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Civilian Radioactive Waste Management System
Management & Operating Contractor

Saturated Zone Flow and Transport Expert Elicitation Project

January 1998

Prepared for:

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Civilian Radioactive Waste Management System
Management & Operating Contractor

Final Report
Saturated Zone Flow and Transport Expert Elicitation Project
January 29, 1998

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1.0 INTRODUCTION

1.1 OBJECTIVES

This report presents results of the Saturated Zone Flow and Transport Expert Elicitation (SZEE) project for Yucca Mountain, Nevada. This project was sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants, Inc. (Geomatrix). for TRW Environmental Safety Systems, Inc. The DOE's Yucca Mountain Site Characterization Project (referred to as the YMP) is intended to evaluate the suitability of the site for construction of a mined geologic repository for the permanent disposal of spent nuclear fuel and high-level radioactive waste. The SZEE project is one of several that involve the elicitation of experts to characterize the knowledge and uncertainties regarding key inputs to the Yucca Mountain Total System Performance Assessment (TSPA). The objective of the current project was to characterize the uncertainties associated with certain key issues related to the saturated zone system in the Yucca Mountain area and downgradient region. An understanding of saturated zone processes is critical to evaluating the performance of the potential high-level nuclear waste repository at Yucca Mountain.

A major goal of the project was to capture the uncertainties involved in assessing the saturated flow processes, including uncertainty in both the *models* used to represent the physical processes controlling saturated zone flow and transport, and the *parameter values* used in the models. So that the analysis included a wide range of perspectives, multiple individual judgments were elicited from members of an expert panel. The panel members, who were experts from within and outside the Yucca Mountain project, represented a range of experience and expertise. A deliberate process was followed in facilitating interactions among the experts, in training them to express their uncertainties, and in eliciting their interpretations. The resulting assessments and probability distributions, therefore, provide a reasonable aggregate representation of the knowledge and uncertainties about key issues regarding the saturated zone at the Yucca Mountain site.

1.2 RELATIONSHIP OF SZEE PROJECT TO STUDIES OF THE SATURATED ZONE AT YUCCA MOUNTAIN

The SZEE study has two principal purposes: (1) to quantify uncertainties associated with certain key issues in the Total System Performance Assessment (TSPA): and (2) to provide a perspective on modeling and data collection activities that may help to characterize and reduce uncertainties. The next iteration of the TSPA will be conducted for the Viability Assessment (VA) for Yucca Mountain. The TSPA-VA provides a probabilistic assessment of the performance of the potential repository based on the information developed through site characterization and repository design. The technical components of the TSPA are intended to incorporate a range of knowledge and uncertainties. As such, the expert panel's assessment of key technical issues related to the saturated zone—including the expressions of uncertainty—will be directly applicable to the TSPA-VA. For example, an important issue addressed by the experts is the magnitude and direction of advective flux in the saturated zone beneath Yucca Mountain. The expression of uncertainties associated with this assessment across the panel of experts will provide a reasonable basis for the TSPA-VA.

If the Yucca Mountain site is deemed suitable for repository development, the repository would be constructed in the unsaturated zone in welded tuff at a depth of about 250 meters below land surface and a distance of about 250 meters above the regional water table. The potential repository block consists of an eastward-tilted, fault-bounded structural block composed of alternating welded and nonwelded tuffs of Miocene age. The welded tuffs are typified by low rock/matrix porosities and permeabilities and by high fracture densities. The nonwelded tuffs typically have relatively high matrix porosities and permeabilities and are relatively unfractured. Based largely on degree of welding, the tuffs within the unsaturated zone at Yucca Mountain are grouped informally into hydrogeologic units that, from the surface down, are termed the Tiva Canyon welded (TCw) unit, the Paintbrush nonwelded (PTn) unit, the Topopah Springs welded (TSw) unit, the Calico Hills nonwelded (CHn) unit, and the Crater Flat undifferentiated (CFu) unit. The host rock at the potential repository consists of densely welded ash-flow tuff within the TSw unit. Beneath the water table, the saturated zone includes a "lower volcanic aquifer" that consists of the Prow Pass, Bullfrog, and Tram formations.

The SZEE study is intended to complement the ongoing modeling, testing, and data collection programs (conducted principally by the U.S. Geological Survey [USGS] and Los Alamos National Laboratory [LANL]) while contributing to the performance assessment (conducted by the M&O). The SZEE experts were given detailed summaries and presentations of available data, models, and the progress being made in various components of the modeling and testing program,. The focus of the SZEE project was on evaluating the uncertainties associated with the various models, parameters, and components of the SZ regional and site-scale models, as well as providing an independent perspective on the approaches taken in the models. As such, the SZEE project is a logical step in the saturated zone program for the Yucca Mountain project.

The Viability Assessment will rely largely on the next round of performance assessment (TSPA-VA). The TSPA-VA will be an assessment at a particular point in time of the level of knowledge and uncertainties regarding the site characteristics and engineered system that affect performance of the potential repository system. As such, the performance assessment requires a reasonably complete description of all key processes affecting performance, including saturated zone flow processes. Further, the TSPA, as a probabilistic analysis, will include appropriate expressions of uncertainties. The quantification of uncertainties at any given time does not imply that issues have been resolved, that additional data should not be gathered, or that the issues will not be revisited during subsequent evaluations (e.g., licensing). A goal of the SZEE project is to support the TSPA-VA by providing an expression of uncertainties regarding key issues for the saturated zone. This expression has been developed by experts from both within and outside the YMP. As such, results of the SZEE study are realistic and defensible assessments at this point in the characterization program for Yucca Mountain. In addition to providing inputs to the TSPA-VA, the results of the study can also provide a focus for subsequent data collection activities aimed at reducing key uncertainties.

1.3 ORGANIZATION

The SZEE project was comprised four primary groups: the SZEE contractor, the methodology development team (MDT), the expert panel, and the technical specialists. The principal responsibilities of each group are described here; the technical roles of each group are described in detail in Section 2.2 of this report.

SZEE Contractor: Under contract with TRW, the SZEE contractor, Geomatrix, was responsible for conducting all aspects of the project and for delivering this report describing the methodology and the results. The SZEE contractor personnel also were members of the MDT.

Methodology Development Team (MDT): As a group, the MDT served both to carry out the project and to review the progress of the project. Direct participation included developing a project plan, facilitating workshops, eliciting members of the expert panel, and documenting the methodology and results. The review role included reviewing the progress of the study and recommending mid-course adjustments to ensure that the study met its objectives. The members of the MDT and their responsibilities for the SZEE project are summarized in Table 1-1.

Expert Panel: The five widely recognized scientists on the expert panel were responsible for providing and documenting their judgments regarding models, parameters, and uncertainties about saturated zone flow processes at Yucca Mountain. These subject-matter experts were responsible for developing the interpretations that form the technical substance of the SZEE project. Table 1-2 lists the experts on the panel and their affiliations. Brief biographies for members of the expert panel are provided in Appendix A.

Technical Specialists: Numerous technical specialists participated in the project by providing the experts with specialized data, interpretations, or training through workshops and a field trip. A list of the technical specialists and their affiliations is given in Table 1-3. In some cases, members of both the MDT and the expert panel also acted as technical specialists.

1.4 PRODUCTS OF STUDY AND STRUCTURE OF REPORT

The SZEE study was conducted in approximately six months. The project began with developing a plan for the course of the study and identifying the goals to be accomplished and methodologies to be implemented in meeting these goals. Next, the MDT developed and implemented a process for selecting the members of the expert panel, resulting in the selection of five experts. The bulk of the study was centered around three workshops and one field trip. These activities were designed to facilitate interaction among the experts, provide all data needed for their assessments, and provide a forum for discussing a range of technical interpretations. Following the third workshop, the interpretations of each expert were elicited in individual interviews and documented in elicitation summaries. After reviewing the elicitation summaries of all members of the expert panel. the experts finalized their assessments.

This report contains the products of the SZEE project outlined above. Section 2 describes in detail the process followed in eliciting the expert interpretations. Appendices B and C provide summaries of the references and reports provided to the experts. and of the three workshops and the field trip. This information provides written documentation of the technical data discussed by the panel, the formats and content of interpretations presented by outside technical specialists during the study, and the expert panel's preliminary interpretations.

Section 3 of this report presents in detail the final interpretations provided by the expert panel and the results of the study. Both the results for each of the five individual experts and the aggregated results are discussed. Key products of the study are the written elicitation summaries prepared by each expert, which are provided in Appendix D. The experts expended considerable effort to ensure that their summaries provide a reasonably complete record of the thought process they followed in arriving at their interpretations. Information related to quality assurance is provided in Appendix E.

TABLE 1-1
METHODOLOGY DEVELOPMENT TEAM MEMBERS AND THEIR PRINCIPAL RESPONSIBILITIES

NAME	AFFILIATION	RESPONSIBILITIES
Kevin J. Coppersmith	Geomatrix Consultants, Inc.	Project management and planning; methodology development; facilitating workshops; documentation
Roseanne C. Perman	Geomatrix Consultants, Inc.	Project planning and methodology development; organizing workshops and field trip; documentation
Robert R. Youngs	Geomatrix Consultants, Inc.	Project planning and methodology development; documentation of results
Russ Patterson	U.S. Department of Energy	Project planning and oversight; review of project direction
William W. Arnold	Sandia National Laboratories	Project planning and methodology development; workshop planning; documentation
Dwight Hoxie	U.S. Geological Survey	Project planning and methodology development; workshop planning, documentation; documentation
Peter A. Morris	Applied Decision Analysis	Project planning and methodology development; peer review of project direction; expert elicitation methodologies
Martha W. Pendleton	M&O/Woodward-Clyde Federal Services	Project planning and oversight; expert selection process; review of project direction
Patrick Tucci	U.S. Geological Survey	Project planning and methodology development; workshop planning, documentation

TABLE 1-2
EXPERT PANEL MEMBERS

EXPERT	AFFILIATION
R. Allan Freeze	R. Allan Freeze Engineering, Inc.
Lynn W. Gelhar	Massachusetts Institute of Technology
Donald Langmuir	Colorado School of Mines (Emeritus)
Shlomo P. Neuman	University of Arizona
Chin-Fu Tsang	Lawrence Berkeley National Laboratory

TABLE 1-3
TECHNICAL SPECIALISTS PARTICIPATING IN SZEE WORKSHOPS *

WORKSHOP 1 – SIGNIFICANT ISSUES AND AVAILABLE DATA	
John B. Czarnecki	U.S. Geological Survey
Frank A. D'Agnese	U.S. Geological Survey
William W. Dudley	U.S. Geological Survey
Claudia C. Faunt	U.S. Geological Survey
Richard M. Forester	U.S. Geological Survey
Robert Graves	U.S. Geological Survey
Edward M. Kwicklis	U.S. Geological Survey
Arend Meijer	Los Alamos National Laboratory/GCX, Inc.
Grady M. O'Brien	U.S. Geological Survey
James B. Paces	U.S. Geological Survey
Zell Peterman	U.S. Geological Survey
John H. Sass	U.S. Geological Survey
William Steinkampf	U.S. Geological Survey
Chuck Svard	U.S. Geological Survey
Inez R. Triay	Los Alamos National Laboratory
Amjad M.J. Umari	U.S. Geological Survey
David Vaniman	Los Alamos National Laboratory
WORKSHOP 2 - ALTERNATIVE MODELS AND INTERPRETATIONS	
George E. Barr	Sandia National Laboratory
Neil Coleman	U.S. Nuclear Regulatory Commission
D. Cooley	U.S. Geological Survey
John B. Czarnecki	U.S. Geological Survey
Frank A. D'Agnese	U.S. Geological Survey
William W. Dudley	Sandia National Laboratory
Claudia C. Faunt	U.S. Geological Survey
Mary C. Hill	U.S. Geological Survey
John Kessler	Electric Power Research Institute
Linda Lehman	State of Nevada
Bruce A. Robinson	Los Alamos National Laboratory
Jake Turin	Los Alamos National Laboratory
Rick Waddell	HSI/Geotrans
Gordon Wittmeyer	Center for Nuclear Waste Regulatory Analyses
George Zyvoloski	Los Alamos National Laboratory

* Some members of the MDT and the expert panel also acted as technical specialists at the workshops. Their names are not repeated here.

