengths exceeding several kilometers, such as the Solitario Canyon Fault, Drill Hole Wash Fault, Ghost Dance Fault, Paganay Wash Fault, Sundance Fault, Dune Wash Fault) the ^{36}Cl evidence for fast flow paths at the depth of the ESF seems to relate to smaller faults and fracture zones that are not represented in the site scale moisture percolation model. Until more is learned about the spatial distribution of the fast pathways that have given rise to the apparent deep and rapid penetration of percolation waters found in the ^{36}Cl samples taken from the ESF tunnels we believe there will remain unanswered questions regarding the impacts of climatic change and the spatial variability of net infiltration rates on the eventual seepage of moisture into the drifts of a repository at Yucca Mountain.

It is important to note that even though many of the bomb-pulse ^{36}Cl signatures in the ESF appear to be spatially associated with fracture zones and faults, this is not true about all of them. Moreover, according to a recent peer review of ^{36}Cl studies at Yucca Mountain (CRMWS M&O 1998), the absence of clearly recognizable bomb-pulse signatures at some sampling stations in the ESF does not necessarily imply the absence of rapid flow paths, but could be due to mixing and dilution with waters containing lower concentrations of ^{36}Cl. We agree with these reviewers that it is highly probable there are many more rapid flow paths through the rocks at the repository horizon in Yucca Mountain than have been surmised on the basis of bomb-pulse ^{36}Cl samples to date, and these may exist virtually anywhere, not necessarily just in association with the major fractures or fault zones. Although there has been a significant site characterization program at Yucca Mountain, the available site characterization information is insufficient to identify or predict the number, location and nature of these rapid flow paths through the rock units at Yucca Mountain. We are aware that the YMP has apparently undertaken full periphery geologic mapping of the tunnel walls of the ESF and identified fracture zones and intensely fractured regions on the geologic maps. We have seen a few figures of the ESF showing some such features but we were unable to obtain maps from the YMP showing all the fractures, fracture zones, intensely fractured zones and faults that have been mapped in the

ESF[1]. We expect these maps indicate numerous fracture zones exist in the rock exposed by the ESF tunnel. However, there is a particular lack of site characterization information for the rock units that are currently proposed for the repository. We strongly recommend the YMP develop a better understanding of the geologic and hydrologic conditions of the region of rock that has been targeted for the repository. Some of this understanding may be derived from a careful examination of conditions in the recently constructed E-W Cross Drift of the ESF. However we expect other geotechnical surveys, excavation, and exploratory boreholes (horizontal) may be needed from the ESF to obtain this information.

In using the bomb pulse ^{36}Cl data to improve the site scale moisture percolation model for drift seepage estimates we also believe two other points should be considered:

1. The presence of bomb-pulse ^{36}Cl does not provide quantitative information about moisture percolation flux rates or distributions. Qualitatively it indicates the flux must have been above the minimum value needed to sustain a component of continuous channelized moisture flow through the PTn, and is evidence for the presence of fast paths that allow very short travel times for some unknown proportion of the percolating water.
2. The locations at which bomb-pulse ^{36}Cl have been observed in the main ESF tunnel and E-W Cross Drift are also probably locations which would respond quickly to increases in moisture percolation flux due to short or long-term climatic changes, with little damping of the excursions or upward shifts by the overlying PTn (i.e., these would be the likely locations for any seeps to form). We recommend long term studies should be established at some of these locations to monitor the moisture saturation effects of such climate episodes.

If fast flow pathways through the mountain equals high local moisture flux, the implication in the current drift seepage analysis is that the locations of the repository drifts that are intercepted by any of these fast flow paths will probably experience seeps, whereas the remainder of the repository may or may not, depending on the overall average percolation flux. For instance under the percolation models representing the present dry climate conditions (10 mm/yr average percolation flux for the repository footprint) seeps would only be expected where the percolation flux is channeled through higher flux pathways, because several documents claim that percolation rates must exceed a threshold of around 25 mm/yr for seeps to occur. We have some reservations about the estimates of this threshold flux which we discuss later (Section 3.4.1 and 3.6). The current drift seepage modeling suggests that, considering the spatial variability of the percolation flux and the material properties over the area of the proposed repository, seeps would only develop in a small percentage of the drifts under the current moisture infiltration/percolation conditions (Tsang et al. 1998). Ideally, as we mentioned previously, multiscale site characterization work should be conducted in the repository horizon

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[1] We also requested geologic maps of the drift seepage alcoves and niches in the ESF showing the distribution and nature of the lithology and fractures mapped on the walls of the excavation. Although we expect such maps should exist no such information was provided to us. In particular we believe this fracture mapping information is needed to properly plan and understand the drift seepage tests and experiments in the alcoves and niches. Although the drift seepage tests were all thoroughly documented none of the reports showed any maps of the fractures observed on the drift seepage test excavations. We recommend this type of fracture mapping information should be incorporated into the planning and reporting of any future drift seepage measurements or tests conducted in the ESF.

to define the geostatistical, geologic and hydrologic properties of these rock units represented in the drift seepage models. We recognize this is both time consuming and expensive and may not be possible until the repository drifts are actually constructed in the repository horizon. As an alternative, we suggest the effects of high flux pathways on drift seepage predictions should be examined by bounding calculations that account for their possible spatial distribution and ranges of hydraulic characteristics. There is also a need to ensure that the spatial distribution and geologic/hydrologic properties of such pathways for high moisture flux are consistently represented in both the site scale and drift scale moisture flow models[2]. We suggest a multiscale continuum approach that utilizes hydrologic, geologic and fracture information from a multiplicity of spatial scales could ensure this consistency.

LBNL's site scale moisture percolation model does not account for preferential and episodic moisture infiltration on either space or time scales that are relevant to drift seepage. Thus the hydrologic inputs that the site scale moisture flow model generates for the drift seepage models are smeared in space-time and therefore inadequate for predicting drift seepage. This linkage between the site scale and drift scale moisture flow models is discussed in greater detail later in Section 3.4.1.

It should be noted here that, as with moisture infiltration, there has not been any direct measurement of moisture percolation flux at Yucca Mountain. We consider it very important that some actual moisture flux measurements should be attempted to try to provide confirmation/validation of the percolation flux as derived from the UZ flow model.

We appreciate the difficulties in trying to measure very low moisture fluxes in the unsaturated rocks at Yucca Mountain, however some of us believe fluxes of greater than 4 mm/yr should be measurable in horizontal boreholes[3] at Yucca Mountain. Although any actual measurements of moisture percolation flux will require a sizable quantity of time in planning, implementing and collection, some of us believe actual in-situ moisture flux measurements are needed by the YMP to provide confidence in the percolation boundary conditions being used for the drift seepage predictions. Some of us further believe it will be particularly important to obtain such direct measurements of moisture flux measurements in the repository horizon below the crest of Yucca Mountain where the moisture percolation rates are predicted to be highest.

3.3 MODELING OF PERCOLATION AND FRACTURE-MATRIX INTERACTION

The UZ flow and transport model report states "Because of the [fracture-matrix] interaction, a site scale UZ flow and transport model without using a defensible fracture-matrix interaction

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[2] Although not directly related to the topic of drift seepage, another aspect of the fast pathways topic we believe is worth pursuing to improve YMP's overall radionuclide release and transport models is to determine whether there are also fast paths through the CHn that are analogous to those through the PTn. At the moment such fast flow pathways in the CHn have not been expected, have not been searched for, and thus have not been incorporated into the radionuclide transport models.

[3] These boreholes should be slightly trending upward to facilitate drainage. Considering the cross-sectional area of a sealed borehole interval to be 0.1 m^2, a flux of 4 mm/yr. corresponds to one ml/day. Although this in itself should provide measurable moisture volumes after a few weeks, we expect it would take a long time for the measurement system to equilibrate (months or possibly years). Careful planning (the use of a well-designed or wetted borehole backfill perhaps) may reduce this time period for equilibration. The design of the collection system could be tested in a controlled laboratory environment to ensure that measured flow equals percolation flux.

formulation would not be considered viable" (Bodvarsson and Wu 1998). We agree. We also note that at the present time there is no defensible formulation of the fracture matrix interaction term in the current moisture percolation modeling of Yucca Mountain (e.g., Liu et al. 1998).

Throughout all YMP's UZ flow model and drift seepage model documentation it is generally accepted that nearly all the moisture percolating downward through the TSw travels through the fracture network (95%) and the flow through the matrix contributes very little. For modeling steady moisture percolation through the TSw this seems reasonable. As such, modeling the percolation using a dual permeability model with a low fracture-matrix area reduction factor appears to be an adequate approach. In Table 9.4-1 of the UZ flow and transport model report (Bodvarsson and Wu, 1998), the reduction factor is calculated, using inverse modeling of matrix saturation, to be relatively constant throughout the TSw at about 0.005. The reduction factor is low despite the steadily increasing degree of matrix saturation between the elevation of the PTn and the proposed elevation for the repository horizon. There is documented concern, however, expressed by the TSPA Peer Review Panel (Page 15, TSPA Peer Review Panel, 1998) in using such a low reduction factor in this inverse modeling. Adjusting the reduction factor in the calibration process to match infiltration estimates and matrix saturation does not give any consideration to the physical process involved. The TSPA peer review panel concluded that "the dependence of the reduction factor on the system parameters needs to be conclusively and unambiguously determined" (TSPA Peer Review Panel, 1998). We echo this concern and thus we are concerned with the inverse modeling approach that was used to derive this reduction factor.

3.4 DRIFT SEEPAGE

It is our view that the current and future needs of repository Performance Assessment (PA) should provide a measuring stick for assessing the usefulness and level of uncertainty that can be tolerated in the understanding of seepage mechanisms, modeling predictions and future work in the area of estimating drift seepage. Currently, the YMP PA calculations for a repository at Yucca Mountain (DOE 1998) require estimates of two moisture seepage quantities:

- The seepage fraction, or fraction of waste packages contacted by seeps.
- The seep flow rate, or flow rate of water onto those packages that are contacted by seeps.

Current PA strategy divides the proposed plan area of the repository at Yucca Mountain into various subregions to simplify waste package and source term calculations. This means that the seepage fraction and seep flow rate needs to be estimated for each of these various subregions separately.

Preliminary scoping calculations performed by Sandia (Wilson 1999) showed that the fraction of waste packages contacted by moisture seeps has a significant impact on quantitative estimates of repository performance, much more so than the seep flow rate. Thus, while being able to correctly estimate seep flow rates is important for PA, determining how spatially extensive the seeps will be in the future repository drifts appears to be of greater importance to PA. This implies that the models used for predicting seeps should produce credible estimates of both the seep rate and the spatial distribution of the seeps into the repository drifts at Yucca Mountain. Rate alone is not sufficient for estimating the fraction of waste packages that will be contacted by seeps.

Being able to estimate seepage rates and their spatial distribution requires an understanding and incorporation of at least the first-order controls on seepage at Yucca Mountain, and an understanding of how these controls vary spatial throughout the repository block subregions. The controls are the physical processes that affect the movement and seepage of moisture into the repository drifts, while their variability relates to the variability in the underlying geology and the hydrologic boundary conditions.

3.4.1 Linkage Between Moisture Percolation Model and Drift Seepage Models

The moisture percolation flux at the repository horizon is derived from LBNL's site scale UZ flow and transport model (Bodvarsson and Wu, 1998) and is used as the moisture input to LBNL's drift scale seepage models (Tsang et al. 1998). The drift seepage models allow a higher resolution of the spatial heterogeneity of hydrologic conditions in the vicinity of the repository drifts and use a porous continuum approach to represent the heterogeneous fractured rock in the close vicinity of the repository drifts. Whereas the grid size for describing spatial heterogeneity is 100 - 200 m for the site scale model, the drift scale model has a grid size of 0.5 m and smaller grids have been investigated. The drift seepage models are used to define the percentage of the moisture flux moving downward through the unsaturated, fractured rocks at the repository horizon that will seep into the repository drifts.

LBNL's UZ site scale flow model generates hydrologic inputs for the drift-scale model that are smeared in space-time and we believe the spatial and temporal resolution of the hydrologic inputs at the interface with the drift scale model are inadequate for the prediction of drift seepage. This inadequacy overshadows the ability of LBNL's drift-scale model to represent the geostatistics of rock heterogeneity locally with a relatively high degree of resolution. In our view, the space-time resolution of the site-scale UZ model at the repository horizon is much lower than is required to adequately represent the range of spatio-temporal frequencies, and amplitudes, of hydrologic pulses that may be potentially responsible for drift seepage. Drift seepage is a local phenomenon that occurs in part on the spatial scale of individual droplets of water. As such it cannot be fully understood or described by means of concepts or models that lack a corresponding scale of resolution. So far LBNL's drift seepage models have not tried to describe the moisture movement into repository drifts at this small scale of resolution. Thus we believe the interface between the site-scale moisture percolation model and the drift scale model has inadequate resolution. We also believe the boundary condition at the drift wall has insufficient resolution.

Instead of using the low-resolution (coarse grid) site-scale UZ flow model to compute moisture fluxes at the top boundary of the high-resolution (fine grid), drift-scale model, we recommend the YMP should consider one or both of the following options: (a) extend the high-resolution, drift scale model to the surface of Yucca Mountain and generate net infiltration at the surface stochastically so as to include pulses that exhibit multiscale random fluctuations in space-time; or, (b) generate multiscale percolation rates at the top boundary of the drift-scale model stochastically in a similar manner. We also urge the YMP to include in the moisture flow modeling of Yucca Mountain the possibility of transient pulses of moisture percolating rapidly and deeply through moderately large fracture networks and assess the effects of these transient pulses on drift seepage estimates.

3.4.2 Threshold Flux

The LBNL drift seepage modeling team has developed, on the basis of available drift seepage experiments, an empirical relationship between percolation rate above a drift and seepage into the drift. This relationship, obtained by linear regression of scattered experimental data, has been used by the team to show that no drift seepage will occur when the moisture percolation rate is below a certain threshold. Though we agree, based on our understanding of capillary theory, that such a threshold could exist, we are not convinced that the available experimental data are yet sufficient to quantify this threshold in a way that would apply to untested portions of the rock within the proposed repository horizon, or even to tested portions of the rock under conditions other than those created during LBNL's drift seepage experiments. We acknowledge that the seepage experiments conducted in the ESF by LBNL and the USGS have provided useful insight into the mechanics of drift seepage under induced flow conditions; however, these conditions are not the same as those expected to develop when the repository becomes operational. Furthermore, the deduced threshold seems close to the noise level of the data, especially since the experiments have been affected by strong advective drying due to ventilation of the ESF (we discuss this later in Section 3.6.1).

LBNL's current drift seepage models assume that moisture flux must exceed a threshold flux rate (25 mm/yr) before seepage will develop. Furthermore, the drift seepage models show that a significant proportion of the moisture percolating through the mountain could be diverted around the repository drifts due the effects of a capillary barrier formed at the drift surfaces. It is our view that the confirmation of drift seepage models should not only focus on correctly predicting the quantity of water seeping into a drift, but should also be shown to correctly model the quantity of moisture expected to be diverted around the drifts.

3.4.3 Conceptual Model of Drift Seepage

A good description of LBNL's conceptual model for seepage into drifts was provided by Birkholzer, Li, Tsang and Tsang (1998). However, we are of the view that the description of the conceptual model is incomplete. The fracture-matrix interaction process leading to the diversion of water around the drifts (the capillary barrier effect) is not well described. We found on closer examination however, that LBNL's models for drift seepage do incorporate many of the physical processes that we believe are relevant to drift seepage. Our comment here is more related to the current state of documentation of how the elements of the conceptual model are addressed within the drift-scale seepage process models. However, our review of all the moisture flow and drift seepage documents provided by the YMP (Appendix 2) suggests to us that there is no collective agreement yet within the YMP on what factors will have most influence on drift seepage into the proposed repository drifts at Yucca Mountain. The YMP should develop a clear, concise description of the drift seepage model to overcome this deficiency.