3.0 ASSESSMENT OF KEY ISSUES

3.1 INTRODUCTION

The experts involved in the Saturated Zone Flow and Transport Expert Elicitation (SZEE) addressed a variety of technical issues related to the saturated zone beneath the potential repository at Yucca Mountain and the downgradient flow system. The key issues that the SZEE panel was asked to address are given in Table 3-1. Included are issues important to the Total System Performance Assessment ([TSPA]; e.g., hydraulic conductivities of hydrogeologic units, flux at the water table beneath the site, dilution and dispersivity, and hydrochemical transport parameters of key radionuclides). In addition, the experts were asked to provide their perspectives on issues related to conceptual models and groundwater flow modeling (for instance, cause and importance of the large hydraulic gradient north of the site, impact of climate change on saturated-zone hydrology, controls on dilution and dispersion, importance of the repository thermal load on saturated zone hydrologic properties). Finally, the experts were asked for their perspectives on additional data collection or modeling activities that could serve to reduce the uncertainties in the characterization of the saturated zone flow and transport system. The experts' evaluations are given in their elicitation summaries (Appendix D) and are summarized in Table 3-2 and this section.

It is important to remember the context of the experts' evaluations. First, the goal of this expert elicitation was to quantify the *uncertainties* associated with various aspects of the saturated zone hydrologic system so that the TSPA-VA can incorporate a range of uncertainty when modeling important processes. As a result, the experts focused considerable attention on what is known from the available Yucca Mountain data and *what is not known*, and the reasons for that lack of knowledge. The reasons could include data gaps, complexities in the flow system, nonpertinent data, or multiple models consistent with the data. Rather than merely identifying and acknowledging the uncertainties, the experts were required to provide—to the extent possible—their quantification of the uncertainties for certain key issues with reference to the technical literature when applicable. For example, the experts provided their assessments of the hydraulic conductivities of the key hydrogeologic units beneath the site and downgradient from the site, utilizing Yucca Mountain data bases that they considered most pertinent as well as their own experience. Likewise, the experts characterized their knowledge and uncertainty regarding the mechanisms for dilution of contaminants in the saturated zone. In light of the very sparse data gathered for the Yucca Mountain site, their assessments of the degree of dilution that might be expected in the downgradient flow paths express a large degree of uncertainty.

It is also important to note that the experts' evaluations are, to a large extent, an expression of the professional judgment of each expert and are not based on extensive modeling or calculations carried out for this study. These judgments are derived not only from a consideration of Yucca Mountain data, but also data and observations from previous experience at analogous sites. Members of the panel were given a limited time in which to review Yucca Mountain data sets, test results, and models. Further, the experts were unable within the time-frame of the project to conduct their own analyses and calculations. In many cases, the experts relied on the results of analyses presented in workshops by the Yucca Mountain researchers, their colleagues on the panel, or other researchers.

The results of the SZEE expert assessments have potential application in both the upcoming TSPA-VA and the ongoing site characterization program. The TSPA is a probabilistic analysis that is capable of incorporating uncertainties, including those expressed by the SZEE expert panel. The panel members reviewed the saturated zone process modeling carried out for the previous iteration of the TSPA (TSPA-95). By focusing on the issues of most importance to the TSPA, their evaluations will provide useful information on parameter uncertainties and will improve the models to make them more realistic and to better characterize the uncertainties. Likewise, comments made by the panel on the attributes and suggested improvements the regional framework and site-scale hydrologic models will help to improve those models as well. Several members of the panel have considerable experience in designing and conducting field-testing programs and provided advice regarding focused experiments that, they believe, could reduce significantly the present level of uncertainty. For example, most members of the panel applauded the C-well hydraulic and tracer tests and encouraged continuation of large-scale, long-term tests of this kind to provide realistic hydraulic properties over the scales of interest to performance assessment.

3.2 SUMMARY OF EXPERT INTERPRETATIONS

This section summarizes the interpretations made by members of the SZEE panel regarding certain key issues related to flow and transport in the saturated zone at Yucca Mountain. The intent is to provide the reader with a perspective on the evaluations made by the experts, the manner in which each issue was addressed, an overview of the technical bases for the interpretations, the uncertainties identified by the experts, and the degree of convergence or divergence in the aggregate range of interpretations across the panel. The summary here is not intended to be exhaustive. For a more complete exposition of the interpretations made by the experts, the reader is directed to the elicitation summaries given in Appendix D.

The key issues shown in Table 3-2 are discussed below.

3.2.1 Overview: Conceptualization of Saturated Zone Groundwater Flow

The experts were asked to consider the saturated zone flow system within the region (defined by the boundaries of the regional hydrologic model) and to focus on the site-scale within a few kilometers of the Yucca Mountain site. Their conceptual models deal with issues that are important to saturated zone flow and transport in the area beneath the site and downgradient to distances of 5 to 30 km, which are presumed distances to potential receptor locations.

The experts reviewed the available data related to the regional and site-scale groundwater flow models and, based on this review, concluded that the dominant flow direction from the YM potential repository site in the saturated zone is to the southeast to Fortymile Wash and thence south to Amargosa Valley. The primary hydrogeologic units of interest carrying flow at Yucca Mountain are the "lower volcanic aquifer," consisting of the

Upper Tram, Bullfrog, and Prow Pass formations; the volcanic aquitards or confining units of the Calico Hills Formation; the Paleozoic carbonate aquifer; and the valley fill alluvium. All of the experts expressed a belief that the downgradient flowpaths from Yucca Mountain likely occur within the lower volcanic aquifer and, farther south, within the valley fill alluvium, but likely do not include the carbonate aquifer. The principal basis for this conclusion is evidence for elevated hydraulic heads within the carbonate aquifer in the Yucca Mountain area. There are few data from southeast of Yucca Mountain to constrain this interpretation, and the regional groundwater model suggests that the flowpaths may enter the carbonate aquifer at distances of 10 km from the site and then rise back into the volcanics and alluvium farther downgradient.

In general the regional hydrologic environment is assessed by the experts to be complex and to be characterized by high permeabilities. Faults and major fractures are important components of this flow regime, and the hydrogeologic units are more important for identifying the nature of fracturing and faulting than for their matrix characteristics. It is noted by the panel that most of the flow appears to be channelized in preferential flow paths, which, based on flowmeter data, appear to represent only 5 to 20 percent of the thickness of the hydrostratigraphic units. At regional distances of several kilometers, the system appears to be highly interconnected. The role of major faults and fracture systems is judged to be very important, although it is not clear to what extent these features need to be—or accurately can be—included explicitly in the hydrologic models. An alternative would be to account for them with "effective" hydraulic properties of the hydrogeologic units. Drs. Freeze and Neuman note that, although the present regional and site-scale models account for faults as vertical disruptions of hydrostratigraphic units, the faults themselves may have their own hydraulic properties. Dr. Freeze concludes that they may be highly transmissive along strike, but have low transmisivity perpendicular to their trend.

Several experts note that although the regional and site-scale hydrologic models are being used to account for available data sets, they are not yet at a sufficient degree of development to provide accurate predictions of certain key parameters such as the flux beneath the site. Likewise, it is noted that the two models have not yet been made completely consistent between themselves. In the absence of significant transients due to pumping or other influences, Dr. Freeze concludes that a steady-state assumption probably is appropriate for the analysis at the scales of the present models.

As will be seen in later assessments of hydraulic parameters, most of the experts make their assessments based on data gathered at scales that are comparable to the scales of the hydrologic models (e.g., several hundred meters to a few kilometers), rather than single-hole tests or laboratory tests. The experts judge that the most significant data set of this type derives from the C-well hydraulic tests.

3.2.2 Large Hydraulic Gradient

The experts on the SZEE panel were asked to provide their perspectives on the so-called "large hydraulic gradient" north of the site. Specifically, they were asked for their assessment of the probable cause of the feature, its potential importance to understanding the saturated zone, and the potential for significant short- or long-term changes in the feature. At the workshops, the panel was exposed to discussions of alternative interpretations of the feature based on the available data.

In general, the experts boiled down the various hypotheses for the cause of the feature to two basic models having any significant credibility, which were summarized and discussed by Drs. Neuman and Freeze at the third workshop. In the "saturated zone" model, the feature is interpreted to be the result of a water table slope within a fully saturated flow system and is related to topography, recharge patterns, and geology. Dr. Freeze notes that geologic features could include a vertical low-permeability feature, a horizontal low-permeability feature, or a deep drain. In the "perched water" model, the flow system consists of an upper saturated zone underlain by a wedge of unsaturated rocks over the regional water table. It is acknowledged by proponents of both models that, if it exists, the wedge of unsaturated rocks probably is very close to saturation.

Across the panel, the perched zone model is slightly preferred based on the available data. It is noted, however, that the differences between the perched and saturated models is merely the degree of saturation of the "wedge" between the upper and lower water table. It should also be noted that a wide array of hypotheses for the origin of the feature were not given significant credibility by the panel.

There were differences of opinion across the panel regarding the importance of the large hydraulic gradient. Dr. Neuman concludes that the feature is unique in the region because it does not appear to correspond to any obvious geologic feature, and its importance lies in incorporating it into an understanding of the site hydrogeology and in reducing the uncertainty in representations of flow and transport in the Yucca Mountain area, including defining inflow boundary conditions for the site groundwater flow model. Drs. Freeze, Tsang, and Gelhar conclude that the feature is not unique in the region and do not believe that resolving the cause of the feature has significant implications to the saturated zone issues. Dr. Gelhar notes that its real significance may be in indicating the presence of low-permeability zones and perched water, which likely will be more extensive with climate change.

Finally, the experts conclude that the probability of any large transient change in the configuration of the large hydraulic gradient (e.g., a sudden "breakthrough" of the feature) due to earthquakes or other mechanism is extremely low. Further, long-term transient readjustment of gradients is given a very low probability. Dr. Neuman notes that during wetter glacial periods, the "wedge" of unsaturated Calico Hills aquitard rocks may become fully saturated, perhaps leading to a decrease in the gradient.

3.2.3 Flux Beneath Yucca Mountain

An important input to the TSPA is the magnitude and orientation of flux at the top of the saturated zone beneath Yucca Mountain. All of the experts addressing this issue provided their assessments of flux as an estimate of specific discharge, q, which is related by Darcy's Law

$$q = Ki$$

to the hydraulic conductivity, K, and the hydraulic gradient, i.

At the water table beneath the site the dominant aquifer carrying the flow is the "lower volcanic aquifer" in the site-scale hydrologic model, which consists of the Prow Pass, upper and lower Bullfrog, and Tram formations, with the lower Bullfrog being the most transmissive. Therefore, the estimates of hydraulic conductivity are given for this hydrogeologic unit as well as the other hydrogeologic units in the site-scale model, including the volcanic aquitard or confining unit (represented by the Calico Hills Formation), valley-fill alluvium, and the Paleozoic carbonate aquifer. Dr. Neuman also provides his assessment of the hydraulic conductivity of the upper volcanic aquifer, which is the Topopah Springs Formation.

Because the application of the assessed hydraulic parameters is at the scale of the current site-scale model (elements of 1500 x 1500 x 100 m), the parameters are given as averages over the scales of the various hydrogeologic units. The experts note that their parameters reflect the influence of major fractures and perhaps small faults at these scales; major faults and fault zones are generally assigned their own hydraulic conductivity values. It is noted by the experts that the ranges of the local averages that they provide is far less than the expected point-scale variabilities. Although the hydraulic gradient in the site area is subject to uncertainty, its relative contribution to the uncertainty in specific discharge is small. The experts, therefore, focused their attention on the uncertainties in hydraulic conductivity.

Hydraulic Conductivity

The data sets that the experts used to arrive at their assessments of hydraulic conductivities for the hydrogeologic units included single-hole tests, multiple-hole tests, and experience at other locations. In general, the heaviest reliance was placed on multiple-hole pumping tests at the C-wells. Because the single-hole tests may not sample the larger interconnectivity of the system and local transmissive zones, they may underestimate the hydraulic conductivity. Although there are relatively few data, the C-wells tests are judged to sample a larger area comparable to the element size of the site-scale hydrologic model. In most cases, the experts provide a range of hydraulic conductivity values that is wider than those obtained from the C-wells studies, reflecting their uncertainty in the range of conductivities that might characterize the units at other locations within the region.

The hydraulic conductivity estimates assessed for the hydrogeologic units are shown in Figures 3-1a through 3-1n. For comparison purposes, the probability distributions are given as cumulative distribution functions (CDF). Also given is the composite CDF, which combines the assessments of the individual experts, assuming their assessments are weighted equally.

Specific Discharge

The assessed hydraulic gradient in the site vicinity is approximately 0.0003 to the southeast. Dr. Neuman notes that, because of its low amplitude and the relative few data, the absolute value of the gradient and its direction are uncertain; he uses a range of 0.0001 to 0.0004.

Based on the assessed gradient and hydraulic conductivities, the specific discharge is assessed. Because the lower volcanic hydrogeologic unit is at the water table beneath the site, the experts' specific discharge values are based primarily on the hydraulic conductivity values for this unit (or the Bullfrog unit, which is the thickest and most transmissive component of the lower volcanic hydrogeologic unit). The CDFs for specific discharge are shown in Figures 3-2a through 3-2e.

Some of the experts also provided estimates of average velocity, v

$$v = q/n$$

where n is the average porosity. Estimates of average porosity for the various units are based primarily on each expert's experience with comparable units elsewhere.

3.2.4 Influence of Climate Change

The SZEE experts were asked for their judgments regarding the influence that future climate change might have on the saturated zone flow system, particularly related to changes in water table elevation or changes in the flow system downgradient from the repository.

The experts generally agree that the position of future water table changes related to future climate change are best estimated by evaluations of past water table changes associated with previous glacial periods. The geochemical and paleodischarge evidence for past elevations of about 80 to 120 m above their present level is generally endorsed by the panel as being reasonable. It is noted by some of the experts that a particular purpose of the regional hydrologic model—once properly calibrated—should be to provide estimates of the influence of climate change on the hydrologic system. Dr. Gelhar notes, however, that at the present time the uncertainties associated with using the regional model in this way could lead to predicted water table changes that are unreasonable relative to the levels interpreted from other data.

It is concluded that changes in the flow system during wetter glacial periods could lead to more transients, perhaps changes in flow direction and hence greater dilution, and changes in flux levels. All of these could affect the processes that affect the dispersion and dilution of a contaminant plume. However, it was also noted that these changes may not, in fact, occur over short time periods, thus allowing the system to adjust to a new steady state. Further, as noted by Dr. Gelhar, the magnitude of changes to hydraulic gradients and flux may not be large enough to lead to significant changes in dispersion and other flow system characteristics important to radionuclide transport.

3.2.5 Conceptual Models of Saturated Zone Transport

The experts provided their assessments of the key aspects of conceptual models of the saturated zone transport system and processes. It is noted that the primary transport mechanism for contaminants from the repository is advective transport, particularly along preferential flow paths. This transport is envisioned by most of the experts as occurring along flow tubes that emanate from beneath the repository and proceeding downgradient within the volcanic aquifer and the alluvium, with little or no flow in the carbonates.

Disregarding mixing within an extraction well, the experts conclude that the likely mechanisms for dilution of the contaminant plume are molecular diffusion and advective dispersion. They conclude that there are few mechanisms that lead to substantial mixing, such as turbulent eddies, transients, or fingering. In general, the experts reject a "stirred tank" model that assumes mixing at the water table of contaminants from the unsaturated zone with groundwater traveling horizontally in the saturated zone. Instead of a substantial "mixing depth," the experts judge that the contaminant plume will remain discrete, with little mixing at the water table, and lateral flow tubes in the saturated zone will be pushed deeper. The vertical width of the plume is estimated to be on the order of a few tens of meters, with dilution restricted to that which occurs through vertical dispersion. The experts generally conclude that there will be relatively small amounts of lateral and vertical dispersion along the flowpaths from the repository to distances of 5 to 30 km from the site.

Dr. Neuman argues that dispersion cannot be interpreted as dilution. He notes that a dispersion coefficient is an expression of the degree of resolution and is time- and scale-dependent. Dr. Gelhar concludes that longitudinal "macrodispersion" is controlled primarily by the degree of variation in hydraulic conductivity and its correlation scale. He and other experts also note that transverse dispersivity will have the strongest control on plume spreading and dilution for Yucca Mountain, and that transverse dispersivity is controlled by fluctuations in the direction of hydraulic gradients.

3.2.6 Dilution Factor/Dispersivity

The TSPA incorporates the degree of dilution that might occur at regional distances of 5 to 30 km. The experts'assessments are expressed as either a "dilution factor" or as estimates of dispersivity. "Dilution factor" is defined as the ratio between the initial contaminant concentration and the highest concentration at a point some distance from the source. According to Dr. Freeze, key assumptions for his assessment of dilution factors are: the contaminant source is tens to hundreds of meters in dimension; the source is steady and non-decaying; the distances of interest are 25 km ; and the assessment is for thousands of years after initiation. The assessment of dilution factors given by Drs. Tsang, Langmuir, and Freeze are shown in Figures 3-3a through 3-3c. The values range from 2 to 100, with a median estimate of about 12. Note that Dr. Tsang estimated a dilution factor of about 2 to 10 within flow channels (which is comparable to the assessments made by Drs. Langmuir and Freeze). He also provides an estimate of dilution factor that includes the capture zone of the production well, but, although recognizing the importance of this aspect, the other experts did not include dilution in the production well in their estimates.

Dr. Gelhar provides estimates of longitudinal and transverse dispersivity for distances of 5 and 30 km. Dr. Neuman suggests that high-resolution, statistically based conditional flow and transport calculations be conducted and that, as a crude rule of thumb, the longitudinal and transverse dispersivities should be fractions of the length of the local-scale grid cell.

3.2.7 Effective Fracture Density

Effective fracture density is defined as the average spacing of significant fractures that carry the flow. The estimates range from 10 to 100 m and are based primarily on the frequency of major fractures mapped in the Exploratory Studies Facility, detailed surface geologic mapping, and indications of flowing zones in pump tests. Dr. Freeze notes that, of the effective fractures for flow, only those in nonwelded, bedded, or zeolitized tuffs are effective from a dual-porosity, matrix-diffusion point of view.

3.2.8 Hydrochemical Transport Parameters

The principal transport parameters used by the TSPA are sorption coefficients (Kd) for radionuclides. In past TSPAs, a "minimum Kd" value was estimated for each radionuclide that represented a conservative value. In TSPA-VA a full probability distribution of Kd values will be defined and used to describe sorption behavior and its uncertainty. This approach is endorsed by Dr. Langmuir over the "minimum Kd" approach.

Dr. Langmuir notes that the approach taken by the Project, which considers only sorption reactions as the geochemical control on maximum concentrations, is highly conservative. He suggests that solubility and redox reactions also should be considered. As an example, Dr. Langmuir suggests that a key issue for radionuclide transport and retardation is whether or not—and the degree to which—flowpaths from the repository enter the carbonate aquifer at distances of 5 to 30 km because of the potential for adsorption of Np(V) by calcite. He concludes that adsorption of Np(V) by trace or minor minerals in the tuff, which are relatively ubiquitous and include Fe and Mn oxyhydroxides and calcite, could reduce Np concentrations in the rock matrix by orders of magnitude.

An important issue identified by the panel is the degree to which groundwater flow paths will include significant residence time in the rock matrix, thus allowing for matrix diffusion. Dr. Neuman suggests that the only direct evidence for possible matrix diffusion on a field scale is the separation of PFBA and bromide tracters in the C-wells tracer tests; he concludes that the results are somewhat ambiguous. He and Dr. Tsang would expect advection through the matrix to occur (perhaps represented by slow flow tubes) where fractures are not in direct contact (e.g., within strata-bound fractures).

A related issue is the degree to which the laboratory-derived sorption data are applicable to field conditions. Dr. Gelhar concludes that the laboratory-derived values cannot be used without knowing how representative they are of field conditions. Dr. Tsang cites recent cases where laboratory- and field-derived sorption studies have yielded comparable results—thus lending credibility to the use of laboratory results—but notes that the ten-fold discrepancy between C-wells data and laboratory data may imply that the flow-field is not properly conceptualized. Dr. Langmuir addresses this issue by providing a distribution of "effective Kd" values that considers the potential for various conditions and reactions along the flow path. In this way the effective Kd values can consider the laboratory sorption values as well as the conditions in the field that would cause them to be higher or lower, or to increase or decrease the range of uncertainty in Kd values. Dr. Langmuir concludes that in the Yucca Mountain region the effective Kd values will generally be higher than the laboratory values. He provides his assessments of effective Kd values for Np and U for the various hydrogeologic units.