As we mentioned earlier we believe that drift seepage is a phenomenon that occurs on the spatial scale of an individual droplet of water. It should be enough, in principle, for a narrow rivulet of water within a fracture to intersect the drift in order to allow a droplet to form at the intersection. This narrow rivulet may, but need not, span the width of the fracture. Based on the work of Tokunaga and Wan (1997), one cannot exclude the possibility that a narrow rivulet could form and flow as a film along asperities of only one low-permeability wall of a fracture. The formation and persistence of such rivulets is a dynamic and possibly chaotic process, which depends not only on the internal geometry and mineralogy of fracture asperities, but also on boundary and internal flow conditions which vary with time. The process also depends on multiple scales of heterogeneity from that of a droplet through those of asperities within a fracture, to those of individual fractures, strata-bound fracture networks, and features that transcend individual strata such as large-scale fractures, fracture zones, and faults. Preferential flow channels may form by: a combination of episodic, focused infiltration due to funneling near the soil surface; the presence of preferential flow channels of elevated permeability within the rock; and, flow instability. Various mechanisms for the formation and persistence of preferential moisture flow channels at Yucca Mountain have been recently described by Pruess (1999). DiCarlo et al. (1999) have shown experimentally that once channels of elevated saturation, and hence permeability, form in an otherwise unsaturated porous medium, they may persist for very long time periods due to hysteresis. Future drift seepage modeling should examine these multiple scales of heterogeneity and consider the effects of film flow and droplet formation on the resulting models.

LBNL's drift-scale seepage models consider at most two scales of spatial autocorrelation for log saturated hydraulic conductivity, both considerably larger than the scale of a droplet, and none clearly related to any actual scale of measurement or hydrogeologic feature. These models could be improved materially by basing (conditioning) them on geostatistical analyses of actual data and features (we have not seen any such analyses); by relating the geostatistical and stochastic analyses to the scale of available measurements and/or observations in an unambiguous manner; and by including in the analyses a hierarchy of spatial autocorrelation scales, coupled with a corresponding hierarchy of numerical grid scales, so as to allow the formation and investigation of preferential moisture flow channels on a multiplicity of spatial scales: from that of a droplet; to flow within individual fractures; to flow within the interconnected network of fractures and faults surrounding the repository drifts.

We do not believe LBNL's simplification of the fracture-matrix interaction is adequate in the drift-scale modeling for predicting the location and quantity of drift seepage. Using low or zero values for the interface factor as calibrated from inverse modeling at the mountain-scale does not capture the relevant physical processes that will cause seeps to develop into a drift. We believe an active fracture model (Chapter 8 UZ flow and transport model report, Bodvarsson and Wu, 1998) provides a better physical description for the integration of the fracture and matrix. In the analysis of drift seepage, the matrix must be adequately represented in the model. The active fracture model receives only limited exposure in the inverse modeling of the measured saturation and potential, however, by having a more rigorous approach to fracture-matrix interaction it may be well suited for application to drift seepage.

Our understanding of LBNL's conceptual model to describe the process of the seepage and dripping of moisture into the drifts of a repository at Yucca Mountain is drawn from LBNL's documentation of the drift scale modeling (Tsang et al. 1998). One area where we believe the concepts are less well described is in how water can be translated laterally around the repository drifts.

Water can be diverted around the drift (i.e., the capillary barrier) if there is a potential gradient driving the water laterally. This lateral flux will occur primarily through fractures very near the excavation surface. The observation of enhanced drift seepage from the shot-crete in Alcove 1 in the ESF supports this. It appears that water was held in storage in the porous shot-crete in Alcove 1 and had no network of small, interconnected fractures to aide in lateral flow around the drift. Models for the effectiveness of the capillary barrier in diverting or preventing moisture seepage into the repository drifts should be consistent with all seepage tests and observations in the ESF including the observations of enhanced seepage from the shot-crete in Alcove 1.

The threshold flux is related to the maximum rate of water transfer from the top of the drift to the walls. This should not be expected to be a unique value but will depend upon the characteristics of the fractures, the matrix, and the dimensions of the drifts. It may well also depend upon the duration of higher (episodic?) flux events. That is, under certain conditions seeps may be more likely under conditions of lower sustained fluxes than under a higher but more transient flux. For the matrix to be important in the conceptual model of drift seepage it is not critical that water will be imbibed great distances into the matrix, only that imbibition occurs and this affects the overall matrix potentials. Under steady conditions, matrix potentials should be in equilibrium with fracture potentials and hence they may have an influence on the flux diverted around a drift.

In considering the effects of short-term episodic flux of moisture on drift seepage predictions, the imbibition of water into the matrix could result in storage of water over short term and this moisture could be subsequently released under subsequent conditions of lower average flux. For this discussion, imbibition could include storage in short, dead end fractures and micro-cracks, since in the models it is not always possible to differentiate. Imbibition at the top of the drift could also be coupled with release of water from storage elsewhere. This flux could result in a gradient of potential in the combined fracture-matrix system. It should also be recognized that such episodic fluxes could introduce hysteresis effects in some of the properties that control drift seepage. Some of LBNL's drift seepage modeling suggests these hysteresis effects may be significant and should be accounted for.

Any model used to predict the seepage of moisture into the repository drifts at Yucca Mountain should carefully consider the matrix-fracture interaction. A model which defines the interaction as a function of fracture saturation seems appropriate. If YMP's current drift-scale models are too coarse to examine the conceptual matrix-fracture interaction aspects then more detailed sub-models should be developed to assess whether the drift-scale seepage models appropriately represent the physical matrix-fracture interaction processes that could affect seepage at a scale of one or two fractures.

Another aspect the YMP should consider in the drift seepage modeling being performed by LBNL is the effect of disregarding fractures that have a trace length less than 1 m in the analysis. LBNL's current drift seepage models (Tsang et al. 1998) use fracture frequency data derived from scanline mapping of the crown of the ESF tunnels or scanline mapping of surface exposures (pavements) of the various Yucca Mountain rock units and permeability data from packer tests to calculate values of fracture aperture (b), van Genuchten alpha (α_f) and fracture porosity (ϕ). These values are used in the models to calculate the location and rate of drift seepage. In their analyses LBNL have only used the data representing fractures with tracelengths exceeding 1 m. Closer inspection of the scanline data (Sweetkind and Rautman 1998) reveals that this represents less than 20% of the fractures actually observed in these rock units[4]. In some cases more than 90% of the fractures have tracelengths less than 1 m. In

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[4] On a related topic, but one not of direct relevance to the DSPR review, we found it surprising that two YMP documents (Bodvarsson et al. 1998; Sweetkind and Rautman 1998) quoting the same source of line scan fracture data reported significantly different values for frequency of fractures exceeding 1 m in trace length. This was particularly disturbing since the unit where there was a large difference (0.1 fractures/m

the particular case of the proposed repository unit (TSw 35) only 1% of the observed fractures have trace lengths exceeding 1 m. Although it may be acceptable to ignore the role these smaller fractures may play in describing how moisture will move in the far field, tens of meters away from the drifts, we believe the role of the smaller fractures needs to be accounted for in modeling moisture movement and seepage in the near field of the drift openings (within a few meters). If the smaller fractures are considered in the approach used by Tsang et al. (1998), the values of b, α_f, and ϕ are significantly different than if only the fractures longer than 1 m are considered. In some cases the values calculated for α_f and ϕ differ by several orders of magnitude if the very large number of fractures smaller than 1 m are considered in the analysis.

In addition to including the effects of the smaller fractures in the drift seepage analysis, we also believe it will be useful to obtain fracture and permeability data that represents the different PA modeling regions of the proposed repository. Currently there is virtually no hydrologic data available for the rock units being considered for the repository. The scanline data we have seen for the ESF reveals substantial spatial variability in the intensity and characteristics of the fracturing. This variability is not random, but rather has patterns some of which can be related to lithology and other geologic features, such as large scale fracture zones and faults for instance. We expect there could be some different spatial patterns to the fracturing in the different PA modeling areas of the repository area and incorporating this information would improve drift seepage predictions in these areas.

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versus 1.42 fractures/m) was TSw 35, the unit selected as the main unit for the proposed repository.

3.4.4 Numerical Model Formulation: Stochastic Continuum Versus Discrete Fracture

There have been two numerical simulation approaches adopted by the YMP for modeling various aspects of drift seepage at Yucca Mountain: a stochastic continuum approach using Version 1.11 of LBNL's ITOUGH2 code (Finsterle 1997), and a discrete fracture approach utilizing the WEEPS model (Gauthier 1994).

A continuum model represents the moisture flow properties of the site by means of bulk parameters rather than by parameters associated with individual rock components such as matrix blocks and fractures. A stochastic continuum (SC) model considers these bulk properties to vary randomly in space. Major features such as layers, faults and prominent fracture zones are typically embedded in these SC models as discrete features with their own spatially varying bulk properties. An important advantage offered by continuum models is that flow need not be restricted to fracture planes but may occur along channels or rivulets developed within the fractures, within the matrix, or some combination of the two. These channels and rivulets are dynamic in that they vary with the flow regime and their geometry is much more complex than can be represented by current discrete fracture models. Because it is usually much easier to measure bulk hydraulic properties of the rock than the hydraulic properties of individual matrix blocks, fractures or channels, there is motivation for using continuum models that rely on measurements of the bulk hydraulic properties of the rock. As shown by Neuman (1987) and Neuman and Di Federico (1998), SC models are capable of accommodating bulk medium properties that are measured on any feasible and consistent support (measurement) scale. This support scale need not (and generally does not) constitute a Representative Elementary Volume (REV) of the rock in the traditional sense.

One disadvantage of SC models is that they do not explicitly represent fracture connectivity at scales smaller than the scales of modeling discretization, nor is the effective fracture connectivity between stochastic blocks always explicitly preserved. La Pointe et al. (1996) have illustrated how the computation of bulk effective properties can lead to erroneous estimates using stochastic continuum models. The errors occur through failure of a tensorial formulation of permeability, which underlies single or dual porosity, dual permeability continuum codes, to correctly incorporate fracture network connectivity. Such situations could easily occur in modeling drift seepage at Yucca Mountain. Likewise, the use of permeability values obtained through packer tests to estimate the permeability of larger rock blocks is not always straighforward. For example, Geier et al. (1992) working on data for the Finnsjön site in Sweden showed that the values of hydraulic conductivity calculated from packer tests had little correspondence with block scale hydraulic conductivity values. Another problem in using packer test data in fractured rock to provide input to blocks larger than the packer test scale is that the spatial correlation structure in the packer test results may be quite different from that found at the block scale. This may require a complex analysis beyond a geostatistical regularization that considers changes in the measurement scale. As shown in La Pointe et al. (1995) working in saturated, fractured rocks at Äspö, Sweden, the spatial correlation seen in packer test results may be due to the scale of connectivity being larger than the scale of the packer tests, and not an inherent property of the rock mass flow properties at much larger block scales. Appendix 4 provides further discussion and illustrations of this difficulty for representing the flow characteristics of fracture networks.

Current discrete fracture (DF) models consider flow to take place parallel to fracture surfaces under saturated conditions, either as sheet flow or in channels. As such, they may not be suitable for modeling unsaturated moisture flow in fractured porous rocks such as tuffs where the fractures are only partially occupied by water, especially since the water tends to concentrate along narrow portions of the fracture plane where apertures are smallest and capillary tension is highest. To describe unsaturated flow using DF models, information is needed about the spatial distribution of apertures for a number of fractures for each fracture set, which is both difficult and expensive to obtain in the field. An additional difficulty is that fracture walls in tuffs are generally permeable and the matrix is porous, so under unsaturated conditions, flow may take place across fracture planes with greater ease than along fracture planes. Current DF models, including the WEEPS model used by the YMP, do not include many of these effects. Until discrete fracture models are developed that can properly represent unsaturated moisture flow and the requisite detailed field data are collected, we do not recommend the YMP utilizes DF models for estimating drift seepage into the proposed repository at Yucca Mountain.

Our recommendation to rely on SC rather than DF models is reinforced by the fact that air permeability tests conducted at Yucca Mountain by the YMP, and at the Apache Leap Research Site in Arizona by Guzman et al. (1996) and Illman et al. (1998), show pneumatic behavior of unsaturated fractured tuffs at these sites to be well characterized by means of bulk properties on a variety of support scales ranging from 0.5 m to many tens of meters. Whether or not the same is true for the unsaturated hydraulic behavior of the fractured rocks surrounding the ESF and the proposed repository at Yucca Mountain, on scales that are relevant to the assessment of drift seepage, has not yet been addressed by the YMP.

YMP's Stochastic Modeling of Drift Seepage Using ITOUGH2

For purposes of drift seepage modeling, LBNL has represented bulk fracture permeability in ITOUGH2 as a statistically homogeneous, random field with one or, at most, two distinct scales of spatial autocorrelation. The parameters of this random field were assumed rather than inferred from field data. The DSPR panel is of the opinion that two scales of spatial correlation are insufficient to describe the multiple scales of heterogeneity that control drift seepage at Yucca Mountain. We believe that a multiscale approach to SC modeling, similar to that described by Neuman and Di Federico (1998), would be better suited for the purpose. We are however not unanimously optimistic that this or any other SC approach would be sufficient for the reliable prediction of drift seepage at Yucca Mountain. As we have illustrated in Appendix 4, there can be problems in relating the spatial correlation of permeabilities derived from packer tests to that of the underlying fracture pattern. There may also be problems in relating air permeabilities to hydraulic conductivities and other relevant parameters under unsaturated conditions. Alternative approaches may need to be examined and/or developed.

In particular, fractures and flow channels on scales of millimeters to centimeters may play an important role in the generation of droplets on the walls of a drift when seepage is taking place. For example, it was noted by Trautz and Cook (1999) that the "Wetting front moves up small fractures after first appearing at niche ceiling." Clearly, fractures very much smaller than the major fault zones probably play a very important role in determining the rate, volume and location of moisture seepage into the repository drifts. Since these smaller fractures cannot be ignored, their effect must be incorporated into the numerical model through the incorporation of measurable parameters defined on comparable scales. Currently LBNL's SC drift scale modeling does not incorporate the effects of these smaller fractures, although some very detailed modeling was performed for the Alcove 4 drift seepage tests which showed that extremely fine meshes were needed to represent the two inclined fractures discretely (Oldenberg et al. 1999).

It was found that the results of Test 2 in niche 3650 could be matched "quite well" if it was assumed that "an anisotropic permeability structure with a two-orders-of magnitude smaller permeability in one horizontal direction" exists (Tsang et al. 1998, page 10). The assignment of this strong anisotropy was an attempt to account for the effect of a distinct vertical fracture set on moisture movement in the rock. While it may be possible to represent the discrete nature of moisture flow through such fractures in this fashion, it may be difficult to predict the appropriate vertical-to-horizontal anisotropy ratio without appropriate permeability tests at scales of relevance. There has been no attempt to determine the directions and magnitudes of principal permeabilities around drifts at Yucca Mountain by direct in situ testing.

The current YMP strategy for assigning bulk medium properties to the ITOUGH2 model relies on measured air permeabilities, inverse modeling, and a considerable number of unverified assumptions. It is not clear to us that the resultant parameter values, and their adopted ranges of variability represent actual rock properties at the Yucca Mountain site and reflect their corresponding uncertainties. We recommend that this question be addressed by the YMP.