3.2.9 Other Issues

The SZEE expert panel provided their judgments on a number of other issues related to the saturated zone in the Yucca Mountain area, including thermohydrology, colloids, water table changes due to disruptive events, and anisotrophy.

3.2.9.1 Thermohydrology

Regarding the potential effect on the saturated zone of the thermal elevation due to repository heating, panel members generally concur on the possible effects on the saturated zone, but are somewhat divided on the relative importance that these effects might have. Potential effects from the expected increase in temperature at the saturated zone beneath the repository are changes in viscosity, precipitation and dissolution of minerals, and reduction in the vertical plume width due to buoyancy. Dr. Freeze concludes that the impact of repository heating could be significant to saturated zone flow and transport. In addition to the effects noted above, he believes that the effects also could include transient patterns of perched saturation, fracture drainage, convection cells, and increased recharge to the water table. Dr. Tsang believes that convection will not occur because heat is being added to the top of the saturated zone and concludes that the impact on permeability due to precipitation and dissolution will not be great. Dr. Langmuir notes that, depending on the location and extent of dissolution and reprecipitation of calcite and silica, pores may become clogged and lead to additional residence time for sorption to occur in the matrix. Dr. Gelhar expects the thermal effect on the saturated zone to be modest.

3.2.9.2 Colloids

Dr. Langmuir is the only member of the panel to provide an assessment of the importance of colloids in the saturated zone. He defines three types of colloids, and notes that the conditions required for the transport of colloids are fast pathways. The key actinide of concern in colloidal transport is plutonium (Pu). Dr. Langmuir summarizes his assessment of what the fate of colloids will be. Many will be filtered out in the backfill or invert within the drift. Degradation colloids (such as Pu oxides) and radiocolloids will be undersaturated with respect to the groundwater as soon as they move away from the waste. They therefore will tend to dissolve in the groundwater, and once in solution tend to be adsorbed by rock surfaces in fractures and especially the matrix. Actinides on the surfaces of geocolloids will tend to desorb with groundwater flow, and to be readsorbed by surrounding rock surfaces, which have the same surface bond strengths toward the actinides but have unoccupied surface sites and orders of magnitude more reactive surface area.

3.2.9.3 Water Table Changes from Disruptive Events

In light of alternative interpretations of evidence for the position of past water tables and the potential for future water table changes, the experts were asked for their judgments regarding the potential magnitude of water table changes that might accompany disruptive events such as earthquakes, as well as the potential for long-lived or permanent changes in water table. (Note that the potential for transient or permanent changes to the large hydraulic gradient were summarized previously in Section 3.2.2).

All of the experts addressing this issue concluded that changes to the water table associated with earthquakes will not be significant and will not be long-lived. Dr. Freeze and others note that earthquakes can perturb the stress field and can produce short-lived spikes of increased fluid pressure in confined aquifers. Because these events do not cause a significant transfer of water, he reasons, they are not likely to lead to large or long-lived changes in water table elevation. Dr. Neuman notes that fluctuations from earthquakes tend to be rapid, short lived, and on the order of centimeters to meters; and Dr. Tsang concludes that the expected changes will be transitory in the time-frame of the respository.

3.2.9.4 Anisotropy

The experts were asked to provide their assessment of anisotropy of the flow system at scales appropriate to the site-scale model as a ratio between the horizontal and vertical anisotropy and in the horizontal plane. Those experts addressing the issue expressed their belief that there would be significant horizontal to vertical anisotropy at these scales due to layering of the system. Horizontal to vertical anisotropy ratios range from 3:1 to 100:1. Dr. Tsang notes that the degree of anisotropy accounted for in the modeling is dependent on how much of the horizontal layering structure is accounted for discretely. Dr. Neuman notes that, in the absence of discrete representation of layering and faults in the models, an estimate of anisotropy could be assigned to each hydrogeologic unit, and the directions of the anisotropy could be parallel to fault planes. Anisotropy in the horizontal plane is suggested by the pattern of drawdown associated with the C-wells, notes Dr. Gelhar. Dr. Tsang is skeptical of the interpreted elliptical shape, but would expect horizontal anisotropy resulting from flow in major faults and fractures.

3.2.10 Recommendations for Reducing Uncertainty

In light of the key issues related to the saturated zone, the experts provided their judgments regarding activities that could be conducted to reduce uncertainties in these key issues. The activities identified include both additional data-collection activities and modeling/analysis activities. The activities are given in the elicitation summaries (Appendix D) and are summarized in Table 3-2.

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TABLE 3-1
KEY ISSUES TO BE ADDRESSED BY THE SATURATED ZONE EXPERT ELICITATION PANEL

1. Conceptual model of groundwater flow in the saturated zone beneath the potential repository.
2. Magnitude and direction of advective flux in the saturated zone beneath the potential repository.
3. Conceptual model of groundwater flow in the saturated zone downgradient from the potential repository.
4. Conceptual model of solute dilution in the saturated zone downgradient from the potential repository.
5. Applicability and quantification of large-scale transport parameters, such as dispersivity and mixing depth.
6. Applicability and quantification of the minimum Kd approach to chemical retardation of important radionuclides, such as Tc, Np, I, and Pu.
7. Applicability of C-wells hydraulic and tracer-test data to provide flow and transport parameters for site-scale saturated zone flow and transport modeling.
8. Estimates of regional recharge and discharge used in regional-scale saturated zone flow modeling.
9. Use of geochemical data to characterize the regional and site-scale saturated zone flow system.
10. Effects of future climate change on transport of radionuclides downgradient from the repository.
11. Extent of rise in the water table beneath the potential repository in response to climate change or disruptive events.
12. Conceptual model of the large hydraulic gradient and the impact of this feature on transport of radionuclides downgradient from the repository.
13. Degree of flow channelization in the saturated zone at intermediate to large scales as it relates to radionuclide transport.
14. Possible thermal/chemical/mechanical alterations of the saturated zone system in response to the repository.
15. Estimates of the geochemical conditions relevant to radionuclide transport in the saturated zone, specifically Eh and pH.
16. Possible influence of colloidal transport of radionuclides.

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16. Possible influence of colloidal transport of radionuclides.

TABLE 3-2
SUMMARY OF KEY ISSUES

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
Overview: Conceptualization of SZ Groundwater Flow	+Flow travels vertically downward (with tortuosity) in the unsaturated zone and travels approximately horizontally at the water table along hydrogeologic units +Subhorizontal flow in SZ will encounter major faults where it can digress, spread out, or even bifurcate +The primary hydrogeologic units carrying flow from YM to distances of 5 to 30 km are the volcanic aquifer (Bullfrog) and valley-fill alluvium; there is evidence for upward flow from the carbonate aquifer but may be small +Flow in both the unsaturated and saturated zones is expected to be channelized as preferred flow paths +Flow channelization is due to major geologic structures (faults, fractures, permeable units) and to smaller-scale heterogeneities in permeability. +Major structures can be put in the flow models explicitly; smaller-scale heterogeneities may result in local fast paths that have velocities ten times surrounding rock and small dispersion; the latter to be evaluated with models using geostatistics involving parameters such as: average permeability, variance, and correlation lengths +Only 10% to 20% of fractures contribute to flow and maybe only 1% - 10% significantly +The hydraulic properties of faults are poorly determined and should be evaluated through interference tests	+Groundwater follows a path southeast from Yucca Mountain to Fortymile Wash and south to Amargosa Valley +Elevated heads in carbonate aquifer under YM probably preclude groundwater flow from volcanics into carbonates +Residence time of groundwater in the volcanic rock matrix is vitally important to radionuclide retardation +$\delta^{14}C$ ages suggest the youngest waters beneath YM are about 6000 yrs and beneath Fortymile Wash are 7100 to 4200 yrs, which may reflect dilution with infiltration from snowmelt runoff +Hydrochemical data suggest flow beneath YM is combination of contributions from snowmelt recharge at Pahute Mesa and Timber Mountain and local snowmelt recharge; infiltration appears to be occurring along Fortymile Wash +Hydrochemical data suggest that ground water under YM contributes a negligible fraction of flow to groundwaters in Fortymile Wash	+No fundamental uncertainties in nature of flow system +Primary feature is high permeability of hydrogeologic environment +Faults and structural features are important to 3-D hydrogeology at several scales +Faults may have low hydraulic conductivity perpendicular to them and enhanced conductivity parallel to them +Focusing and channelization are important and likely prevalent +Flow from site is to southeast and then to south at Fortymile Wash +No significant short-term transients; steady-state analysis is appropriate	+Reasonable outline of basin boundaries; major hydrogeologic units, faults/structures; depth to groundwater; location/extent of recharge/discharge areas. +Uncertainty re presence, depth, continuity of major units in Timber Mountain area and elsewhere. +Flow may take place across basin/sub-basin boundaries. +Information about hydraulic properties is limited; much of it small-scale and thus not representative; virtually no data about hydraulic properties of faults/fault-zones; pneumatic data not yet used in saturated zone analyses. +In models, faults are not assigned hydraulic properties; pneumatic permeability shows 3-D anisotropy. +Recharge estimates are most reliable where evaluated directly, least where based on Maxey-Eakin method. +Discharge estimates are most reliable in springs and wells; much less so where evapotranspiration dominates. +Vertical gradients are poorly defined. +There is no direct way to assess groundwater flow rates from north/west into Yucca Mountain area. +Small gradients, and corresponding fluxes, are sensitive to measurement errors; fluxes should be compatible with recharge/discharge data. +Site-scale/regional flow models are consistent neither with each other nor with measured hydraulic properties. +C-cluster pumping tests provide the most reliable/relevant hydraulic parameters on scales from meters to kilometers. +Lateral anisotropy is manifestation of faults; should be included in models. +Calibration of site-scale/regional models is of questionable validity. +Uncertainty of model input data not fully/convincingly quantified. +Current site-scale/regional flow models are not reliable. +The Death Valley basin forms an integrated flow system all parts of which communicate with each other hydraulically at various rates. +The C-well pumping tests exhibit binary behavior, but the rock probably contains a hierarchy of components. +Tracer tests in C-wells yield unusually high "fracture porosity" which is in fact representative of both fractures and matrix.	+Flowmeter logging shows that water is moving through only a small part of the overall vertical section; flowing zones are not in same horizons within geologic units +Volcanic aquifer is highly transmissive downgradient from site and there is a complicated flow network +Probably good deal of interconnection at scale of hundreds of meters to kilometers +Not clear whether transmissive flow paths need to be modeled discretely or if related to faults +Regional model important for evaluating effect of climate change on flow system; not sufficient to impose flux conditions on site-scale model +Flow from repository likely will not involve carbonate aquifer +Continuum model for alluvium probably sufficient +Influence of small intraformational heterogeneitites downgradient from site incorporated into dispersion terms

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TABLE 3-2
SUMMARY OF KEY ISSUES (Continued)