Wherever possible, the SC parameters and their statistical properties should be based on actual field data, rather than on assumed values. The field data should be collected over as many different scales as is feasible. For example, future pneumatic testing in boreholes should not be confined to a single interval size between packers but carried out over a range of such interval sizes, to assess the effect of nominal support scale on the values and statistics of air permeabilities. The locations of the pneumatic tests should be chosen to allow an assessment of the correlation structure of air permeabilities over multiple distance scales of relevance to the drift seepage model. The possibility that this correlation structure represents multiple scales of spatial heterogeneity should be examined carefully. We believe that it should be easy to embed in ITOUGH2 multiscale geostatistical descriptions of bulk fracture permeability (Neuman 1987), based on the notions of self-affinity and random fractal fields, similar to those proposed by Neuman and Di Federico (1998).

ITOUGH2 allows differentiating between the roles of matrix blocks and fractures in the flow process by treating the rock as a dual continuum. Under this option, the transfer of water between overlapping matrix and fracture continua is linearly proportional to the bulk pressure differential between the two continua, with a coefficient of proportionality (interface factor) that is determined through inverse modeling. The interface factor in the ITOUGH2 code is calculated from the interface area between fractures and matrix, and the size and shape of the matrix blocks (Tsang et al. 1997). Reports submitted by the YMP to the DSPR Panel do not indicate how these parameter values will be calculated for the different rock units at the location of the proposed repository, let alone for the different subregions of the repository that are represented in the PA models.

Inverse Modeling

Another way to estimate the hydraulic parameters of a continuum model, implemented by LBNL in their ITOUGH2 code (Finsterle 1997), is to use inverse modeling. Such modeling yields an estimate of model parameters and may also provide statistical measures of estimation uncertainty. A comparative study of leading statistical inverse procedures, applied to modeling groundwater flow through the fractured Culebra dolomite at the Waste Isolation Pilot Plant near Carlsbad, New Mexico, has recently been published by Zimmerman et al. (1998). This study clearly indicates that inverse procedures are replete with pitfalls and do not yield reliable results unless they are based on numerous field observations of hydraulic pressure, as well as on direct measurements of the hydraulic parameters to be estimated. A discussion of difficulties associated with inverse modeling at Yucca Mountain, by means of the ITOUGH2 code, is included in the report of Liu et al. (1998). It is not clear to us that sufficient data exist to allow reliable estimation of all parameters required for the prediction of drift seepage at Yucca Mountain.

The difficulty is compounded by the intensive computational effort that is required for a fully three-dimensional application of ITOUGH2. For this reason, only five one-dimensional vertical submodels were used for inversion in the work reported by Liu et al. (1998) when applying the code to unsaturated moisture flow at Yucca Mountain. We are not convinced that this is adequate for three-dimensional modeling. We recommend that if inverse modeling is to be used for YMP drift seepage analyses, its adequacy to the task must be clearly demonstrated, and associated parameter as well as predictive uncertainties need to be reliably assessed.

3.4.5 Model Verification

Model verification consists of detailed testing and benchmarking of the software against results obtained by other means (analytical, numerical using other software, experimental). A verification document typically describes the functionality of the code, criteria against which this functionality is to be tested, and a series of corresponding test cases. The goal of code verification is not to demonstrate suitability for any particular modeling application, but to establish that the mathematical model has been properly formulated and implemented in software. Any codes used by the YMP for drift seepage calculations for PA purposes should have undergone rigorous verification. We note that ITOUGH2 has been qualified under an approved YPM Quality Assurance Program (Finsterle et al. 1996) and as such is "verified".

3.4.6 Model Validation/Confirmation

The Panel does not believe that long-term predictions of drift seepage under existing or expected future site conditions at Yucca Mountain can be meaningfully validated. At best, it should be possible to confirm some of the key assumptions that enter into the drift seepage model and to compare model predictions against some controlled experimental results. The larger the spatial volume and set of conditions covered by such experiments, and the longer their time duration, the closer can the drift seepage model approach validation. However, no amount of experimentation will render the model "validated" in a way that would fully satisfy all potential critics. We believe the YMP should focus on confirming experimentally as many assumptions built into the drift seepage models, as much of their predicted output, as is technically and programmatically feasible. Only by conducting meaningful experiments geared toward model confirmation, on a suitable range of space-time scales, is there any hope to build technical support for and confidence in the YMP drift seepage models.

The experimental work carried out thus far in the niche seepage studies within the ESF does not constitute confirmation of the drift seepage models developed by LBNL to date. At best, the experiments have provided some insight into drift seepage phenomena and allowed some limited calibration of the model to site data. Much of the modeling done so far has involved sensitivity studies or been used for experimental design. For example, Tsang (1997, 1999) describe modeling results concerning drift seepage in two and three dimensions under a variety of assumptions about driving forces (percolation rates at the top boundary) and rock properties (homogeneity versus heterogeneity, fracture spacing and other geometric properties, bulk fracture permeability, corresponding geostatistical parameters, and interface factor). Their analysis illustrates how model outputs (drift seepage rates and flow patterns) are affected by variations in model inputs and parameters. It constitutes a sensitivity analysis but not model confirmation.

Tsang et al. (1998) summarize five seepage tests performed in niche 3650. Table 23 of their report lists measured data, and Table 24 lists some model outputs. The authors comment that "Overall, the agreement with test results is very good..." (Tsang et al. 1998, page 10). However, no criteria are specified as to what an acceptable agreement would be, and how these criteria would relate to the needs of PA.

LBNL's modeling of the migration of construction water in the CWAT holes provided another opportunity to test the drift seepage modeling capability (Finsterle et al. 1999). The test was designed to predict Br/Cl ratios, which show evidence that construction water had penetrated into the rock. The middle nonlithophysal rock unit was modeled for CWAT #1 and #2, while the upper lithophysal unit (TSw 35) was simulated in CWAT #3. The conclusion from this exercise was that the models "Qualitatively reproduced [the] observed construction water signal". However, the models and the measured Br/Cl ratios did not agree well in CWAT #3 where the models predicted much deeper penetration. This difference was explained by suggesting that the Br/Cl ratio reflects matrix values rather than fracture values. If so, the measured Br/Cl values cannot be used to test how well the code predicts seepage through the fracture system used for predicting seepage into repository drifts at Yucca Mountain.

A final issue regarding validation is that no drift seepage experiments or tests have yet been carried out at Yucca Mountain in rocks at the site of the proposed repository. As we stated previously, there is evidence that patterns of fracturing differ between the various rock units at Yucca Mountain as do their texture and mechanical as well as hydraulic properties. For example, fracturing in the lithophysal units appears to be very different than that in the non-lithophysal units, and we would expect these differences to influence seepage mechanisms, rates and pathways. Even if the numerical models were able to predict correctly the outcome of seepage experiments that have been performed in the niches of the ESF, this would not necessarily mean that they can predict seepage in areas of the mountain where fracture development and hydraulic properties are different. Model sensitivity studies that have been carried out by LBNL in conjunction with the alcove and niche seepage experiments clearly demonstrate that variations in fracture and matrix properties can significantly alter drift seepage. It follows that regardless of how well the models may appear to perform when compared against experiments in the ESF, their ability to perform equally well when applied to the proposed repository remains in question.

The drift seepage modeling done so far by LBNL for the YMP has been extremely useful, especially for experimental design, interpretation, and sensitivity studies. However we believe that more experimental and modeling work needs to be done to help test and confirm as many aspects of the drift seepage models as may be feasible. Modeling should include the prediction of rates and space-time distribution of drift seepage prior to performing corresponding experiments. It is not sufficient to back-calibrate parameters so as to fit the model to experimental data. Ideally, the YMP should strive to confirm the ability of the model to predict the rates and spatial occurrences of seepage at scales considered relevant to PA. Consideration should therefore be given to conducting seepage experiments on space-time scales that are much larger than those of experiments conducted by the YMP thus far. Several such experiments should be contemplated at various locations in the ESF and in various lithologic units that represent more closely the repository horizon.

3.5 LITHOPHYSAL CAVITY FILLINGS

The information that is being obtained by the YMP from examining the lithophysal cavity fillings exposed in the ESF is extremely interesting to the topic of drift seepage. Attempts to bound the percolation flux and seepage into these cavities has resulted in lower estimates of moisture percolation than predicted by LBNL's UZ flow model. What is interesting about these calculations is that they represent moisture percolation seepage that has occurred over very long time frames, whereas most other estimates of moisture percolation flux and drift seepage at Yucca Mountain have not yet been confirmed by actual measurements of moisture flux. The number of assumptions required to perform the calculation of moisture flux using the lithophysal cavity fillings data renders these percolation values highly indefensible; however, we believe there should be a reconciliation between LBNL's site-scale and drift-scale moisture percolation models and the observations of the apparent rate of lithophysal cavity filling. If the site- and drift-scale models can be shown to agree with these observations then we believe there is added strength behind the LBNL's drift seepage predictions.

3.6 DRIFT SEEPAGE TESTS AND OBSERVATIONS IN THE ESF

As we mentioned previously, we are of the opinion that it is of the utmost importance that the YMP obtain an understanding of the current rates and spatial distribution of moisture flux through the fractured rock at the repository horizon in Yucca Mountain. We also believe it is crucial that the YMP continues to use the access provided by the ESF to gain insight into the processes and mechanisms that will govern the location and rate of moisture seepage into the proposed repository drifts. We note that LBNL and USGS researchers have already performed some very useful and interesting drift seepage experiments in special test areas (six alcoves and three niches) constructed off of the ESF tunnel (Wang et al. 1998). We commend the LBNL and USGS scientific staff on their ingenuity and innovations in implementing these experiments. We found the work done for the liquid release tests in niches 3650 and 3566 to be particularly thorough, especially the permeability measurements which reveal the spatial distribution of fracture-controlled permeability in the roof of the drift and show the changes caused by the excavation of the drift (Wang et al. 1998 and Wang and Elsworth, 1999). We are also impressed with the numerical modeling that has been performed by LBNL using the drift seepage models to represent the results of the liquid release tests in niche 3650 (Tsang et al. 1998). We must point out however, that drift seepage experiments and observations have only just begun in the ESF and we believe that there has been insufficient experimental work so far completed on the topic of drift seepage at Yucca Mountain to use the results to confirm the suitability of the models that are being developed to predict the location and rate of drift seepage into the eventual repository drifts at Yucca Mountain. This understanding needs to be developed for the rocks of the proposed repository horizon and we expect many years of continuous experimental work on drift seepage mechanisms are required in Yucca Mountain to obtain the necessary measurements and understanding.

3.6.1 Advective Drying

One issue of concern regarding the drift seepage observations and tests performed in the ESF so far is that the high rate of advective removal of moisture from the walls of the excavations by evaporation into the ventilation air flow has been (and remains) a major problem in any attempts to observe ambient moisture seepage into the ESF or to quantify the moisture seepage fluxes induced into the drift seepage test areas.

Evaporation occurs throughout the ESF. Measurements show that the effect of evaporation has lead to a region of dry-out around the ESF that already extends to at least three meters (and perhaps more) into the rock. Similar dry-out is occurring in the experimental niches and drift seepage test areas as a consequence of ventilation. This dry-out is inducing a gradient potential towards every excavation, and the evidence of this gradient is reflected in the measurements of liquid potential using psychrometers. The monitoring of matric suctions (potentials) by the USGS and LBNL in boreholes from the experimental drifts at Yucca Mountain has shown convincingly that the near-field measurements are strongly affected by advective drying. Evaporation rates as high as 2 mm/day have been documented in the drift seepage alcoves and we would expect greater evaporation rates in the drifts and along the surface of the main ESF tunnel. We believe that under these conditions any attempts to measure the water contents, water suctions (potentials), and seepage fluxes in areas where evaporation dominates the flow process, and then extrapolate to repository conditions where there will be no evaporation, could underestimate the repository drift seepage fluxes.

The argument, that because no moisture seeps have been observed in the ESF the ambient moisture flux is very low, needs to take account of the high rates of moisture loss due to evaporation. For instance if any other areas of dampness occurred in the ESF similar to that observed in niche 3566, they would have dried before being observed without the careful excavation and observations conducted in the niche 3566. Therefore it is not possible to assess the relative dampness on the walls of the tunnels of the ESF as an indicator of the relative distribution and rates of moisture flux at the repository horizon. The high rate of evaporation also reduces the quantity of moisture dripping from the roof of an experimental niche or alcove as measured in a collection system. In a borehole liquid release test, evaporation can affect the amount of water going into storage in rock which is in the region of dry-out near an excavation surface. Whether or not these effects are of great consequence is perhaps not as important as the fact that the amount of evaporation in the ESF has not been quantified. Thus some of the drift seepage experimental results are questionable. Therefore we highly recommend that humidity in the experimental rooms should be controlled as much as feasible during future seepage test and experiments. Where it is perhaps not feasible, the evaporation should be quantified (perhaps by monitoring near surface humidity gradients to determine evaporation rates and more thorough monitoring of the effect of evaporation on matrix potentials). We believe an assessment of the effects of evaporation on seepage experiment conclusions is essential.

LBNL's current drift-scale moisture seepage models for Yucca Mountain require saturation to occur at the drift boundary before seepage into the repository drifts can occur. The evaporation of moisture at (an behind) the drift walls, coupled with the formation of droplets of condensation on the drift walls (or directly on other surfaces within the waste emplacement rooms, such as directly on the canisters) is currently not considered in the models. We believe the transfer of moisture from the rock into the drifts by evaporation/condensation needs to be accounted for in the YMP's drift seepage models.

3.6.2 Threshold Flux (Capillary Barrier)

The use of some of the liquid release test data to define threshold fluxes as a function of fracture permeability is interesting but not convincing. Although we believe that a threshold moisture flux condition in the rock must be overcome before drift seepage will occur (i.e., the capillary barrier), we are not convinced that there is a uniquely defined rate of moisture flux (say 25 mm/yr as an example) below which moisture seepage will not occur into the drifts of a repository at Yucca Mountain.

The niche tests performed so far in the ESF have not quantified the performance of a capillary barrier around the drifts. The moisture fluxes that have been induced in the liquid release tests are much too high to be relevant to most of the expected rates of moisture flux into the repository at Yucca Mountain. It will be important for the models to show they can model small, steady moisture fluxes into and around the drifts. What is also needed from the experiments is a measure of the amount of moisture diverted laterally around the drifts. It could be argued that the seepage not collected during the experiments so far was held in storage in fractures above the roof of the drift, and possibly later released into the excavation as evaporation. Only when the effects of advective drying by evaporation have been eliminated (or properly accounted for) can meaningful measurements be made of the threshold flux. The tests and the models also both need to clearly show that moisture under steady representative fluxes can be diverted laterally around the drifts as a consequence of capillary forces and the amount of moisture diverted around the drifts needs to be quantified.

3.6.3 Seepage Observations and Test Locations

As we mentioned previously, LBNL's models of moisture percolation through Yucca Mountain suggest that the rates and spatial distribution of the moisture flux at the repository horizon are directly related to position under the surface topography of the mountain. In these models, the areas immediately beneath the crown of the mountain are expected to have higher percolation rates. So far the observations and tests of drift seepage have been performed in the main ESF tunnel outside the proposed location of the repository horizon and where the rates of ambient moisture percolation are expected to be much less that for much of the repository horizon. We urge the YMP to examine options to situate some drift seepage tests in conditions representing both the rock units and moisture percolation flux conditions expected for the repository horizon. Similarly, because some scenarios assume much wetter climates could develop in the future, we recommend the YMP design some drift seepage tests to simulate the higher rates of moisture percolation flux postulated during these wetter climates (i.e., up to 90 mm/yr percolation flux for areas of the repository beneath the crest of Yucca Mountain).

3.6.4 Excavation Effects on Drift Seepage Experiments

We believe the mechanical effect of excavation on drift seepage requires more attention and we elaborate on this further in Section 3.8. LBNL's studies at niche 3650 showed there was a two order of magnitude difference in measured air permeability in the near field region of the roof of the niche before and after excavation. We would expect that stress redistribution caused by excavation should lead to an increase in the permeability in the direction parallel to the excavation. This is not what was observed at niche 3650. As we noted previously, the measured and modeled data from the liquid release test #2 are in better agreement if there was a two order of magnitude smaller permeability in the horizontal direction. However, this pattern of permeability change is not in keeping with expectations from excavation disturbance. Under the stress conditions at the depth of the repository at Yucca Mountain, it is most likely that stress relief displacements will always be inward, opening fractures parallel to the excavation surfaces as well as leading to shear displacements along low dipping fractures in the near field. Shear displacements can result in either decreased or increased fracture apertures depending on the magnitude of displacement. It is also probable that fractures normal to the excavation surfaces will close and become less permeable as a consequence of excavation. Although the permeability of the vertical fractures in the roof may decrease, the increase in permeability of the horizontal fractures can account for the large overall permeability increase as measured in niche 3650 air permeability tests. There was also evidence in the liquid release tests that, in some cases, moisture movement through the rock followed a different path before and after excavation. There is evidence to suggest vertical fractures near the drift closed leading to the development of moisture seepage into the drifts along lower dipping fractures.

Shear displacement may in fact have as great an effect on permeability as extensional opening. In the extreme, the movement of blocks or wedges can result in complicated changes in permeability near the drift opening. We believe there is a need for mechanical modeling to assess the influence of drift excavation on the interconnected fracture pathways near the drifts. This must be done in parallel with an examination of the influence of aperture change on moisture flux. It is important to resolve both the influence of stress change on fracture properties and the influence of fracture aperture on flux, in order to develop a conceptual model for the influence of excavation disturbance on the capillary barrier surrounding the repository drifts. Since excavation damage will affect the rock very close to the excavation, in the region considered to include the capillary barrier, it is likely that excavation disturbance will have a measurable impact on the potential for lateral moisture flow around the repository drifts. We expect these effects will be intensified when the repository introduces high thermal loads to the rock mass surrounding the repository drifts. To date there has been no effort by the YMP at addressing this issue under ambient temperature conditions let alone to consider the effects of the high thermal loads.

3.7 FUTURE DRIFT SEEPAGE EXPERIMENTS AND TESTS

We were not provided any detailed plans for ongoing or possible future drift seepage experiments in the ESF. During our visit to the ESF, the principal investigators responsible for the drift seepage observations and tests offered numerous suggestions for improving or extending the work they had started in the niches and alcoves. In addition the PI's discussed their thoughts for future new experiments, including two possible niche studies in the newly constructed E-W Cross Drift and a possible drift to drift seepage test between the E-W Cross Drift and the main ESF tunnel.

The TSPA-VA report (DOE 1998) recommends several new drift seepage test and experiments in the ESF and we understand some of these are currently underway. However, we have received insufficient information to provide much critical or constructive comment of the ongoing or future drift seepage experiments that the YMP might be planning in the ESF. We find it particularly surprising and disconcerting that despite the recommendations of the TSPA-VA report (DOE 1998) and the emphasis placed on this drift seepage work by the TSPA-VA Peer

Review Team (CRWMS M&O 1999) that there do not appear to be any formal plans for such work.

We strongly urge the YMP to develop formal plans for future drift seepage tests and experiments at Yucca Mountain. We believe such plans, if properly reviewed and coordinated within the YMP (including with the engineered barrier program and repository design), could serve to help focus future drift seepage work on achieving objectives. For instance, during our review of the documentation available to us, we found it difficult and confusing to determine the main objectives and findings of the drift seepage tests that have been performed in the ESF so far, although the presentations given by LBNL's drift seepage modeling and experimental team leaders during our 1999 January meetings were very helpful. We believe the YMP should conduct more (and better integrated) moisture seepage measurements and tests in the ESF and recently constructed E-W Cross Drift. We believe the tests and experiments should be combined and consolidated wherever possible into fewer, larger, and longer term tests or experiments to optimize and maximize the 3-D instrumentation and monitoring available.

We also believe future drift seepage measurements and tests in the ESF should be planned to extend for long time frames because moisture movement and seepage are slow processes under the current rates of moisture percolation through Yucca Mountain and evaporation into the underground openings. Periodically, higher rates of moisture movement may occur through the mountain in response to infrequent episodic climate conditions and long term monitoring of moisture movements may be able to determine if these episodic events alter the spatial distribution and rate of moisture percolation at the repository horizon. We offer the following suggestions regarding such future drift seepage measurements and tests.

We recommend liquid release tests and drift seepage experiments should be resumed in the ESF. To provide better information for the seepage models, future liquid release tests should be designed to measure the percentage of the liquid release collected in the drift as before, but they should also examine where the water not collected in the drift ends up. The water diverted around the drift needs to be collected, perhaps in a relatively short horizontal slot formed by overlapping boreholes. Whether a compartmentalized collection system is used in a slot, or just a global collection of all the water diverted around the drift, will depend upon resources available. Sufficient potential measurements should be included in the test designs to facilitate calculations of the percent of water going into storage and estimate the amount of water lost to evaporation. To prevent water loss due to evaporation, the room humidity should be increased artificially to near 100% for these tests. If this is not entirely feasible, the moisture collection trays in the drift should be effectively sealed to the roof of the drift to prevent evaporative losses. We also feel future drift seepage tests must be done in rock representative of the repository horizon, that is, the lower lithophysal (TSw 35) and/or middle non-lithophysal units (TSw 34).

Although LBNL's drift seepage model shows promise, the fluxes induced by the liquid releases during the fracture/matrix interaction tests in Alcove 6 were too great to facilitate an examination of the fracture-matrix interaction. Most of the water in these liquid release tests traveled though fractures, however, there was a significant response of the matrix potential as measured by the psychrometers. The response of the psychrometers should be examined in the models for fracture-matrix interaction. We believe the facility at Alcove 6 is well designed to measure the fraction of water that seeps vertically as well as the fraction that travels somewhat laterally. However, future moisture seepage tests in Alcove 6 should include more sensors (psychrometers, heat dissipation probes) to assess the gradients in liquid potential within the test site, as well as to assess the amount of the water retained as storage in the rock blocks.

In any future liquid release tests in the ESF niches or tests in Alcove 6, the induced moisture flux must be small enough to make conclusions regarding the breakdown of the capillary barrier under the slow, near-steady rates of ambient moisture flux through Yucca Mountain. The tests completed so far provide a better indication of how well episodic high rate fluxes can be modeled. Using the current equipment it will be difficult to apply water at a low rate for long duration to simulate the lower moisture fluxes; perhaps a system that applies a metered spray in the injection zone rather than ponding of water is a solution.

The long term measurement of drift seepage proposed at Alcove 7 in the ESF is interesting. One difficulty we have with the test objectives as we understand them, is that it is hoped to gain some appreciation of drift seepage as a function of possible small variations in percolation flux. It would be important, therefore, to combine the test with some measure of moisture percolation in the vicinity of Alcove 7 and the alcove should be sealed to reduce evaporation loss.

A drift to drift moisture percolation/seepage study, if conducted from the E-W Cross Drift to a niche in the ESF must be carefully designed. If a moisture flux is applied to the floor of a test alcove in the E-W Cross Drift and no seepage is collected in the test niche off the ESF main tunnel then it will be important to determine where the water went (i.e., around the drift, into storage in fractures, translated laterally at the boundary between the upper-lithophysal and middle-non-lithophysal TSw units).

3.8 ROCK MECHANICS CONSIDERATIONS

Boyle and Rowe (1999) note that the response of the rock at Yucca Mountain to repository excavation and heat from the emplaced wastes may include the development of cracks and fractures in the rock near the drift openings. Potential impacts on repository performance could be caused by changing mechanical loads on the waste packages as rock fragments fall on them and changing the seepage of moisture into the repository drifts by affecting drift shape and altering the hydrologic properties of the near field fractures and rock matrix. So far the rock mechanics work at Yucca Mountain appears to have been almost completely dedicated to determining the size of the largest possible rock block that could fall on the waste package. The result has been to engineer a robust waste container capable of withstanding tremendous impacts. However, any implications of the rock mechanics of Yucca Mountain with respect to how it impacts on predictions of moisture seepage into the repository drifts seem to have been virtually ignored. We believe this is a significant gap in the YMP's current drift seepage program.

3.8.1 Stress Change and Fracture Properties

A recent paper presented at the 37th U.S. Rock Mechanics Symposium (June, 1999) by Wang and Elsworth noted that changes in the normal stress acting on an existing fracture will change the aperture and hence affect the permeability. A calculation was presented by these authors which illustrated that stress change due to excavation can account for the two order of magnitude increase in permeability observed in the rock just above the roof of niche 3650 in the ESF at Yucca Mountain. The fact that stress change results in new fracture properties is an accepted fact and is acknowledged briefly in the TSPA-VA report (DOE 1998). What is interesting is that any similar analysis to that provided by Wang and Elsworth appears to be non-existent in the YMP documentation. There is no evidence that there is a consistent understanding as to whether such an increase in fracture aperture will be a benefit or detriment to the performance of the capillary barrier around a repository drift and hence its effect on drift seepage at Yucca Mountain is unknown. Decreased apertures will be less permeable, yet will be under conditions of higher degree of saturation and thus they may, in fact, become preferential pathways for drift seepage. Also, subhorizontal fractures opening up above the roof of a repository drift may facilitate storage of the water directly above the drift until conditions change and it can later seep into the drift. It is thus conceivable that stress-induced changes to fractures in the roof of a repository drift could result in greater moisture seepage into the drifts than currently expected. We believe further work is needed to determine relationships between aperture change and stress change around repository drifts at Yucca Mountain and to assess the potential impacts of these changes on predicting seepage into the repository drifts.

3.8.2 Stresses Around a Room at Yucca Mountain

There is a surprising dearth of knowledge about rock stresses at the Yucca Mountain repository site. The most apparent reference for information on rock stresses until now is the hydraulic fracturing that was conducted by Stock, Healy Hickmand and Zoback in 1985. In a paper, also presented at the 37th U.S. Rock Mechanics Symposium (June, 1999), Lee and Haimson describe one successful hydraulic fracturing test, and this appears to be the only stress information obtained at Yucca Mountain since construction of the ESF. We are perplexed that at such an important site there are so few measures of rock stress. At Yucca Mountain, it is generally agreed that the weight of the overburden is the vertical stress and that the vertical stress is a principal stress. However, since the repository is in the confines of an uneven surface topography it is unlikely that the vertical stress will be a principal stress throughout, and the stress orientation will vary with location. Small changes in principal stress orientation can have significant affects on the performance of an excavation.

Lee and Haimson (1999) find the horizontal stresses at the repository horizon at Yucca Mountain to be less than 3 MPa anywhere regardless of direction and this is consistent with the average from Stock et al. 1985. Since this stress level is unlikely to lead to large blocks of rock falling from the roofs of the repository drifts at Yucca Mountain then the use of the rock stress information by the YMP seems to have ended here.

The Yucca Mountain Site Description in the TSPA-VA report (DOE 1998) draws upon rock stress information obtained from test in nearby Ranier Mesa and bounds the horizontal to vertical stress ratio to between 0.3 and 1.0. Based on the current knowledge of in-situ stress conditions at the Yucca Mountain site, the stresses in the roofs of the repository drifts can be either tensile or compressive, leading to either opening or closing of vertical fractures around the drift excavations. Notwithstanding the paucity of data, if we assume the most accepted stress condition for Yucca Mountain then we can expect fractures will open up in tension in the roofs of the excavations directly above every waste package in the repository. (Under these stress conditions we would not expect new tensile fractures to be created, only existing fractures to be opened.) The current models for drift seepage at Yucca Mountain tend to suggest there will be increased storage of water in the roofs of the repository drift (due to the capillary barrier), therefore we would expect these opened fractures to impact (reduce) the integrity of the capillary barrier and be likely locations for drips to form. While we don't necessarily believe that these stresses exist throughout, and the stresses will certainly vary spatially, the sparseness of both stress data and geomechnanical analyses does nothing to discredit such conclusions. Conversely, some discussions in the reports on drift seepage modeling have concluded that smaller apertures are preferential pathways for drift seepage, hence stress conditions leading to fracture closure could be a worst case with respect to increasing the rates of moisture seepage into the repository drifts.

We acknowledge that compressive stresses resulting from the temperature increase during the heating phase of the repository will overwhelm any tensile or low compressive stresses caused by excavation. However the TSPA-VA report (DOE 1998) states that "thermal processes would only dominate the distribution and movement of air, water vapor and liquid water for hundreds to thousands of years following repository closure". This implies that following this initial thermal period, gravitational effects will again dominate, as is described in the TSPA-VA report as the "Late Heating Period >2000 yrs." The TSPA-VA report also acknowledges that "Some changes, such as fracture closure that would result from thermal-mechanical effects, may be temporary." It seems prudent, therefore for the YMP to measure and account for the effects of excavation induced fracture opening or closure in the roofs of the repository drifts. It should also be evident that the mechanical effects of the thermal phase of the repository need to be accounted for in such an analysis as well.

3.8.3 Modeling of Roof Integrity

A paper by Chen in the 1999 U.S. Rock Mechanics Symposium (June, 1999), and a paper by Fairhurst in the International Workshop on the Rock Mechanics of Nuclear Waste Repositories (June, 1999) included illustrations of potential rock mass responses around repository excavations at the Yucca Mountain site.

Figure 4.1 (from Fairhurst 1999) illustrates potential slip planes along subvertical fractures after excavation and before thermal heating. Figure 4.2 (from Chen 1999) illustrates a potential configuration of blocks around a drift after a seismic event but before heating. In either illustration it is not difficult to conceive how the capillary barrier to drift seepage surrounding the drift has been permanently affected. Repository heating tends to close fractures and reduce the impact of seismic events. These illustrations are included here to demonstrate that although modeling effort is underway by the YMP to assess roof stability for engineering a repository at Yucca Mountain, it appears none of the modeling has been directed at understanding the implications of geomechanical responses to predicting moisture seepage into the repository drifts.

3.8.4 Elements of Future Rock Mechanics Work

The unsaturated zone of the Yucca Mountain tuff offers the potential to divert a significant portion of the percolating moisture around a repository drift. Under ambient conditions, it appears capillary barriers will form around the repository drifts that will have an important impact on the spatial distribution and rate of drift seepage. However, unless work on the topic of drift seepage is somehow coupled with an understanding of the rock mechanics at Yucca Mountain it will not be hard to conceive mechanisms created by the conditions around the excavations that would result in a breakdown of some or all such capillary barriers.

3.9 THERMAL EFFECTS

Though we were asked to ignore the effects of the thermal conditions that may develop following the emplacement of nuclear waste in the proposed repository, we feel we must address this question briefly in our report. One point to make is that placement of wastes, which generate temperatures close to or above 100° C within the repository, could alter the near field environment in ways which would render the prediction of drift seepage much more difficult than is already the case under natural ambient thermal conditions. We believe it will be a significant challenge for the YMP to predict or bound, in a credible manner, the effects that possible geochemical alterations and geomechanical induced erosion or collapse of the repository drift would have on rock properties and seepage under such anthropogenic conditions.