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
Large Hydraulic Gradient	+The LHG is not a unique feature in the region; use the regional model to evaluate the significance of alternative interpretations +Favor the perched zone model (0.6) over the saturated zone model (0.4) +Very low probability of sudden or large changes to the LHG		+Issue is why water-table slope shows a break north of site rather than gradual slope; large hyrdraulic gradients are common in region +Two credible interpretations: saturated flow system or perched flow system +Saturated flow system (70%); perched flow system (30%) +Given saturated model: 65% of control by horizontal features, 35% by vertical features +Not critical to settle LHG mechanism; minimal implications to SZ flux at YM +Likelihood of sudden "breakthrough" is zero; major, long-term transient readjustment of gradients is very low likelihood	+Large apparent hydraulic gradient (LAHG) at Yucca Mountain is unique in that it does not correspond to any obvious geologic or topographic feature. +Conceptual framework for the LAHG important to answer questions such as "Is inflow into the Yucca Mountain area from the north significant and, if so, where does it occur and at what rates? Is flow from the north diverted into Crater Flat or along Fortymile Wash? If so, how and to what extent?" +Tentatively favor the perched system model (0.95) because conceptually straight forward and supported by numerous observations while contradicting none; probability of 0.4 with the semiperched model, and 0.1 with all remaining models +Calico Hills aquitard appears to be at or just below full saturation in the area of the LAHG, a minute addition of water would render unit fully saturated. Therefore likely that conditions in the LAHG area vary temporally, and spatially, between perched and semiperched. The semiperched model is not viable stand-alone interpretation	+Not a crucial issue; importance lies in indication of perched water and low-permeability zones, which will likely be more extensive with climate change +Interpretation as perched is somewhat preferred because of its simplicity
SZ Flux Beneath Yucca Mountain					
Approach	+Single-hole tests may underestimate the hydrogeologic unit's hydraulic conductivity; most current tests are based on a convergent or divergent flow field, but results are applied to transport calculations in large area with flow field closer to a parallel pattern +Place more confidence in interference tests and long-term tests		+Use traditional approach: establish hydrogeologic framework, perform flow-net analysis for flow tubes, estimate hydraulic conductivity, and use Darcy's Law to calculate specific discharge.	+Consider range of hydraulic gradients, range of hydraulic conductivities for five permeable units based on C-wells and composite for volcanic units using layer thickness; calculate average fluxes and velocities	+Sources of uncertainty and limitations make regional and site-scale models not useful for predicting flux beneath site +Rely primarily on data from C-wells; single-borehole data may not sample larger-scale interconnectivity of system +Range of transmisivities in C-wells suggests factor of 2 to 3 variation in specific discharge; expect order-of-magnitude variation as move to distances of 5 km
Hydraulic Conductivity, K (cm/sec)	+Uncertainty in K for the Bullfrog unit (the most transmissive unit) given by the cumulative distribution function (CDF): K_{volc} (cm/s) — Percentile of CDF 10^{-1} — 99% 10^{-2} — 50% 10^{-3} — 20% 10^{-6} — 1% +This assessment includes the effects of small-scale fractures but not major faults +Volcanic aquitards would be factor of 10 to 1000 (log uniform distribution) less		+Assuming application at scale of site-scale model (much less uncertainty than spread in point-scale values) *[See Elicitation Summary for distributions]* Unit — Median — Bounds Alluvium — 10^{-3} — 10^{-4} - 10^{-2} Volc. Aquifers — 3×10^{-4} — 3×10^{-5} - 3×10^{-3} Volc. Aquitard — [20 - 180X less than volc. aquifers] Carbonates — 3×10^{-4} — 3×10^{-5} - 3×10^{-3} Faults — [2 - 18X more than volc. aquifers]	+Most reliable data for Topopah Springs come from pneumatic injections tests; for lower volcanic aquifer from C-wells pumping tests; ranges of K for lower volcanic aquifer units come from Geldon et al. (1997): Upper Volcanic Aquifer $K_{TS} = 2 \times 10^{-5} - 3 \times 10^{-2}$ (geometric mean 10^{-3}) Lower Volcanic Aquifer $K_{PP} = 1.4 - 3.5 \times 10^{-3}$ $K_{UB} = 1.1 - 3.5 \times 10^{-3}$ $K_{LB} = 2.5 - 7.4 \times 10^{-2}$ $K_{UT} = 1.4 - 5.3 \times 10^{-2}$	+Assume average values for the hydrogeologic unit and include faults and other features within unit; range of point values would be much wider +Assuming lognormal distribution, geometric mean and ±2σ values of K (cm/sec): Unit — Mean — ±2σ V. Aquifer — 6.9×10^{-3} — $[6.9 \times 10^{-4} - 6.9 \times 10^{-2}]$ V. Aquitard — [10-100X less than volc. aquifer] Carb. — 1.2×10^{-2} — $[1.2 \times 10^{-4} - 1.2 \times 10^{0}]$ Alluvium — 1.2×10^{-1} — $[1.2 \times 10^{-2} - 1.2 \times 10^{0}]$ +Assume that the K for volcanic aquitards is log uniform distribution between 10X and 100X.

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TABLE 3-2
SUMMARY OF KEY ISSUES (Continued)

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
Specific Discharge, q (m/yr) Beneath Site	+Assuming hydraulic gradient of 0.0003: q_{volc} (m/yr) — Percentile of CDF 9.5×10^{0} — 99% 9.5×10^{-1} — 50% 9.5×10^{-2} — 20% 9.5×10^{-5} — 1% Note this flux, or specific discharge, is only across the Bullfrog unit, where most flow travels		+Hydraulic gradient = 0.0003 +Lognormal distribution of q: median, 10^{-1}; bounds, 10^{-2} to 10^{0} +Note that this distribution includes the effects of major faults	+Hydraulic gradient = 0.0001 to 0.0004 +Lognormal distribution of q: geometric mean, 10th and 90th percentiles: Upper Volcanic Aquifer $q_{TS} = 6.4 \times 10^{-2}$ [3.2×10^{-2} - 1.3×10^{-1}] Lower Volcanic Aquifer $q_{PP} = 1.4 \times 10^{-1}$ [4.4×10^{-2} - 4.4×10^{-1}] $q_{UB} = 1.2 \times 10^{-1}$ [3.5×10^{-2} - 4.4×10^{-1}] $q_{UB} = 2.7 \times 10^{0}$ [7.9×10^{-1} - 9.3×10^{0}] $q_{UT} = 2.9 \times 10^{-1}$ [4.4×10^{-2} - 6.7×10^{0}] Composite Lower Volc. Aquifer $q_{LV} = 1.4 \times 10^{0}$ [3.9×10^{-1} - 5.0×10^{0}] +Local fluxes: log normally distributed, mean equivalent to above means, 40th and 60th percentiles equivalent to the 10th and 90th percentiles above	+Hydraulic gradient = 0.0003 +Lognormal distribution of q: geometric mean, 0.6 m/yr -2σ = 0.06 m/yr $+2\sigma$ = 6 m/yr
Average Velocity (m/yr)	+Porosity is estimated at 10%, which includes both fracture and relevant matrix porosity. This is consistent with current information from C-well tests. Then, velocities are ten times the specific discharge above	+C-14 ages of groundwater in wells UE 29a2 (8 yrs) and Wt-15 at a distance of 9.5 km indicate a groundwater flow velocity of 1.4 m/yr in upper Fortymile Wash alluvium	+Average linear velocity (m/yr): median, 3; bounds: 0.3 to 30	+Porosities: *Lower Volc. Aquifer:*Range of kinematic porosities lognormally distributed with geometric mean, 10th and 90th percentiles: 1% [0.1% - 10%] *Carbonates:* normally distributed about a mean of 3 % with 10th and 90th percentiles equal respectively to 1% and 5%. *Alluvium:* Gaussian with a mean of about 12% and 10th and 90th percentiles respectively of 6 and 18%. +Average velocity computed by Monte Carlo sampling from porosity and specific discharge distributions, assuming they are uncorrelated	+Assume that 1% to 10% of volcanic aquifer is transmissive, and average flow rate within transmissive zones is 10X average flow rate for the unit +Effective fracture porosity of volc. aquifer: 10^{-3} seems plausible; could range from 10^{-5} to 10^{-1} +Effective porosity of alluvium: truncated normal distribution: Mean, 0.25; -2σ, 0.1; $+2\sigma$, 0.4; bounds (0,1)
Climate Change	+Reasonable to expect that future water-table rises will be comparable to those interpreted for past glacial cycles +To evaluate its impact on site, model needs a definite and consistent coupling between site and regional models	+High confidence in geochemical evidence for position of past water table levels from past glacial episodes, maximum elevation of 120 m above present levels +Position of past levels provides reasonable constraints on future water table elevations	+Water table change, Δwt (m): median, 75; bounds 25 to 150 + Change in flux, q_g/q_p: mean, 3.2, bounds: 1 to 10	+Variations in climate may affect large-scale, long-term features of basin wide subsurface flow such as regional modes, areas and rates of recharge and discharge, regional groundwater elevations, overall directions and magnitudes of hydraulic gradients throughout the basin, and corresponding groundwater fluxes and velocities. +Associated changes in weather patterns may alter smaller-scale, shorter-term space-time variations in subsurface flow; such variations may also affect dispersion which depends on space-time fluctuations in groundwater velocity. +There is paleodepositional evidence that groundwater elevations beneath Yucca Mountain have occasionally exceeded current elevations by 80 - 120 m. +Properly calibrated groundwater flow models may help analyze future climatic effects on regional and site-scale flow regimes. +A wetter climate than that of today may cause the Calico Hills aquitard on the north side of Yucca Mountain to saturate and thus allow the large apparent hydraulic gradient in this area to dissipate.	+Primary influences are rise in water table and increase in perched water conditions +Paleodischarge data suggest rise of 100 m seems reasonable +Using regional model, uncertainties in recharge could mean rise as high as 200 m +Do not expect drastic changes in gradient (perhaps 2 to 3 times); expect flux to fall within above range given above toward the high side +May be changes in direction of gradient and more transients during glacial periods, which could affect dispersion +During wetter climates, expect factor of 2 to 3 times in transverse dispersivity, no change in longitudinal dispersivity

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TABLE 3-2
SUMMARY OF KEY ISSUES (Continued)