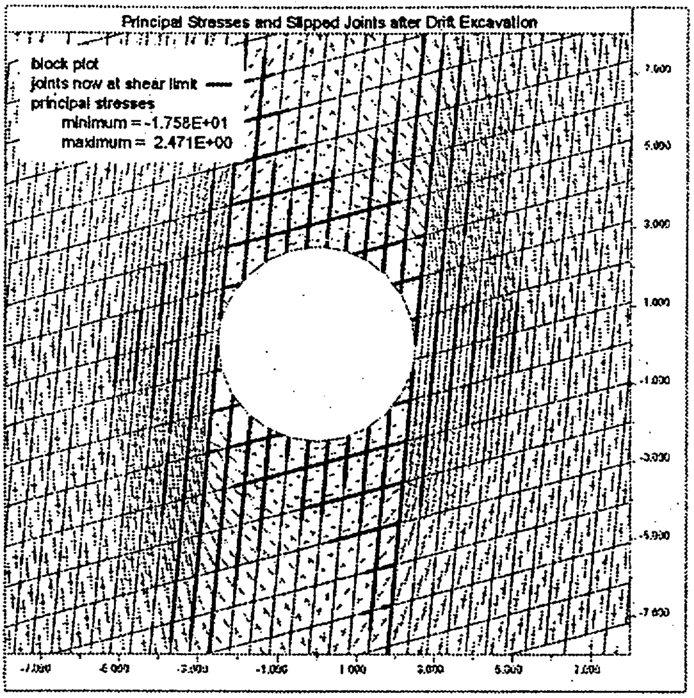

Figure 4.1

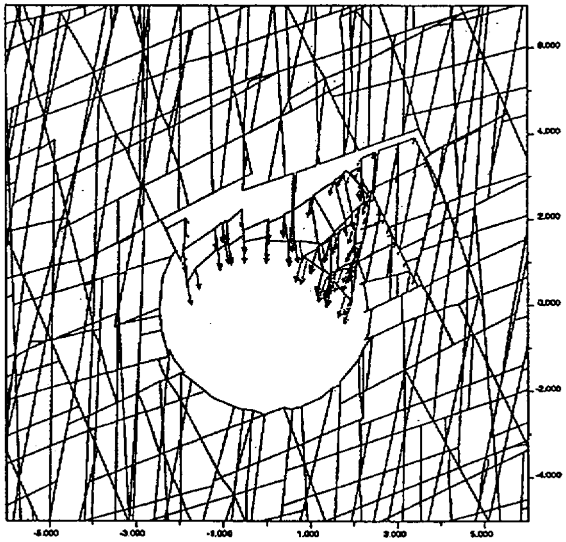

Figure 4.2

Thermal effects have been considered in the engineering analyses for the YMP repository and experiments addressing heat pipe effects (i.e., the backflow of water into the waste canister zone) are currently being planned by Sandia and the USGS as part of tests to support the development of engineered barriers. We believe this is appropriate since a total analysis could not be completed without some kind of assessment of the dynamics of the thermally induced drying followed by the subsequent backflow of water and its impact on the integrity of the canisters. However, we feel more attention needs to be paid to understanding the thermal effects on the moisture percolation conditions in the field rock surrounding the repository as well as on the properties of the rock and fractures immediately surrounding the drifts that govern how moisture will seep through the roof of the repository drifts.

The future generation of heat in the repository drifts will have a significant hydrologic impact, so much so that the near-field moisture flow regime will be disturbed for a significant period of time. Heat will drive water away from the waste emplacement areas (in the drifts), for times up to 500 years or more. However, as things cool down there will be a return of liquid and vapor flow in quantities that could impact the integrity of the waste canisters. We raise a concern that corrosion rates of the canister can be accelerated by both the liquid and water vapor return flow. As the drift area elevates in moisture and humidity the probability of corrosion of the canisters could also increase.

The YMP's current drift-scale seepage models require moisture saturation to occur at the drift boundary before seepage into a drift can occur. Evaporation of water at and immediately behind the drift walls, coupled with the formation of droplets by condensation on these walls or directly on the nuclear waste canisters, are not considered. We believe the moisture drift seepage modeling needs to reflect the impact that very high humidity (100%) moisture conditions will occur in the repository drifts over a very long times (1000s of years).

3.10 ENGINEERED BARRIERS

Efforts are underway for the YMP by Sandia (and the USGS) to study physical models of repository drifts at Yucca Mountain and to developed engineered barriers that might control and divert seepage within drifts. We were not formally briefed on this activity. However, a test plan (Sandia 1998) was distributed to the panel and it is our understanding that over six months of testing has now occurred. From a review of the planning document we offer the following comments of some of the concepts:

1. The capillary barrier tests utilize ¼-scale drift compartments. Direct scaling of water flux is not possible so extrapolation from the results of the tests must be viewed with caution, particularly when the impact of length and slope of the capillary barrier are considered.

2. Initial conditions using dry materials (soils) are planned. Over time, the soil material can become wetted, through a variety of mechanisms (vapor transport, condensation, etc.). The greatest flow will occur when the soil is wettest, so some preconditioning of the soil materials should be considered in the test to simulate long-term water content conditions.

3. Water Flux Issues. Elevated water flux (infiltration) to rates of 300 mm/yr are to be funneled to a single fracture located in the crown of the drift. Such a rate is expected to bound the critical infiltration conditions for the demonstration test. This appears to be a conservative test. However, the water flow in a small scale capillary system cannot be replicated for a

larger scale since the slope-length and associated boundary conditions will be different. Small defects in the boundary between the fine and coarse soil could cause significant variation in the actual length of diversion (lateral flow) before breakthrough is observed. In addition, the concerns expressed by the panel about the eventual collapse of the drift cavity will not be reflected in this test. The non-conservative issue here is that a collapsed drift may create a flow field that could channel flow into the underlying coarse material if the fine material was in some way displaced (so that the capillary barrier was disrupted). Ensuring that the capillary barrier in an engineered backfill system is thick and stable might help prevent such phenomena from impacting the performance of the barrier system.

4. Choice of soil types. The layering sequence is critical to the analysis. Soils that are only marginally different in textural and pore size distribution will tend to show less divergence than soils that have strikingly different pore size distributions. Some work has been done to provide theoretical estimates of water storage and diversion in capillary barriers by the University of New Mexico (Stormont 1997). However, it does not appear that the materials selected were optimized using any pore-size distribution criteria. It appears that under the water flux regime imposed, that the soil textures of the two materials being tested are too close together for effective water storage and also the divergence of water will not be maximized. It should be made very clear what the intent and purpose of the material selection is for the testing. Failure of the test (water moving into the coarse material) may largely be a result of poor selection of materials). Selecting a range of materials should be done with some caution.

5. Thermal testing. It is not clear how the thermal testing can replicate the heat pipe effects (water vapor moving away from and liquid water moving back into the cavity) that might occur in the drift cavity. In the thermal study the actual soil types, the water contents and the scale of the system are all critical to the outcome of the testing. It is not clear that issues related to scale and soil physical properties have been clearly evaluated at this point in the study, though the experimenters correctly recognize the fact that the water flux cannot be scaled. Some decisions need to be made on the intent of the thermal testing. In summary, the engineering tests of the capillary barrier to divert seepage water is interesting and could provide direct evidence that even high rates of seepage could be controlled around the waste canisters. In the early years the heat loading will typically drive water away from the canisters. After thermal cooling, however, the water could impact the waste. The studies with the ¼ -scale drift compartments may provide some results that can be used in seepage control design. However, caution must be used to ensure that the tests mimic in all ways possible the waste repository configuration and that the capillary barrier, created to divert water away from the canisters, is stable over time and designed to divert the maximum amount of water possible.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 PANEL's CONFIDENCE IN YMP's DRIFT SEEPAGE ESTIMATES

Conclusion

The DSPR Panel concludes that the YMP does not yet have the necessary information, nor the appropriate models to accurately predict the spatial and temporal distribution of the moisture that will enter the drifts of a repository at Yucca Mountain. There is currently a great deal of uncertainty associated with many aspects that relate to the ability to estimate drift seepage at Yucca Mountain and thus we are not confident that the YMP's current approach for generating drift seepage estimates can be adequately justified and defended. We do not believe it is realistic that the YMP attempt to develop models that might be expected to "predict the current and future rates and locations of moisture seepage into the repository drifts at Yucca Mountain", especially for the long time frames required for PA analysis. Instead, we believe the YMP should develop models that can provide reliable statistical measures and bounds for estimating drift seepage rates and locations. Such models will need to rely on sound statistical descriptions of the upstream moisture boundary conditions (infiltration and percolation), downstream drift boundary conditions (including drift geometry and elements of the repository design that affect this boundary) and all of the features, events and processes that control moisture transfer and seepage into the repository drifts. We conclude that there is considerable room for improvement in this area of the YMP program not the least of which involves: developing a thorough plan for ongoing and future experimental and modeling work that is closely integrated with developments in the program areas of repository design and engineered barriers; conducting additional, comprehensive drift seepage measurements, tests and experiments in the ESF and the potential repository; and, obtaining additional site characterization information for a wide range of spatial scales (from a few tens of centimeters to many tens of meters), especially for the rocks of the repository horizon, that can be used to develop multiscale relationships of the geologic heterogeneity that controls moisture movement through the rocks at Yucca Mountain. We offer detailed conclusions and recommendations on drift seepage and related issues in the following.

4.2 DRIFT SEEPAGE ISSUES

4.2.1 Conceptual Model for Drift Seepage

Conclusion

Our review of all the moisture flow and drift seepage documents provided by the YMP suggests there is no collective agreement yet within the YMP on what factors will have most influence on drift seepage into the proposed repository drifts at Yucca Mountain. Areas where we believe the concepts are less well described, or where there is insufficient understanding, are: the effects of focused or channeled flow as it enters the drift seepage model; the effects of transient moisture fluxes and hysteresis on drift seepage; how moisture can be translated laterally around the repository drifts; what controls the formation/breakdown of a capillary barrier around the drifts; the effects of moisture storage in fractures above the drifts; fracture/matrix interaction effects; the effects of evaporation/condensation on both liquid and vapor fluxes within the fractures and rock matrix surrounding the drifts, across the drift surface, and on the formation of droplets inside the drift; the effects of drift surface roughness and geomechanical disturbances on drift seepage; and, how to represent the multiscale nature of hydrogeologic heterogeneities as well as hydrologic inputs in the drift-scale model. We consider drift seepage to be a local phenomenon that will be controlled by a wide variety of features, events and processes, some of which occur on the spatial scale of individual droplets of water. We are therefore of the opinion that drift seepage cannot be understood or described by concepts or models that lack a corresponding scale of resolution. So far the YMP has not developed a conceptual model of drift seepage that accounts for the full range of spatial and temporal scales, which may be relevant to drift seepage at Yucca Mountain.

Recommendation

In our view, what requires a better understanding for drift seepage modeling are the magnitudes as well as space-time fluctuations of moisture flux at the input boundary of the drift-scale model (infiltration, percolation), conditions at the output end (waste emplacement drift), knowledge of the range of hydrologic properties for the rocks of the repository horizon at a multiplicity of spatial scales, and a thorough knowledge of the features, events and processes that result in the formation/breakdown of the capillary barrier and determine how moisture is diverted around the drift openings. The YMP should develop a clear, concise description and theoretical as well as experimental justification of the conceptual model it uses for drift seepage.

4.2.2 Evaporation and Condensation of Moisture Within the Repository Drifts

Conclusion

We believe the conceptual model should take account of the role that evaporation/condensation may have in governing moisture movement into the repository drifts. We have seen no evidence that the YMP is able to estimate the amount of moisture that enters the repository as evaporation under current or expected future conditions. This moisture can condense within the repository drifts to form liquid droplets on the drift walls, drift liners, drip shields, or the waste canisters. This aspect of moisture movement is not presently accounted for in the YMP's PA models. We were told (informally) that any such condensation would form droplets of distilled water that would have negligible corrosion effects. We have seen no evidence to corroborate this and remain concerned that it might not be conservative to neglect moisture evaporation/condensation in the PA.

Recommendation

We encourage the YMP to investigate the effects of moisture entering the repository drifts by evaporation, and forming water droplets by condensation, on canister corrosion and radionuclide transport from the repository. Such an effect, if significant, could render drip shields ineffective as a counter measure. The YMP should either justify why the effect is neglected or include it explicitly in the PA.

4.2.3 Threshold Flux

Conclusion

The LBNL drift seepage modeling team has developed, on the basis of available drift seepage experiments, an empirical relationship between percolation rate above a drift and seepage into the drift. This relationship, obtained by linear regression of scattered experimental data, has been used by the team to suggest that no drift seepage will occur when the moisture percolation rate is below a certain threshold. Though we agree, based on our understanding of capillary theory, that such a threshold could exist, we are not convinced that the available experimental data are yet sufficient to quantify this threshold in a way that would apply either to conditions other than those that prevailed during the experiments or to untested portions of the rock. The threshold flux should not be expected to be a unique value (25 mm/yr is used in LBNL's drift seepage model) but will depend upon the space-time distribution of deep percolation above the repository, the heterogeneity and anisotropy of the hydrologic characteristics of the fractures and the matrix rock surrounding the drifts, the dimensions and roughness of the drifts, and conditions within and near the surface of the drift.

Recommendation

Analyses concerning the effectiveness of the capillary barrier in diverting or preventing moisture seepage into the repository drifts should be developed that account for all the features, events and processes that could affect the capillary barrier. These corresponding models should be consistent with all seepage tests and observations in the ESF, including the observations of enhanced seepage that emerged from the shot-crete in the roof of Alcove 1 during the moisture infiltration test.

4.2.4 Moisture Flux Around the Drifts

Conclusion

We expect lateral flux of moisture around the drifts to occur primarily through fractures very near the excavation surface above the roof and around the walls of the drift. No measurements have been made during the drift seepage tests conducted by the YMP so far to determine how much moisture has been diverted laterally around the drifts and how this diversion takes place.

Recommendation

It is our view that the drift seepage models should not only reliably predict the quantity of water seeping into the drifts, but should also reliably model the quantity of moisture expected to be diverted around the drifts and the mode of this diversion. Future drift seepage tests or experiments should be designed to measure the amount of moisture diverted around the drift openings, as well as determine how much moisture is retained as storage in fractures or the rock matrix above the drifts.

4.2.5 Data on Rock and Fracture Heterogeneity

Conclusion

Our review of the drift seepage modeling approach used by LBNL shows that only fractures longer than 1m are considered. Mapping in the ESF reveals there are many fractures shorter than 1m, especially in the main rock unit being proposed for the waste emplacement areas of the repository. If these smaller fractures are considered, the values determined for fracture aperture (b), van Genuchten alpha (α_f) and fracture porosity (ϕ) are significantly different than if only the fractures longer than 1 m are considered.

Recommendation

The YMP should consider fractures that have a trace length less than 1 m in the drift seepage analysis. Although it may be acceptable to ignore the role these smaller fractures may play in describing how moisture will move in the far field, tens of meters away from the drifts, we believe the role of the smaller fractures should be accounted for either directly or indirectly in modeling moisture movement and seepage in the near field of the drift openings (within centimeters to a few meters).

4.2.6 Knowledge of Hydrologic Conditions in the Repository Area

Conclusion

Currently there is virtually no fracture or hydraulic properties data available for rocks that surround the proposed repository. There is no assurance that the hydraulic properties of these rocks are similar to those that surround the ESF.

Recommendation

We believe the YMP should obtain fracture and hydraulic property data that represents rocks around the proposed repository. The data should be analyzed using geostatistical approaches that can establish multiscale relationships.