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
Conceptual Model	+Need to consider three stages of tracer transport: source term at the interface between unsaturated and saturated zones, stream tubes and dispersion, and flow paths reaching "fence" and extraction well capture zone +Channelized flow in UZ will lead to localized, higher-concentration "point sources" +Degree of channelization in SZ depends on the degree of heterogeneity; spacing of these channels depends on spatial correlation structure of permeability heterogeneity +Propose "bundle of particle lines" model	+Field tests provide description of large-scale hydraulic properties, but not particularly useful for assessing local properties at scales appropriate to geochemical properties +Three general groundwater types in YM area distinguishable from chemistry: alluvial groundwaters, volcanic rock groundwaters, and groundwaters in the deep regional carbonate aquifer +Key issue for radionuclide transport is whether or not--and to what degree--flowpaths from repository enter the carbonate aquifer at distances of 5 to 30 km; regional model suggests they do at distances of 10 km; Np(V) adsorption by calcite would be expected in the carbonate aquifer	+Primary transport mechanism is advective transport +Advection occurs along preferential flow paths; therefore, downgradient flow paths are flow tubes in volcanic aquifer and alluvium; little or no flow in carbonate aquifer +Lateral and vertical dispersion are likely to be small +Retardation of radionuclides will occur from matrix diffusion and sorption; minimal in welded tuffs; more effective in zeolitized and bedded tuffs +Few mechanisms lead to substantial mixing of the plume, perhaps climatic transients	+Only mechanisms for dilution (in absence of withdrawal) are molecular diffusion, advective dispersion, turbulent eddies (unlikely), density effects (can either enhance or prevent mixing), or fingering (unlikely) +No scientific basis for "stirred tank" model +Dispersion coefficients compensate for inability to resolve intricacies of advective transport and local-scale dispersion in a heterogeneous porous and/or fractured rock; only if one samples on a scale comparable to that of unresolved heterogeneities should one expect dispersion to imply mixing and dilution. +As field-scale dispersion is associated with incomplete resolution of medium heterogeneities, one can reduce it by including in flow and transport models more detail about heterogeneity. +Since one never has exhaustive information about all details of heterogeneity, stochastic approaches provide an appropriate framework for the analysis of flow and transport in heterogeneous media. +Dispersivities increase with their scale of definition +Dispersion implies mixing and dilution only when mean travel distance is large enough for a plume to sample heterogeneities of all relevant scales in the longitudinal direction of flow, and when the source of contamination is wide enough so the plume can sample all such heterogeneities in the transverse direction. +Focused flow is ubiquitous throughout both the unsaturated and saturated zones in the basin on many scales.	+Scales of interest are 5 to 30 km; appropriate to use continuum models and exclude localized effects of faults and local heterogeneities +Aquifer system will be well connected at these scales; larger-scale features (confining units, faults) will change geometry of plume rather than cause dilution +Degree of dilution controlled by local dispersion and molecular diffusion, and strongly influenced by fine-scale variations in flow field
Dilution Factor/ Dispersivity	+Do not expect much dilution in the flow paths between the source and the capture zone of the user wells; molecular diffusion will occur within and between flow channels and there will be small longitudinal dispersion +Over distances of kilometers, expect dilution of factor of 2 and less than 10 within flow channels +Significant dilution will occur only at UZ-SZ interface (poorly studied) and at production well +"Dilution factor" that includes the capture zone of the production well could lead to dilution factors of about 100 dependent on various conditions	+A number of factors can lead to dilution of contaminants: turbulence (not expected in volcanic aquifer), temperature and density effects, dispersion, differences in permeability, transient in flow system, and head changes due to climate changes +Dilution factor of peak radionuclide release at distance of ~30 km might range from 10 to 50.	+Dilution factor: ratio between initial contaminant concentration and highest concentration at point some distance from source + Assuming: sources tens to hundreds of meters dimension; steady, nondecaying source, 25-km distance, thousands of years after initiation: Dilution factor: median, 10; bounds, 1 to 100	+Perform high-resolution, statistically based conditional flow and transport calculations +Include narrow channels of elevated permeability +Crude rule of thumb: longitudinal dispersivity equal to 1/10 the length of local-scale grid cell; transverse dispersivity 1/10 to 1/3 of longitudinal	+Longitudinal macrodispersion controlled primarily by degree of variation in hydraulic conductivity and its correlation scale +Transverse dispersivity controlled by fluctuation in the direction of hydraulic gradient; transverse dispersivity strongest control on plume spreading and dilution for YM case with steady release of contaminant +<u>Longitudinal Dispersivity</u> Assuming lognormal distribution, geometric mean and $\pm 2\sigma$ values: <u>For 5 km:</u> 50 m [5 m - 500 m] <u>For 30 km:</u> 100 m [3.2 m - 3200 m] +<u>Horizontal Transverse Dispersivity</u> 0.5 m [0.016 m - 16 m] +<u>Vertical Transverse Dispersivity</u> 5 mm [0.16 mm - 160 mm] +Assume a correlation between longitudinal and transverse dispersivity

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TABLE 3-2
SUMMARY OF KEY ISSUES (Continued)

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
Mixing Depth and Effective Fracture Density	+"Mixing depth" is not a realistic concept +Range of distances between significant fractures is 10 to 100 m +Note only 10% to 20% of fractures are hydraulically conductive		+Vertical flux is comparable to lateral flow; thus flow tubes from infiltration will remain discrete, with little mixing at water table; lateral flow tubes will be pushed deeper +Effective fractures for flow spaced at 10 - 50 m. Of these, only those in nonwelded, bedded, or zeolitized tufts are effective from a dual-porosity, matrix diffusion point of view	+No scientific basis for mixing depth +Expect buoyancy of warmer waters from repository and small vertical dispersivity to keep radionuclides at shallow depth except where intersected by major vertical fractures or faults	+Vertical width of plume is about 23 m, which is not the same as a "mixing depth" +Mixing due to vertical dispersivity across width of repository would be about 4.4 m +Average flow zone spacing 100 m to 200 m
Hydrochemical Transport Parameters	+Should be possible to use laboratory sorption parameters (Kd), but ten-fold discrepancy between C-wells data and laboratory data may imply that the flow field is not properly conceptualized +Lateral diffusion over long periods into intervening areas of slow flow should enhance sorption, but this effect may be small	+DOE approach that considers only sorption reactions as the geochemical control on maximum concentrations is highly conservative; should also consider solubility and redox reactions +Distribution of Kd values should be considered rather than "minimum Kd" approach + "Effective Kd" values consider the potential for various conditions and reactions along the flow path and in the YM region are generally higher than the laboratory values +Tc and I are essentially nonsorbing (Kd ~ 0); Pu is controlled by solubility ($\sim 10^{-7}$) +Effective Kd values for Np (ml/g): Volcanics Fractures: range 0 to 10; expected value = 3, beta distribution, variance 0.3 Matrix: factor of 10X to 100X higher Alluvium Kd[Np](ml/g) — CDF 1000 — 100% 100 — 95% 40 — 50% 10 — 10% 1 — 0% Carbonates 100 (0.2) 1000 (0.8) +For uranium use laboratory-derived Kd values		+The only direct evidence for possible matrix diffusion on the field scale at Yucca Mountain is a C-well tracer test the results of which are, however, ambiguous. +Diffusion may take place not (just) into rock matrix but (also) from fast to slower flow paths within fractures. +Transport may occur not only by diffusion into, but also by advection through, matrix (and/or slow paths within fractures); suggested by dual porosity response of C-well pumping tests; especially likely where fractures terminate at interfaces between layers. +Both kinetic phenomena and spatial variability of sorption parameters may affect dispersion; mechanisms are not well understood and field data are scarce.	+Cannot use laboratory-derived values without knowing how representative they are of field conditions
Other Issues					
Thermohydrology	+Thermal effects on the SZ are straightforward +No convection is expected to occur in the SZ +Temperature change may lead to changes in viscosity, precipitation, and dissolution of minerals, but the impact on permeability due to precipitation and dissolution will not be great +Heat pulse will likely have passed by time contaminants reach water table	+Effects are function of whether water flows in fractures or matrix (which includes tight fractures) +If in fractures, effects will occur at greater distances +If in matrix, cause silica to dissolve, move to cooler location, and then precipitate and may clog the system; if calcite is saturated it will precipitate and may clog the matrix and fine fractures, leading to additional residence time	+Impact of repository heating could be significant to SZ flow and transport +Transient patterns of perched saturation, fracture drainage, increased recharge to water table, convection cells, and mineralogic alteration are possible effects		+Expect thermal effect on the SZ to be modest +May be reduction of vertical plume width due to buoyancy

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TABLE 3-2
SUMMARY OF KEY ISSUES (Continued)

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
Colloids		+There are three types of colloids: degradation colloids, precipitation colloids, and geocolloids or pseudocolloids +The conditions required for transport of colloids are fast pathways +Fate of colloids: many will be filtered out in backfill/invert, degradation colloids will tend to dissolve as they move away from the waste and be adsorbed by rock surfaces; actinides on colloids will tend to desorb with groundwater flow and be readsorbed by rock surfaces +Key actinide of concern in colloidal transport is Pu			
Water-Table Changes from Disruptive Events	+Expect changes will be transitory in timeframe of repository	+Very low probability of a significant water-table change associated with earthquakes or other disruptive events	+Earthquakes perturb stress and can produce short-lived spikes of increased fluid pressure in confined aquifers +Do not cause significant transfer of water and are not likely to lead to large or long-lived changes in water-table elevation	+Water-table fluctuations from earthquakes tend to be rapid, short-lived, and on the order of centimetersm to meters +Future earthquakes probably will not produce major or long-lasting changes in groundwater flow regime	
Anisotropy	+Horizontal to vertical anisotropy from 1:1 to 10:1, depending on how much of the horizontal layering structure is accounted for discretely +Little basis for horizontal anisotropy; attach little significance to interpreted ellipse from C-wells drawdown; major faults and fractures could strongly affect the horizontal flow		+Large-scale horizontal-to-vertical anisotropy is expected in the region in response to stratigraphic layering +Small-scale vertical-to-horizontal anisotropy may also be present within individual units because of cooling joints and columnar jointing	+Make the hydrogeologic units anisotropic in horizontal and vertical directions parallel to fault planes	+Expect a 10:1 to 100:1 horizontal to vertical anisotropy +C-wells suggest ~1:10 horizontal anisotropy
Recommendations for Reducing Uncertainty	+Conduct long-term large scale interference tests with pumping in one of the C-wells or another well and observation in many wells on the site; analyze using multi-parameter fit of a numerical model. This may be the most important field experiment at this time +Redrill borehole G-2 and emplace packers to study relative changes in packed intervals (to evaluate LHG) +Use the temperature log data in calibrating model to evaluate upward flow into Bullfrog unit +Recalibrate site-scale model with a definite and consistent coupling with regional model	+C-well tests should be run for longer times +Detailed mapping of available groundwater chemistry and isotopic data for YM/Fortymile Wash system to discharge in Amargosa Desert +Correct and utilize old $\delta^{14}C$ groundwater data +Emphasize interpretation and modeling of ground water geochemical data +Interpret and model groundwater geochemical and hydrologic data to evaluate relative contributions of infiltrating runoff and groundwater from under YM to volume of flow in Fortymile Wash east and southeast of YM +Perform laboratory experiments in closed vessels using rock fragments or an ultracentrifuge and rock cores measuring dissolved oxygen levels and Eh as function of time +Perform experiments on solubility of uranophane in simulated groundwaters in presence of volcanic tuff materials	+For large hydraulic gradient: careful construction of flow net in vicinity of large hydraulic gradient using all available head data in 3-D context; two to three well-place boreholes with special protocols necessary to obtain information on saturation +For fault zone properties: careful mapping of fault properties in ESF; hydraulic tests (like C-wells) in vicinity of known fault; further simulation and calibration of site-scale model +For dispersion, matrix diffusion, and sorption: well-controlled field tracer tests to confirm laboratory Kd values +Major underground testing to clarify thermohydrologic processes associated with repository heating; continued thermohydrologic modeling	+Investigate hydrogeology of Timber Mountain area. +Conduct field tests to help determine the hydraulic properties of faults and fault zones; utilize available information about pneumatic properties of faults in models of saturated zone. +Base calculations of flux not only on site hydraulic data but also on regional recharge and discharge data in self-consistent manner. +Where faults are not incorporated explicitly into flow models, account for them implicitly by rendering units anisotropic. +Plan and conduct additional large-scale long-term hydraulic tests in existing boreholes. +Develop a comprehensive, high-resolution groundwater flow model and render it compatible with all relevant site and basin-wide hydrologic and hydrogeologic data. +Quantify uncertainty of all model input data. Include reliable prior information in model calibration. A model of the entire basin has better defined boundary inflows and outflows than does a site model with artificial boundaries, and is therefore better suited for water balance calculation and calibration. +Strengthen the isotope hydrology program of the Yucca Mountain project; obtain more extensive/reliable information about groundwater	+Conduct large-scale (well spacing of 500 to 1000m), multi-hole hydraulic and tracer tests south of site +Re-evaluate single borehole hydraulic tests +Improve grid resolution of site-scale model and calibrate with C-wells aquifer test data +Evaluate degree of matrix diffusion in situ by looking at differences in hydrochemistry of fracture and matrix water (e.g., Cl^-); also do lab diffusion cell tests on natural fracture surfaces +Improve documentation of C-well multi-tracer test +Improve documentation of lab sorption and diffusion testing