4.2.7 Modeling Spatial Heterogeneity

Conclusion

LBNL's current drift seepage models consider at most two distinct scales of spatial heterogeneity that relate solely to permeability. We expect permeability as well as other relevant rock properties, such as porosity, fracture geometric parameters, and unsaturated flow variables to exhibit spatial fluctuations on a multiplicity of scales. It is important to consider the effects that multiscale heterogeneities may have on the formation of preferential flow channels in the rock and their impact on drift seepage.

Recommendation

Consideration should be given to implementing multiscale geostatistical analyses of heterogeneity and flow around and into drifts at Yucca Mountain. Both continuum and discrete methods to do so have been published in the hydrologic literature. Of particular relevance may be methods that view heterogeneous rock properties as self-affine random fractals, characterized by power variograms, with cutoffs that represent scales of the data support and the flow domain. Regardless of what models of heterogeneity the project decides to adopt, we consider it essential that these models be backed both qualitatively and quantitatively by site data.

4.2.8 Continuum Versus Discrete Fracture Models for Estimating Drift Seepage

Conclusions

Stochastic continuum (SC) models and discrete fracture (DF) models may both play a useful role in the YMP's future drift seepage modeling, although we do not believe the YMP's current DF model (WEEPS) is appropriate. Stochastic continuum models, such as those currently employed for the YMP by LBNL, may be able to provide useful statistical estimates of seepage flux and space-time distribution, but may not be as useful for estimating the location of discrete seeps.

Discrete fracture models, if properly developed and tested may eventually be able to provide useful estimates of the number of discrete seeps. However the YMP's current DF model (WEEPS) does not represent the physical processes of unsaturated moisture flow through fractured porous rocks. Therefore it is not appropriate to use the WEEPS model to estimate the rate and location that moisture will seep into the drifts of a repository at Yucca Mountain where seepage will be controlled by the properties of unsaturated, fractured porous tuffs.

Recommendations

The stochastic continuum model of LBNL should be tested to determine how well it can predict, ahead of time, the magnitude and space-time distribution of moisture seepage fluxes into drifts at the repository horizon in Yucca Mountain under controlled experimental conditions.

If the YMP decides to use discrete fracture models to estimate drift seepage, it needs first to develop and test discrete fracture models that can represent the physical processes of moisture movement through unsaturated, fractured porous rocks. Once developed, these discrete fracture models should be evaluated as part of drift seepage experiments in Yucca Mountain to determine how well they are able to predict, ahead of time, the location and fluxes of discrete seeps. Such discrete fracture models do not yet exist and we expect some fundamental theoretical and experimental development is required before they are available. This theoretical and experimental development could take several years and could be considered "frontiers of science" work.

4.2.9 Appropriateness of Using Inverse Modeling to Derive Continuum Properties

Conclusion

LBNL's use of inversion to obtain parameter values for continuum models, such as ITOUGH2, has many pitfalls, including:

1. The inversions are conducted by LBNL on lesser dimension, spatially restricted submodels, rather than on the entire three-dimensional model to reduce the numerical effort
2. The models are calibrated in one portion of the rock (for example, the ESF), and then are extrapolated to uncalibrated portions of the rock (the repository block) where conditions may be different

Recommendation

The approach used to calibrate a drift seepage model such as ITOUGH2 through inversion to spatially and dimensionally restricted submodels should be evaluated. A test or experiment should be developed to determine how well a continuum model calibrated by inversion for one portion of the ESF can be applied to another portion that has also been properly characterized.

4.2.10 Using Field Experiments for Model Confirmation

The work carried out by LBNL so far in the niche seepage studies in the ESF does not demonstrate that the predictions from LBNL's drift seepage models have been confirmed. The modeling of seepage done so far, are primarily sensitivity studies or have been conducted to help design seepage experiments.

Recommendation

Confirmation of the drift seepage models should consist of a forward prediction of the rate and space-time occurrence of drift seepage prior to performing drift seepage experiments. As a minimal confirmation, drift seepage models should predict the rate and occurrence of seepage at the discretization scale anticipated for input into the PA model. A stronger confirmation would be to do this for tests or experiments performed in all subregions into which the PA eventually divides the repository block.

4.2.11 Adequacy of Drift Seepage Tests

Conclusions

We note that LBNL and USGS researchers have already performed some very useful and interesting drift seepage experiments in special test areas (six alcoves and three niches) constructed off of the ESF tunnel. We commend the LBNL and USGS scientific staff on their ingenuity and innovations in implementing these experiments. However, the drift seepage experiments and observations have only just begun in the ESF and we believe that there has been insufficient experimental work completed on the topic of drift seepage at Yucca Mountain to use the results to demonstrate the usefulness of the drift seepage models for PA. We also note there is no apparent long term plan or strategy for conducting the drift seepage experiments at Yucca Mountain to meet the YMP's requirements for repository license application or repository design.

Recommendations

We urge the YMP to develop an integrated plan for the in-situ drift seepage tests at Yucca Mountain that identifies the relevant drift seepage issues for both license application and repository design and proposes an approach to address these issues through in-situ drift seepage tests in parallel with numerical model development.

We believe that many years of continuous experimental work on drift seepage mechanisms are required in Yucca Mountain to obtain the necessary measurements and understanding. We recommend that such work commence immediately to ensure some results will be available to support the repository license application. Wherever possible, efforts should be made to consolidate the drift seepage tests into fewer but more comprehensive, larger-scale and longer-term experiments. This would allow the experiments to benefit from more thorough 3-D characterization and monitoring. All future drift seepage experiments should include pre-test predictions using drift seepage models.

4.2.12 Locations of Drift Seepage Experiments

Conclusion

So far the observations and tests of drift seepage have been performed in the main ESF tunnel outside the proposed location of the repository horizon and where the rates of ambient moisture percolation are expected to be considerably smaller than over much of the repository horizon.

Recommendation

We urge the YMP to examine options to situate some drift seepage tests in conditions at Yucca Mountain representing both the rock units and range of moisture percolation flux conditions expected for the repository horizon.

4.2.13 Experimental Conditions: Evaporation

Conclusion

One issue of concern regarding the drift seepage observations and tests in the ESF so far is that the high rate of advective removal of moisture from the walls of the excavations by evaporation into the ventilation air flow has been (and remains) a major problem in any attempts to observe ambient moisture seepage into the ESF or to quantify moisture seepage fluxes induced into the drift seepage test areas. Under these conditions any attempts to measure the water contents, water suctions (potentials), and seepage fluxes in areas where evaporation dominates the flow process, and then extrapolate to repository conditions where there will be no evaporation, could underestimate the repository drift seepage fluxes.

Recommendation

Therefore we highly recommend that humidity in the experimental rooms should be controlled to as close to 100% as feasible during future seepage tests and experiments in the ESF. Where it is perhaps not feasible, the evaporation should be quantified. We believe an assessment of the effect of evaporation on seepage experiment results and conclusions is essential.

4.2.14 Excavation Disturbance

Conclusion

Excavation disturbance will affect the properties of the fractures in the rock very close to the excavation, in the region considered to include the capillary barrier. LBNL's work in the ESF has measured hydrologic changes due to excavation in the near-field region of the rock above the experimental drifts. The changes to the hydraulic properties of the fractures caused by the excavation will impact the performance of the capillary barrier. YMP's drift scale seepage modelling has not yet addressed stress-induced changes to fracture aperture or permeability in the rock very close to the excavations and some of LBNL's measurements are not consistent with current models of fracture displacement. It will be important to resolve both the influence of stress change on fracture properties and the influence of fracture aperture on flux, in order to develop a conceptual model for the influence of excavation disturbance on the capillary barrier surrounding the repository drifts.

Recommendation

There is a need for mechanical modeling to assess the influence of drift excavation on the interconnected fracture pathways near the drifts. This should be done in parallel with an examination of the influence of shear and normal stress changes on fracture aperture and with studies of the influence of fracture aperture change on moisture flux.

4.2.15 Drift Roughness and Future Stability

Conclusion

None of YMP's drift seepage models have dealt with the effects of the roughness of the drift openings, the presence of concrete or steel liners and their eventual disintegration, time-dependent displacements of rock blocks along fractures, roof spalling and cave-in, and finally, the possibility of eventual partial closure or complete collapse of the drifts. The drift seepage models used so far for the long term assessment of repository performance have assumed the drift geometry will remain as constructed (but without a concrete liner) for 10's to 100's of thousands of years. We see no evidence that the YMP has the ability to quantitatively predict (nor defend the predictions) these changes in drift shape and tunnel wall geometry; changes in fracture flow characteristics; changes in the properties controlling the development of a capillary barrier; or, the degree to which the drifts will eventually collapse and be filled with rubble. This leads us to question how long the current drift seepage models will reasonably reflect the future reality within the Yucca Mountain repository.

Recommendation

The drift seepage models need to account for these effects in a credible and defensible way. Work should be initiated to understand the significance of these aspects of the present and time-dependent future geometry of the surfaces of the repository drifts on drift seepage estimates.

4.2.16 Linkage Between Site Scale UZ Flow Model and Drift Scale Seepage Model

Conclusion

Preferential and episodic infiltration events, on scales relevant to drift seepage, are not part of the conceptual-mathematical framework that underlies the current LNBL site-scale UZ flow model. As such, the hydrologic inputs that the site scale model generates for the drift-scale seepage models are smeared in space-time and are therefore inadequate for the prediction of drift seepage. This inadequacy overshadows the ability of the drift-scale model to represent rock heterogeneity locally with a relatively high degree of resolution (0.3 - 0.5 m grid).

Recommendation

Instead of using a low-resolution (coarse, 100 - 200 m grid) site-scale model to compute moisture fluxes at the top boundary of a high-resolution (fine, 0.3 - 0.5 m grid) drift-scale model, the YMP should consider one or both of the following options: (a) extend the high-resolution drift-scale model to the soil surface, and generate net infiltration at the surface stochastically so as to include pulses that exhibit multiscale random fluctuations in space-time; (b) generate multiscale percolation rates at the top boundary of the drift-scale model stochastically in a similar manner. The YMP should include in the drift seepage modeling, the impact of transient pulses of moisture percolating rapidly through preferential flow channels at Yucca Mountain.

4.2.17 Linkage Between Drift Seepage and Repository Design/Engineered Barriers

Conclusion

The planned experiments by Sandia and the USGS on the Richards' Barrier are related to drift seepage and should provide useful information on diverting drift seepage away from the canisters by constructing engineered capillary barriers within the materials used to backfill the waste emplacement rooms in the repository. However, unless at some time, there are full-scale studies completed and the impacts of flaws and imperfections in the engineered capillary barrier are evaluated, the studies will be limited in their ability to represent actual drift conditions and demonstrate engineering control to divert seepage away from the waste canisters, particularly under conditions of elevated seepage rates.

Recommendation

We recommend such work should be undertaken.

4.2.18 Coupled Effects

Conclusion

Though we were asked to ignore the effects of the thermal conditions that may develop following the emplacement of nuclear waste in the proposed repository, we feel we must address this question briefly in our report. The placement of wastes, which generate temperatures close to or above 100° C within the repository followed by a period of cooling to ambient temperature conditions, could alter the near field environment in ways which would render the prediction of drift seepage much more difficult than is already the case under ambient conditions. We believe it will be a significant challenge for the YMP to predict, or bound in a credible manner, the effects that possible geochemical alterations and geomechanically induced erosion or collapse of the repository drift would have on near field rock properties and drift seepage under such unfamiliar anthropogenic conditions.

Recommendation

The YMP should consider and account for the coupled effects of the full heating-cooling cycle brought about by the decaying thermal load in future modeling of moisture seepage into the drifts of a repository at Yucca Mountain. If future thermal tests are conducted in the ESF they should include predictions and measurements of moisture movement within the rock surrounding the thermal tests.

4.3 YMP'S ESTIMATES OF PERCOLATION FLUX AT THE REPOSITORY HORIZON

4.3.1 Infiltration Issues

Conclusion

Net infiltration is the primary factor that determines the percolation of moisture through Yucca Mountain, and thus controls the potential for seepage to occur into the drifts of a repository within the mountain. We agree with members of the UZ Flow Model Expert Elicitation Project that there is no precedence to estimate net moisture infiltration in a large unsaturated fractured (or porous) rock complex, such as Yucca Mountain, under semiarid (or other) climatic conditions. Thus, there is no experience to indicate how reliable any model, and any particular set of data, are when used to generate such estimates. We also conclude that the YMP's current assessments of long-term average net infiltration into Yucca Mountain, and its spatial distribution, are of indeterminate quality and should be regarded as highly uncertain; that they may overestimate the percentage of infiltration at the crest of Yucca Mountain, and underestimate it at lower elevations; and that they lack the space-time resolution that may be needed to address issues of focused infiltration. We suspect that focused infiltration of moisture during extreme storm events may play a dominant role in the potential initiation of drift seepage. The "horsetail" fracture patterns identified on the slopes of Yucca Mountain suggests that focused infiltration (funneled flow) probably occurs and likely contributes to localized high velocity percolation rates that may ultimately contribute to drift seepage. Such focused infiltration is not considered in the YMP's current unsaturated zone moisture flow modeling of Yucca Mountain.

Recommendations

We recommend that the YMP should establish greater confidence in the moisture infiltration model for Yucca Mountain and quantify the uncertainty in the estimates of net infiltration into the mountain, particularly for the crest area overlying the footprint of the planned repository. We support a suggestion made by the UZ Flow Model Expert Elicitation Project to thoroughly instrument and study the hydrology of at least one small drainage basin at Yucca Mountain for a number of years. The goal would be to develop a complete local water balance of the watershed and examine infiltration processes on a sufficiently small spatial scale, over a sufficiently long time period, to provide information about both spatially distributed and relatively slow, as well as focused and comparatively fast, rates of net infiltration at and near the soil surface. The study might rely (among others) on rain gauges, detailed mapping of fractures (beneath the alluvium at some locations), nests of piezometers in the alluvium and bedrock, and detailed mapping of depth to bedrock. Measurements could be made of surface flow during storm events and subsurface flow along the bedrock-alluvium contact using trenches, surface runoff gages and weirs, buried pan or wick-type lysimeters, and TDR or capacitance probes. Ideally part of the watershed study should overlie the ESF and/or the area of the planned repository, where other instrumentation (such as tensiometers, neutron probes, and heat dissipation sensors) are monitored in the deep subsurface while pore water is sampled for geochemistry. Information gained from this study would provide support for YMP's infiltration model.

The UZ Flow Model Expert Elicitation Project also proposed to assess long-term average deep percolation through Yucca Mountain by studying matrix flow within the Paintbrush nonwelded (PTn) unit that lies between the TCw and TSw. The study would use pressure, saturation and relative permeability data from boreholes to calculate vertical flux through the PTn by means of Darcy's law. We recommend that serious consideration be given to this proposal and additional data should be collected to perform such vertical flux calculations at various locations in the PTn across the mountain. This would provide an independent confirmation of long-term average infiltration and deep percolation assessed by other means. We recognize that there are relatively large uncertainties in such an approach (often as much as an order of magnitude error in flux estimates). However, within the limitations of the present methodologies this approach may be more reliable than other, less direct methods that have been used, such as water budget (ET estimations), chloride mass balance analysis or estimates from geothermal gradients (thermal profiling).

4.3.2 Percolation Issues

Conclusion

The distribution of slow and fast percolation pathways through the fractured rocks at Yucca Mountain has significant implications with respect to estimating the spatial and temporal distribution of moisture flux at the repository horizon and thus on drift seepage predictions. The YMP has not yet obtained a good measure of the spatial distribution of the hierarchy of fractures and high permeability channels contributing to the fast percolation pathways and there is a great deal of uncertainty of the rate and spatial distribution of fast flow path flux under the current moisture infiltration/percolation conditions. The areal extent of these pathways and the volume of moisture moving through them has received only educated estimates by the YMP so far in the material we reviewed. Until more is learned about the fast pathways that have given rise to the deep and apparent rapid penetration of the percolation waters found in the ESF tunnels we believe there will remain unanswered questions regarding the impacts of climatic change and the spatial variability of net infiltration rates that will inevitably occur at the mountain in the near and far future. These uncertainties in the moisture percolation model for Yucca Mountain introduce large uncertainties in the YMP's estimates of the rate and spatial distribution of moisture flow into the repository drifts.