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TABLE 3-2
SUMMARY OF KEY ISSUES (Continued)

	Chin-Fu Tsang	Donald Langmuir	Allan Freeze	Shlomo Neuman	Lynn Gelhar
				ages. +Drill an additional borehole strategically into the LAHG area, then log and sample it thoroughly enough to allow confirming or denying that the LAHG is an artifact of perched conditions. +Conduct high-resolution, statistically-based conditional simulations of flow and transport; even a small number of such simulations may be useful. Include narrow channels of elevated permeability in such simulations to account for focused flow and transport. +Conduct large-scale, long-term tracer experiments in and around the C-boreholes to obtain meaningful parameters (kinematic porosities, dispersivities, slow/fast path transfer coefficients, retardation factors) for transport simulations.	

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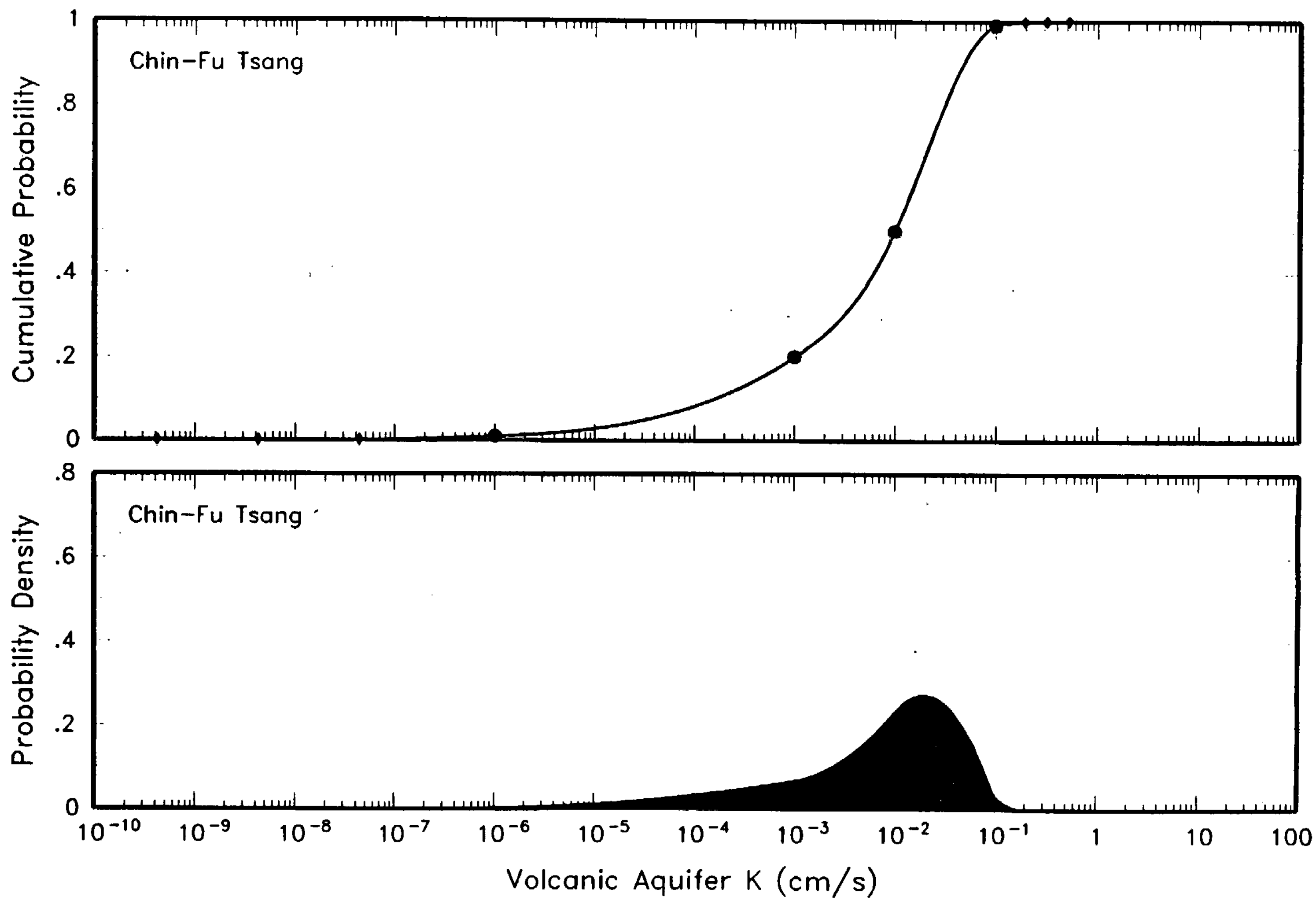

Figure 3-1a **Distribution for volcanic aquifer hydraulic conductivity assessed by Chin-Fu Tsang**

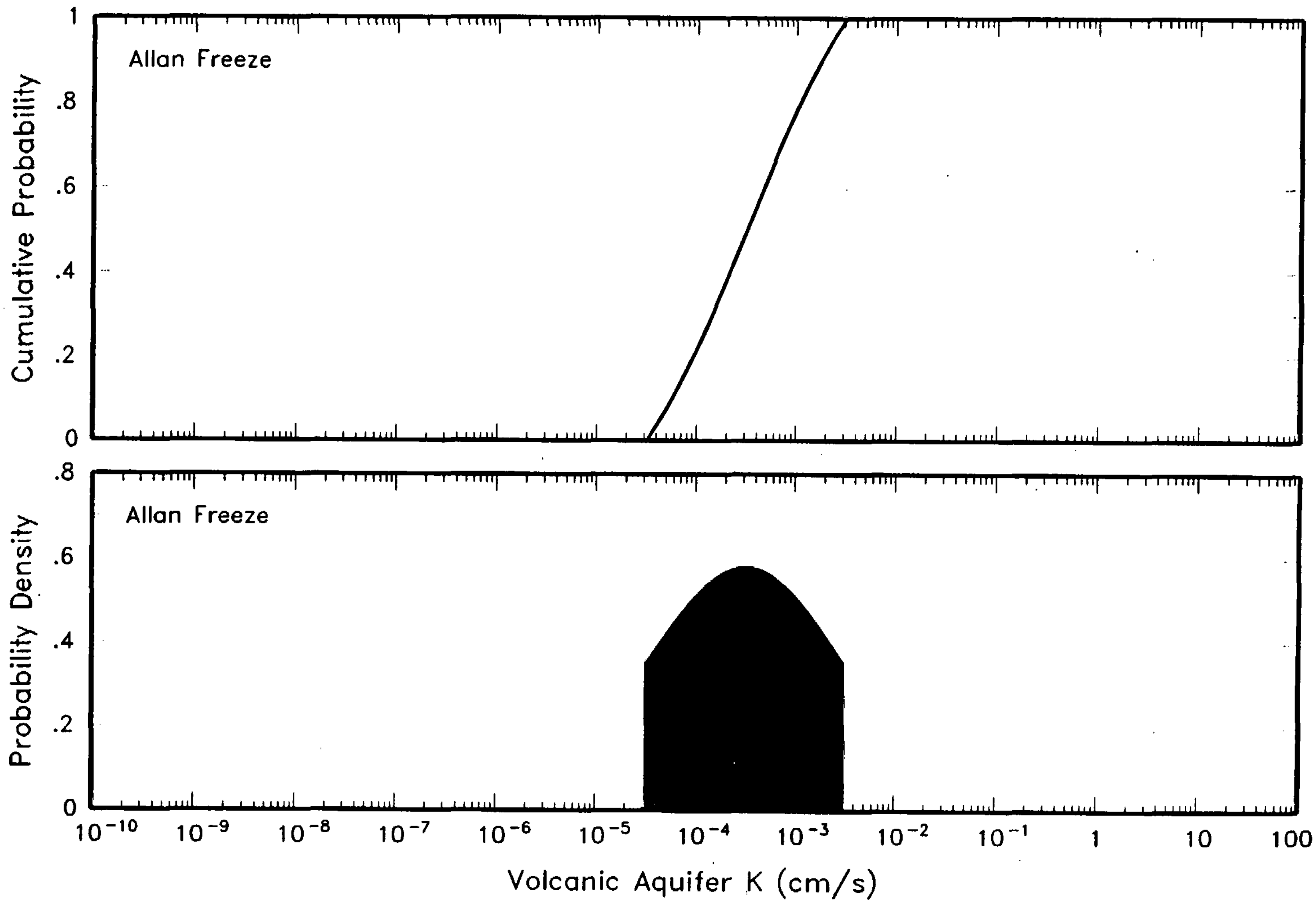

Figure 3-1b Distribution for volcanic aquifer hydraulic conductivity assessed by Allan Freeze