Recommendations

We urge the YMP to develop a better understanding of the geologic and hydrologic characteristics of the complete hierarchy of fractures, faults and permeable channels that cut through the rocks at Yucca Mountain, particularly in the rock units being targeted for the potential repository horizon. We also strongly urge the YMP to quantify the spatial distribution and rate of moisture percolation flux moving through the fast pathways at the repository horizon in Yucca Mountain under current climate conditions. We see this as key to developing credible predictions of the rates and locations of moisture seepage that will enter the repository drifts in the future under dry climate conditions similar to those of today, as well under any postulated periods of wetter climates.

While we recognize the difficulty, some of us consider it important that actual moisture flux measurements should be attempted in Yucca Mountain to provide confirmation of the percolation flux derived from the UZ moisture flow model. According to these panel members some such measurements of moisture flux should be attempted in one or more of the fast flow pathways in the rock units of the proposed repository horizon. These panel members further believe it is particularly important to try to obtain such direct measurements of moisture flux below the crest of Yucca Mountain where the moisture percolation rates are currently estimated to be highest.

The UZ Flow Model Expert Elicitation Project also proposed to assess long-term average deep percolation through Yucca Mountain by studying matrix flow within the Paintbrush nonwelded (PTn) unit that lies between the TCw and TSw. This was included in our Recommendation 4.3.1 concerning infiltration, and we include it again here as part of our recommendations concerning deep percolation.

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APPENDIX 1: DSPR PLAN

PLAN FOR A CONSENSUS PEER REVIEW OF YMP PREDICTIONS OF DRIFT SEEPAGE INTO THE PROPOSED REPOSITORY AT YUCCA MOUNTAIN

This Peer Review Plan has been prepared in accordance with existing project requirements for quality assurance and with the YMP Office Quality Management Procedure (QAP 2.5, Rev. 1, ICN 0), Peer Review. The outline of the Plan follows Section 5.6 of QAP 2.5, Rev. 1, ICN 0, entitled "Performance of a Consensus Peer Review".

A. Statement of Work Product to be Reviewed

The purpose of this peer review is to evaluate the data, assumptions, conceptual models, methodologies and uncertainties associated with the Yucca Mountain Project's (YMP) predictions of drift seepage into the proposed repository at Yucca Mountain over long time frames. The scope is limited to drift seepage predictions under natural temperature conditions. Predictions of the effects of waste-generated heat on drift seepage are specifically not included in this review.

The panel, referred to as the Drift Seepage Peer Review Panel (DSPR), will perform the following tasks:

- define conditions which control seepage into repository drifts at Yucca Mountain
- review the most recent YMP synthesis reports on drift seepage and moisture monitoring tests conducted in niches and alcoves of the ESF at Yucca Mountain
- examine the representativeness of using the inverse modeling technique to obtain the continuum fracture characteristics from a calibrated flow model at the mountain scale for modeling drift seepage
- examine the representativeness of using the continuum fracture network model versus a discrete fracture model for estimating drift seepage
- examine the adequacy and representativeness of the seepage testing approach and field test locations (both present and planned)
- examine the adequacy of interpretation and incorporation of experimentally acquired seepage data into the 3-D UZ Flow Model
- examine the nature and extent of uncertainties produced by changing from the 30 m grid for surface modeling (infiltration model) to the 100-200 m grid for the 3-D UZ Flow Model (percolation flux model) to the very small 0.5 m grid for the drift scale model (seepage model)
- evaluate the current YMP seepage estimates into the repository drifts at Yucca Mountain considering:
  - data on rock heterogeneity
  - interpretations of site hydrogeologic features
  - knowledge of the present and projected future ranges of percolation flux at the repository horizon
  - data and interpretations of matrix and fracture moisture content
  - understanding of partially saturated matrix and fracture characteristics
  - knowledge of the effects of capillary barriers surrounding mined repository openings
  - relevancy of conceptual models
  - appropriateness of assumptions

  - promising or alternative modeling techniques
- state the degree of confidence the Panel has in: 1) the test results obtained from the experimental drift seepage program in the ESF; and, 2) the predictions of repository drift seepage obtained from the YMP numerical modeling efforts.

B. Size and Technical Composition of Drift Seepage Peer Review Panel

The Drift Seepage Peer Review Panel will consist of five reviewers. The reviewers and their respective areas of technical expertise are as follows:

- Mr. Cliff Davison (AECL), Panel Chair
  - Fracture flow/transport

- Dr. Shlomo Neuman (University of Arizona)
  - Unsaturated zone and fracture flow/transport modeling

- Dr. Glendon Gee (PNL)
  - Surface flow processes/infiltration

- Dr. Paul LaPointe (Golder Associates)
  - Geostatistics/fracture flow modeling

- Dr. Neil Chandler (AECL)
  - Geomechanics/rock mass response to excavation

Dr. Bimal Mukhopadhyay of the Management and Technical Support organization (MTS) for the Yucca Mountain Project Office (YMPO) is the Responsible Manager for this Drift Seepage Peer Review. Dr. Ronald Linden of MTS will serve as the YMPO's Review Coordinator for the DSPR panel in Las Vegas. Questions, correspondence, materials or requests for clarification will be directed to the DSPR Panel Chair and the Review Coordinator who will prepare the materials and distribute them to all the DSPR Panel members.

C. Method of Documenting Findings, Concerns and Conclusions

The Drift Seepage Peer Review Panel will maintain written minutes of its meetings, discussions, correspondence and peer review activities throughout the peer review process for use in preparing a Drift Seepage Peer Review Report. Questions, correspondence, materials or requests for clarification regarding the Work Product under review will be directed in writing to the Review Coordinator with a copy to the DSPR Panel Chair. Responses will be distributed to all DSPR Panelists to ensure consistent evaluation during the peer review.

The Drift Seepage Peer Review Panel will prepare a Peer Review Report that documents its findings and conclusions. The Report will identify those findings or conclusions where consensus was reached within the Panel. In cases where consensus could not be reached the additional (or dissenting) findings or conclusions will be included in the Report. The Report will comment on perceived errors or omissions as noted by the Panelists and will include advice or recommendations for changes in such cases. If appropriate or desired, individual statements by Panelists presenting their advice and recommendations will also be included in the Report.

A Drift Seepage Peer Review Report will be submitted by the Panel Chair to the Responsible Manager. The Responsible Manager will evaluate the advice and recommendations in the Drift Seepage Peer Review Report with regard to the technical management and policy implications of accepting each of the recommendations. The Responsible Manager will then prepare an Evaluation Report which will analyze and summarize the advice and recommendations of the Panel.

D. Schedule for Conducting and Reporting Results of the Drift Seepage Peer Review

The Drift Seepage Peer Review will be completed in a series of tasks. The tasks and key schedule dates are given in Table 1 and are summarized below. The DSPR Panel intends to submit a report on its findings and conclusions to the Responsible Manager by 1999 June 30.

Task 1. *Peer Review Preparation*: Some preparation began prior to the completion of the Drift Seepage Peer Review Plan. By 1998 November 8, copies of several relevant documents for the Drift Seepage Peer Review had been assembled by the MTS and distributed to DSPR Panel members. These included:

Background Drift Seepage Materials

- Level 4 Milestone SPC315M4, "Drift Seepage Test and Niche Moisture Study: Phase 1 Report on Flux Threshold Determination, Air Permeability Distribution, and Water Potential Measurement"
- Level 4 Milestone SPC314M4, "Field Testing and Observation of Flow Paths in Niches: Phase 1 Status Report of the Drift Seepage Test and Niche Moisture Study"
- Level 4 Milestone SP33PLM4, "Testing and Modeling of Seepage Into Drifts: Input of Exploratory Study Facility Seepage Test Results to Unsaturated Zone Models"
- Level 4 Milestone SP331CM4, "Drift Scale Modeling: Progress in Studies of Seepage into a Drift"
- Level 4 Milestone SPLC2M4, "Distribution of Post-Emplacement Seepage into the Repository Drifts with Parametric Variation of Intrinsic Properties"
- Level 4 Milestone SPLC3M4, "Models and Bounds for Post-Emplacement Seepage into the Repository"
- First Interim Report, "Total System Performance Assessment Peer Review Panel", June 20, 1997
- Second Interim Report, "Peer Review of the Total System Performance Assessment-Viability Assessment", December 1997
- Third Interim Report, "Total System Performance Assessment Peer Review Panel", June 25, 1998

- "Near-Field/Altered Zone Coupled Effects Expert elicitation Project", Deliverable SL5X41CM, May 29, 1998
- "Unsaturated Zone Flow Model Expert Elicitation Project", Deliverable SL5X4B1M, May 30, 1997
- "ISM 2.0 3-D Geologic Framework Model", by Clayton et al.
- "Drift Seepage Niche Study"
- Level 4 Milestone SLX01LB4, "Abstraction Modeling of Drift Seepage for TSPA/VA", April 3, 1998
- Level 4 Milestone SP331CM4, "Drift Scale Modeling: Studies of Seepage into a Drift", August 1997
- Level 4 Milestone SP331DM4, "Drift Scale Modeling: Studies of Seepage into a Drift", September 1997
- Level 3 Milestone T6540, "Drift Scale Modeling: Scaling and Modeling Testing for Use in TSPA" September 1996
- Level 4 Report for Drift Scale Modeling Task TR33129FBG, "Drift Scale Heterogeneous Permeability Field Conditioned to Field Data"
- Milestone PS4CKLM4, "Drift Scale Modeling: Studies of Seepage into a Drift", June 30, 1998.

Supplemental Information (from VA report)

- VA Volume 1: Overview, Introduction, and Site Characteristics
  - Section 2.2.3.2 Site Unsaturated Zone
  - Section 2.2.3.3 Status of Unsaturated Zone Studies
  - Section 2.2.5 Factors Affecting Radionuclide Transport
  - Section 2.2.6 Potential Effects of Repository Construction and Operation
- VA Volume 3: Total System Performance Assessment
  - Section 3.0 Development of Total System Performance Assessment Components for the Viability Assessment
  - Section 3.6 Unsaturated Zone Transport
- VA Volume 4: License Application Plan and Costs
  - Section 3.1 Site Investigations

Other reports and additional FY1998 deliverables will be added as they are needed or become available.

Task 2. *Peer Review Plan*: The DSPR Panel Chair prepared the Drift Seepage Peer Review Plan (this document) by 1998 November 30.

Task 3. *Preparation for the First Drift Seepage Peer Review Meeting*: This will involve reading and reviewing the distributed materials, requesting additional information, and compiling a series of questions or topics needing discussion at the meeting.

Task 4. *The First Drift Seepage Peer Review Meeting*: This meeting will be held in Las Vegas and at the Yucca Mountain site and will include presentations and discussions with relevant principal investigators from the Yucca Mountain Project, a field trip to the site to view the ESF and examine the drift seepage test alcoves and niches, a DSPR Panel meeting, and an executive session with the Review Coordinator to present and discuss the DSPR Panel's preliminary observations. If needed, a second Drift Seepage Peer Review meeting will be organized to discuss further drift seepage topics with the relevant principal investigators.

Task 5. *Drift Seepage Peer Review Report*: The DSPR panelists will prepare individual contributions for the peer review Report. The DSPR panel chair will compile the individual contributions into a single peer review Report. If needed, the Panel Chair may arrange meetings with DSPR panelists to assist in the preparation of the DSPR Report.

Task 6. *Compilation and Review Check*: The draft DSPR Report will be reviewed by the individual panelists. The report will note areas of consensus and document alternate views and opinions.

Task 7. *Final Presentation*: A final meeting will be held between Yucca Mountain Project Office staff and the Drift Seepage Peer Review Chair to present and discuss the final DSPR Report. Additional DSPR Panel members will be involved as necessary to present the DSPR Panel's findings and conclusions and help resolve any final issues.

E. Criteria to be Evaluated

In addition to the criteria specifically listed previously in Section A (Statement of Work Product to be Reviewed), the general criteria to be applied in the carrying out the Drift Seepage Peer Review will include:

1. validity of basic assumptions
2. alternate interpretations
3. adequacy of requirements
4. appropriateness and limitations of methods and implementing documents used to complete the work project under review
5. adequacy of application
6. accuracy of calculations
7. validity of conclusions
8. uncertainty of results of impact if incorrect.

TABLE 1: DRIFT SEEPAGE PEER REVIEW SCHEDULE

REVIEW ITEM	SCHEDULED DATE
Obtain background products to be reviewed to the DSPR	5/11/98
First DSPR meeting (4 days)	11/1/99
Second DSPR meeting (if needed)	mid 1999 March
DSPR panel members provide results to the chair	30/4/99
Deliver DSPR report	30/6/99

Acceptance Page

Cliff C. Davison AECL, Whiteshell Laboratories and the URL DSPR Panel Chair Review	Bimal Mukhopadhyay MTS Yucca Mountain Project Office Responsible Officer - Drift Seepage Peer

c.c. Ronald M. Linden, MTS
Phil Obertander, M&O
Russell Patterson, DOE
Richard Salness, MTS
William S. Scott, M&O, USGS
Dennis R. Williams, DOE

APPENDIX 2: LIST OF DSPR REVIEW MATERIALS

Background Drift Seepage Materials

- Level 4 Milestone SPC315M4, "Drift Seepage Test and Niche Moisture Study: Phase 1 Report on Flux Threshold Determination, Air Permeability Distribution, and Water Potential Measurement"
- Level 4 Milestone SPC314M4, "Field Testing and Observation of Flow Paths in Niches: Phase 1 Status Report of the Drift Seepage Test and Niche Moisture Study"
- Level 4 Milestone SP33PLM4, "Testing and Modeling of Seepage Into Drifts: Input of Exploratory Study Facility Seepage Test Results to Unsaturated Zone Models"
- Level 4 Milestone SP331CM4, "Drift Scale Modeling: Progress in Studies of Seepage into a Drift"
- Level 4 Milestone SPLC2M4, "Distribution of Post-Emplacement Seepage into the Repository Drifts with Parametric Variation of Intrinsic Properties"
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- Level 3 Milestone T6540, "Drift Scale Modeling: Scaling and Modeling Testing for Use in TSPA" September 1996

- Level 4 Report for Drift Scale Modeling Task TR33129FBG, "Drift Scale Heterogeneous Permeability Field Conditioned to Field Data"

- Milestone PS4CKLM4, "Drift Scale Modeling: Studies of Seepage into a Drift", June 30, 1998.

- CD Rom version of entire TSPA-VA report, DOE 1998

- Hardcopies of selected text from TSPA-VA report, DOE 1998

- VA Volume 1: Overview, Introduction, and Site Characteristics
  - Section 2.2.3.2 Site Unsaturated Zone
  - Section 2.2.3.3 Status of Unsaturated Zone Studies
  - Section 2.2.5 Factors Affecting Radionuclide Transport
  - Section 2.2.6 Potential Effects of Repository Construction and Operation

- VA Volume 3: Total System Performance Assessment
  - Section 3.0 Development of Total System Performance Assessment Components for the Viability Assessment
  - Section 3.6 Unsaturated Zone Transport

- VA Volume 4: License Application Plan and Costs
  - Section 3.1 Site Investigations

- Unsaturated Zone Flow and Transport Modeling of Yucca Mountain, Nevada -Fiscal Year 1998 Report, by Bodvarsson and Wu, 1998

- Progress Report on Fracture Flow, Drift Seepage, and Matrix Imbibition Tests in the Exploratory Studies Facility, by Wang et al. 1998

- Evaluation of Flow and Transport Models of Yucca Mountain, Based on Cl-36 and Chloride Studies for FY98, by Fabryka-Martin et al. 1998

- Evaluation of Flow and Transport Models of Yucca Mountain, Based on Chlorine-36 Studies for FY97, by Fabryka-Martin et al. 1997

- Repository Safety Strategy: U.S. Department of Energy's Strategy to Protect Public Health and Safety After Closure of a Yucca Mountain Repository, by DOE 1998

- Peer Review Report on Chlorine-36 Studies at Yucca Mountain, by Doe et al. 1998

- Ages and Origins of Subsurface Secondary Minerals in the Exploratory Studies Facility (ESF), by Paces et al. 1996

- Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada, by Flint et al., USGS, 1996

- Viability Assessment of a Repository at Yucca Mountain: A Report to the Director, U.S. Geological Survey, by Winograd, et al, 1998
- Final Report Total System Performance Assessment Review Panel, February 11, 1999

APPENDIX 3: AGENDA OF DSPR MEETING (1999 JANUARY 11-13)

Agenda for First DSPR Meeting, 1999 January 11-13, Las Vegas, Nevada

With logistical support from the MTS and USDOE the DSPR Panel convened a meeting January 11-13, 1999 to obtain an overview of the work being performed by the YMP in the area of Drift Seepage. The meeting involved technical presentations and discussions with the Drift Seepage Principal Investigators at the Santa Fe Hotel and Casino, Las Vegas (January 11 and 13) and a field visit to the Exploratory Studies Facility (ESF) to view the drift seepage observations and experiments (January 12). The planned agenda for the meeting was as follows:

Monday, January 11th - Technical Presentations, Santa Fe Hotel/Casino

7:30 Introduction – Comments from MTS and Cliff Davison, Panel Chairman
8:00 Overview of Conceptual and Numerical Model of Yucca Mountain
Presented by: Bo Bodvarsson, Lawrence Berkeley National Laboratory
9:00 Approach of Field Test Investigations of Seepage into Drifts
Presented by: Joe Wang, Lawrence Berkeley National Laboratory
9:30 Break (15 minutes)
9:45 Drift Seepage Experiments Conducted in ESF Niches
Presented by: Rob Trautz and Paul Cook, Lawrence Berkeley National Laboratory
10:45 Infiltration Experiment Conducted in ESF Alcove 1
Presented by: Alan Flint, United States Geological Survey
11:30 Lithophysal Cavity Fillings: Mineralogic Evidence Relevant to Drift Seepage
Presented by: Brian Marshall, United States Geological Survey
12:15 LUNCH
1:45 Migration Below the Drift, Effect of Ventilation on Seepage, and Moisture Monitoring Studies in the ESF
Presented by: Stefan Finsterle and Joe Wang, Lawrence Berkeley National Laboratory and Alan Flint, United States Geological Survey
2:30 TSw Fracture-Matrix Interaction Experiment in ESF Alcove 6
Presented by: Rohit Salve and Jerry Fairley, Lawrence Berkeley National Laboratory
3:15 PTn Fault Flow and Matrix Flow Experiment in ESF Alcove 4
Presented by: Curt Oldenburg and Rohit Salve, Lawrence Berkeley National Laboratory
4:00 Break (15 minutes)
4:15 Open Discussion (various topics)
5:00 Meeting with Peer Review Panel and MTS (Review Manager and Technical Coordinator)

Tuesday, January 12th - Field Trip to Exploratory Studies Facility

Field trip to the Exploratory Studies Facility to see locations and conditions under which the infiltration, fracture-matrix interaction, fault and matrix tests, moisture monitoring, and seepage experiments have been conducted. Field trip attendance was limited to the members of the Drift Seepage Peer Review Panel and selected representatives from USNRC, NWTRB, DOE, MTS and M&O/NEPO. Scientists from the M&O and the USGS were available at various locations within the tunnel to discuss their respective tests and experiments.

6:00 Pick up members of Peer Review Panel at main entrance to the Santa Fe Hotel & Casino and travel to Nevada Test Site.

7:30 Arrive at NTS Gate 100 and obtain access badges.
7:50 Leave Gate 100 and travel to Field Operations Center (FOC), Area 25.
8:20 Arrive FOC and pick up safety equipment (radio, safety glasses, hard hats).
8:30 Leave FOC and proceed to ESF pad.
8:45 Arrive ESF and view underground safety video to obtain ESF Visitor access cards.
9:00 Arrive ESF North Portal and board man-train for travel into the tunnel.

Niche 3 & Cross Over point	(seepage testing - TSw)
Niche 2 and Alcove 6	(seepage and fracture-matrix testing - TSw)
Alcove 4	(fault and matrix flow tests - PTn)
Cross Drift	(moisture monitoring/effects of ventilation TSw)
Alcove 1	(infiltration experiment - TCw)
Alcove 5	(thermal testing alcove - TSw)

4:00 Travel from ESF to Busted Butte

Busted Butte	(UZ transport experiments -. CHn)

Wednesday, January 13th - Resumption of Technical Presentations, Santa Fe Hotel & Casino

7:45 Introduction – Comments from MTS and Cliff Davison, Panel Chairman
8:00 Analysis and Interpretation of Seepage with the Drift Scale Model
Presented by: Stefan Finsterle, Lawrence Berkeley National Laboratory
9:00 Assessment and Prediction of Seepage with the Drift Scale Model
Presented by: Chin-Fu Tsang, Lawrence Berkeley National Laboratory
10:00 Importance of Seepage to TSPA and Alternative "Weeps" Model
Presented by: Mike Wilson, Sandia National Laboratory
10:45 Break (15 minutes)
11:15 Open Discussion (various topics; use this time to address topics such as film flow, chaos theory, tunnel surface geometry, wetting front instability/fingering)
12:00 LUNCH
1:30 Afternoon session involving meetings between DSPR Panel members, the MTS and USDOE staff . The Panel used this time to:

1. assess what they have heard and seen so far and make requests and/or recommendations for further material to review,
2. proceed with internal panel business (structure of Panel Report, schedule, coordination of writing assignments, etc.)
3. pursue any other items or actions they deemed appropriate.

APPENDIX 4: BRIEF ILLUSTRATED DISCUSSION OF SCALE DEPENDENCE OF DESCRIBING FLOW THROUGH FRACTURE NETWORKS AND THE REV CONCEPT: ISSUES FOR THE YMP TO CONSIDER

BRIEF ILLUSTRATED DISCUSSION OF SCALE DEPENDENCE OF DESCRIBING FLOW THROUGH FRACTURE NETWORKS AND THE REV CONCEPT: ISSUES FOR THE YMP TO CONSIDER

The current YMP strategy for calculating effective hydrologic properties for the stochastic modeling of moisture flow appears to be based upon pneumatic testing of packer intervals: using these values directly; or else using the numerical inversion routines in ITOUGH2 to determine parameter values that match moisture flow data. It is not unanimously clear to us that either of these methods for calculating effective hydrologic properties can produce sufficiently accurate parameter values for drift seepage modeling and we offer the following illustrative examples and discussion to point out the pitfalls that can arise in applying these techniques to describe flow through fracture networks.

Figure A.4.1 shows a hypothetical fracture pattern and some 2D square elements. The goal of effective properties is to calculate values for flow parameters, such as permeability, for each grid cell that enables the grid cell to mimic the flow effects of the fracture network (and the rock matrix if the matrix is permeable). The diagram shows that all four squares have continuous fracture pathways from the bottom of the cell to the top. Likewise, cells A and B have continuous fracture paths from left to right. In order to correctly represent the permeability of each of these cells, all four would require some component of fracture permeability in the up-down direction, and cells A and B would require fracture permeability in the left-right direction. This would make it possible for moisture to flow from the top of the model to the bottom or from the left edge to the right.

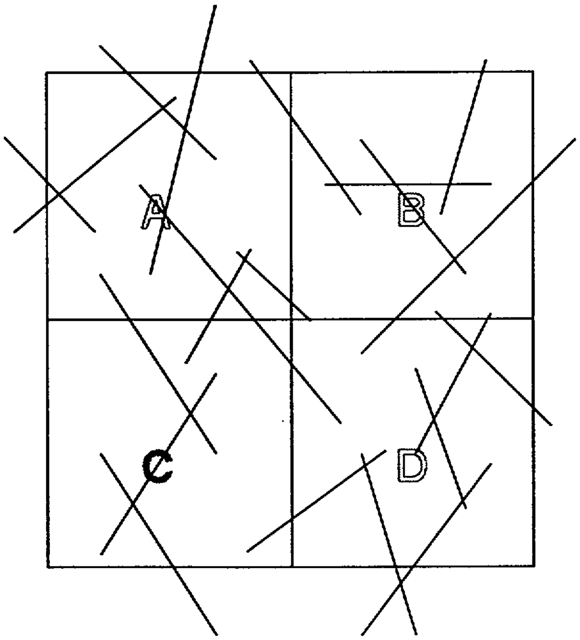

Figure A.4.1

However, when moisture flow is considered on a larger scale, we find that this representation is not correct and could lead to erroneous results. Consider the same diagram, but now as a single larger grid cell (Figure A.4.2).

Figure A.4.2 shows that in fact there is no continuous fracture pathway connecting the top of the model to the bottom, or the left side of the model to the right. Rather, the fracture network is compartmentalized, as shown by the lines we have added to the diagram to separate the fractures into separate clusters. If moisture were introduced to the top of the model, it would not percolate via fracture pathways to the bottom of the model. However, an effective parameter calculation would suggest that continuous percolation would occur, when in fact it could not. Work at the Kamaishi mine in Japan has demonstrated that this type of fracture network compartmentalization occurs at the drift scale. Work in fractured oil reservoirs indicates that compartmentalization of the connectivity of fracture networks is common at larger scales as well.

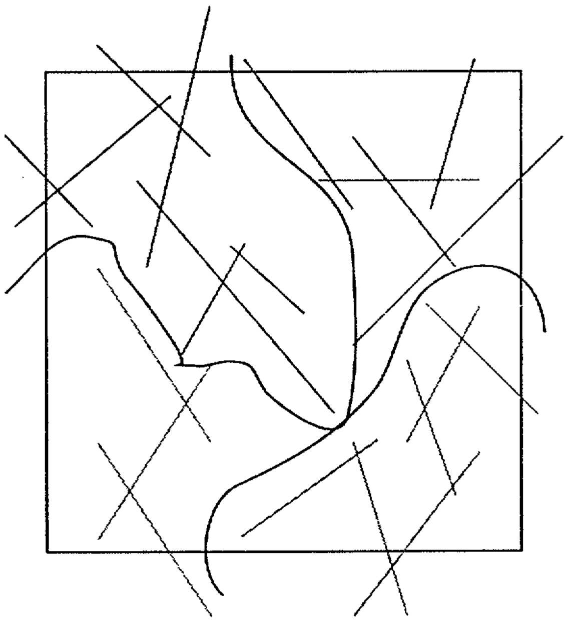

Figure A.4.2

The opposite situation can also occur. Consider Figure A.4.3. Not one of the four grid cells has a continuous pathway from top to bottom or from left to right that is completely contained within the grid cell. This would imply that the effective fracture network permeability in each grid cell is 0.0. However, there are continuous fracture pathways from top to bottom at a larger scale. In this instance, there would be percolation from the top of the model to the bottom through the fracture network, whereas an effective parameter calculation would indicate that there could be none.

Another interesting challenge in calculating effective parameter values for describing moisture percolation through fracture networks is shown in grid cell D of this example in Figure A.4.3.

Presumably, water could be introduced to the fracture on the right side of D and it would flow out the fracture at the bottom of D. To represent this as a tensor, one would have to have a non-zero value for the off-diagonal component, or Kxy. However, there is no component for Kxx or Kyy: they are 0.0. Moreover, as shown by studies of the electrical resistance of line patterns (La Pointe and Hudson 1985), the principal directions of resistance (or conductivity) are not necessarily orthogonal, nor are they limited to two directions even in 2D line patterns. Both these situations are very difficult to capture through a symmetric permeability tensor that underlies the effective permeability parameter approach.

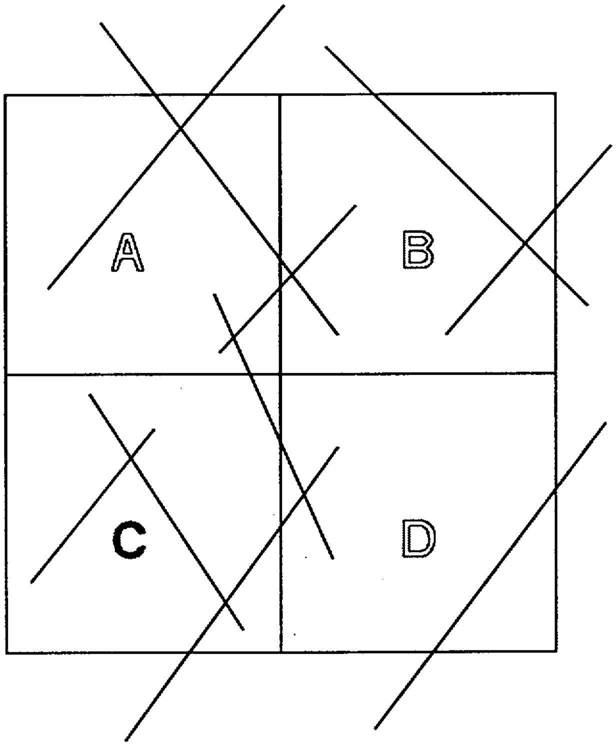

Figure A.4.3

The above examples illustrate the related problem of using parameter values of flow in fractured rocks obtained at one scale by field measurements for use in modeling at another scale. For example, the permeability measured at a 5-meter testing scale may not be representative of what would be seen at a 50 m modeling scale. The scaling of flow and transport properties must be taken into account in SC modeling. Often this is done by suggesting that a Representative Elementary Volume (REV) exists for the fractured rock. The REV is the scale at which the rock can be represented as a continuum and properties at scales greater than the REV can be calculated from measurements at the REV scale. However, there may be some problems with applying the REV concept to Yucca Mountain, as suggested by the comments below:

- "It should be noted that in a fractured medium, the size of the REV may be quite astonishingly large" (De Marsily 1986, pg. 16).

- "The scale at which the continuum approximation is justified [for fractured rock] can be difficult to quantify and in fact may not be justified at the scale of interest, or, for that matter, at any scale" (NRC 1996, pg 331).
- "The concept of the REV may be irrelevant to most field measurements, especially in fractured rock" (NRC, 1996, pg 331).
- "In most circumstances, and especially in multiscale media of the kind fractured rocks are thought to be, an REV can never be defined...There may be a broad class of hydrological problems that are not amenable to analysis with conventional continuum models. This concern is particularly relevant in the case of solute transport" (NRC, 1996, pg. 331).

REFERENCES

De Marsily, G. 1986. Quantitative hydrolgeology. Academic Press Inc., Orlando, FL, 440 p.

La Pointe, P.R. and J.A. Hudson. 1985. Characterization and interpretation of rock mass joint patterns. Geological Society of America, Special Paper 199.

NRC. 1996. Rock Fractures and Fluid Flow: Contemporary understanding and application. U.S. National Committee for Rock Mechanics, National Research Council, National Academy Press, Washington, D.C., 551 p.