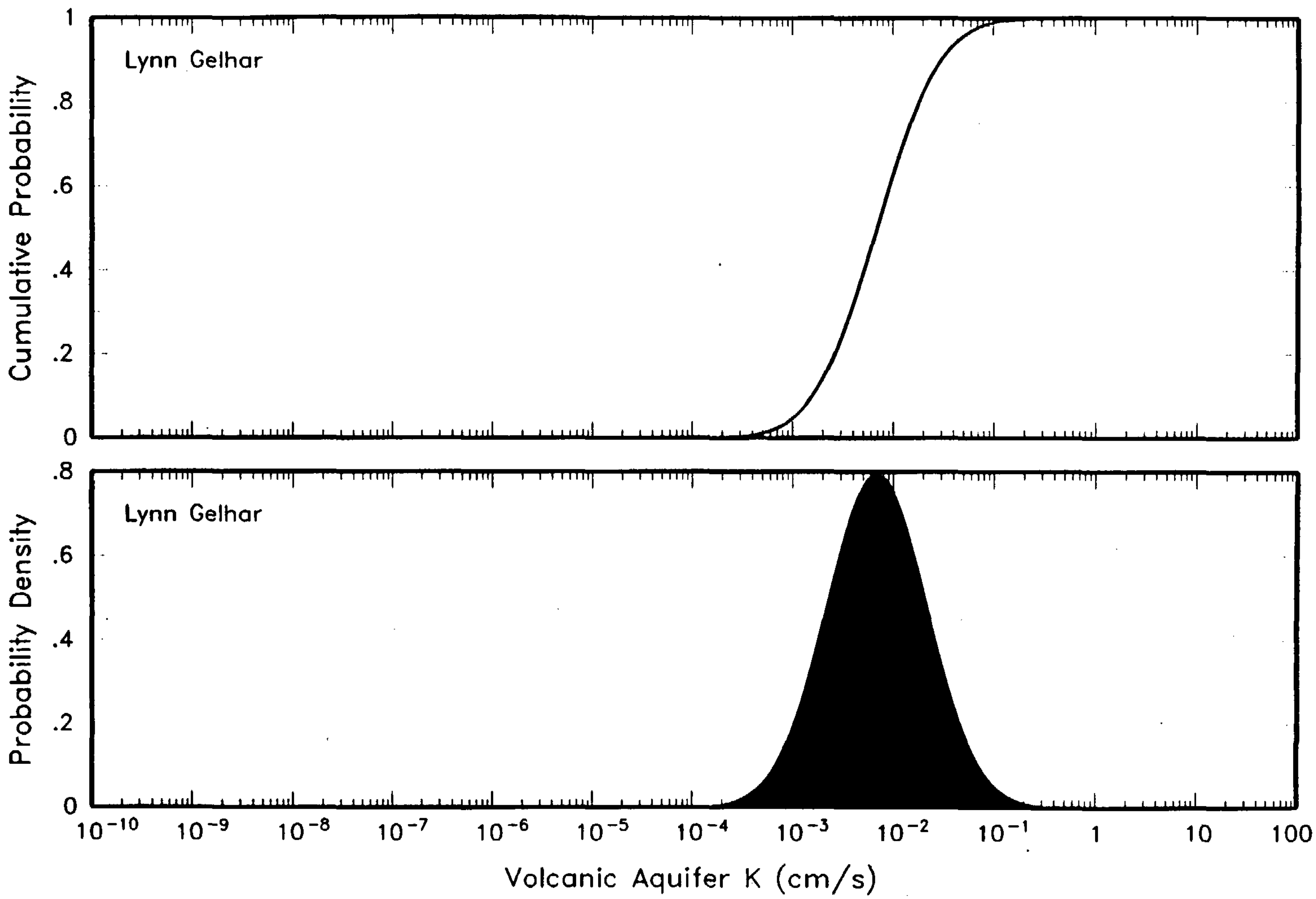

Figure 3-1c Distribution for volcanic aquifer hydraulic conductivity assessed by Lynn Gelhar

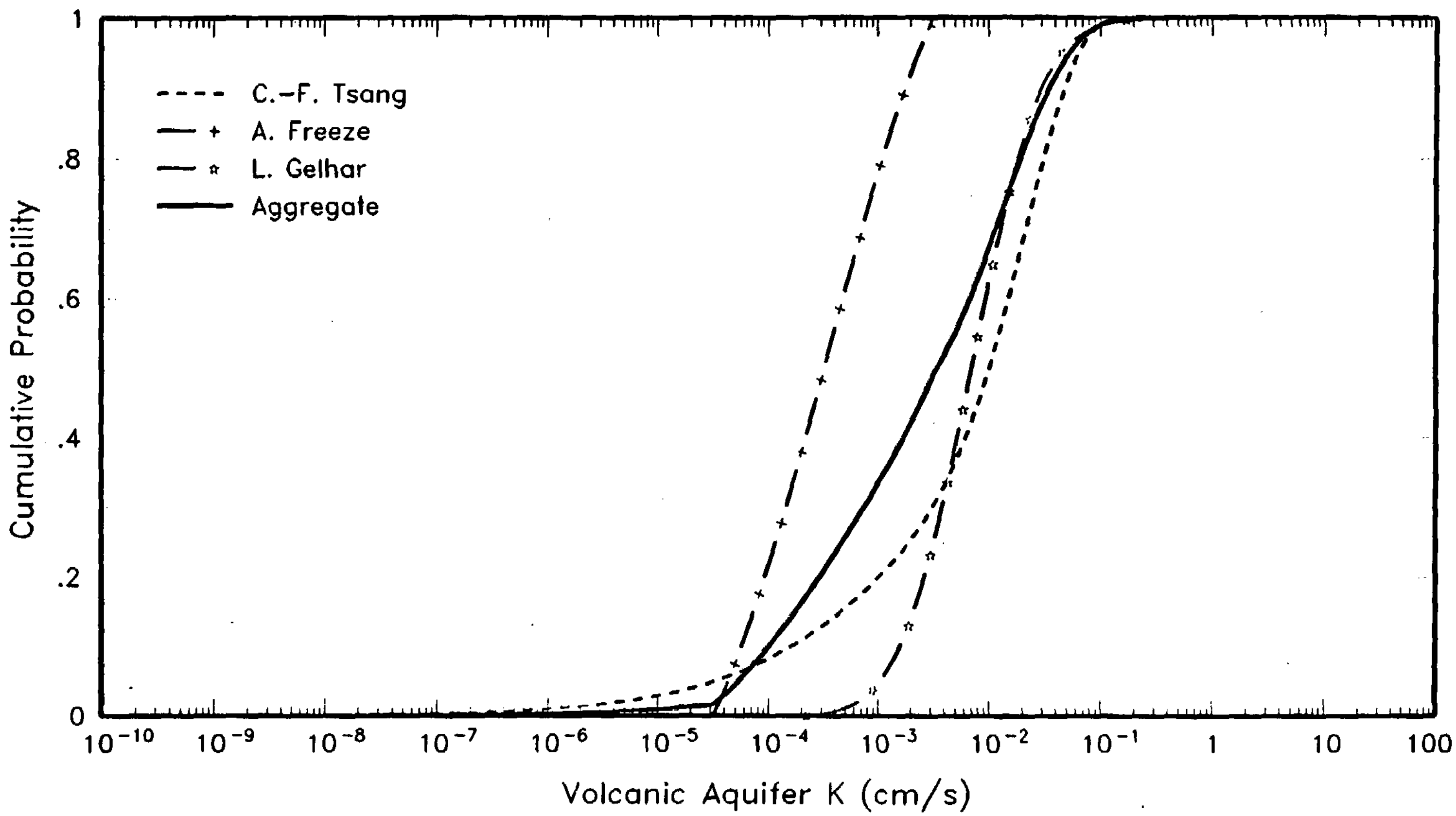

Figure 3-1d Individual and aggregate cumulative distributions for volcanic aquifer hydraulic conductivity

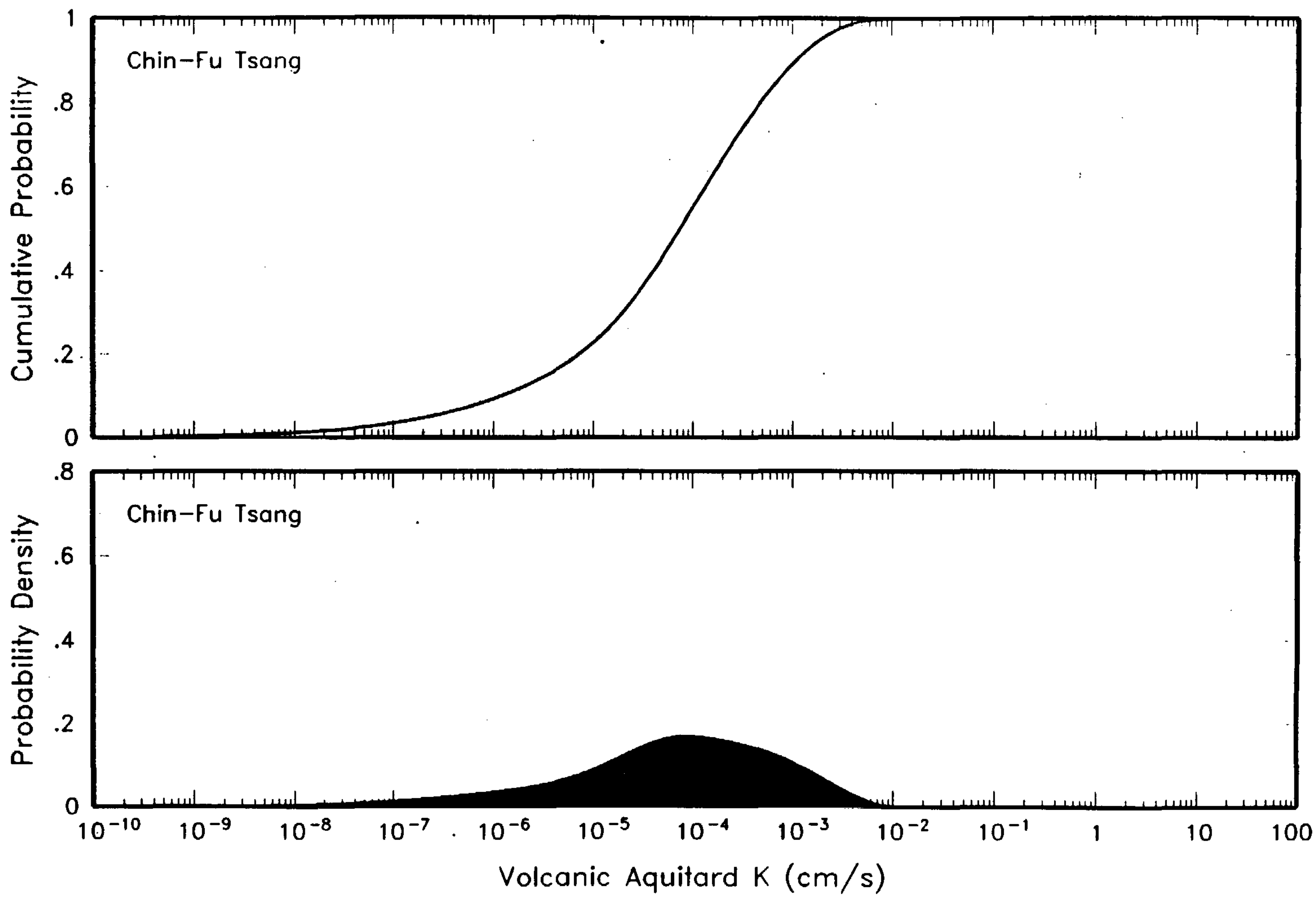

Figure 3-1e Distribution for volcanic aquitard hydraulic conductivity assessed by Chin-Fu Tsang

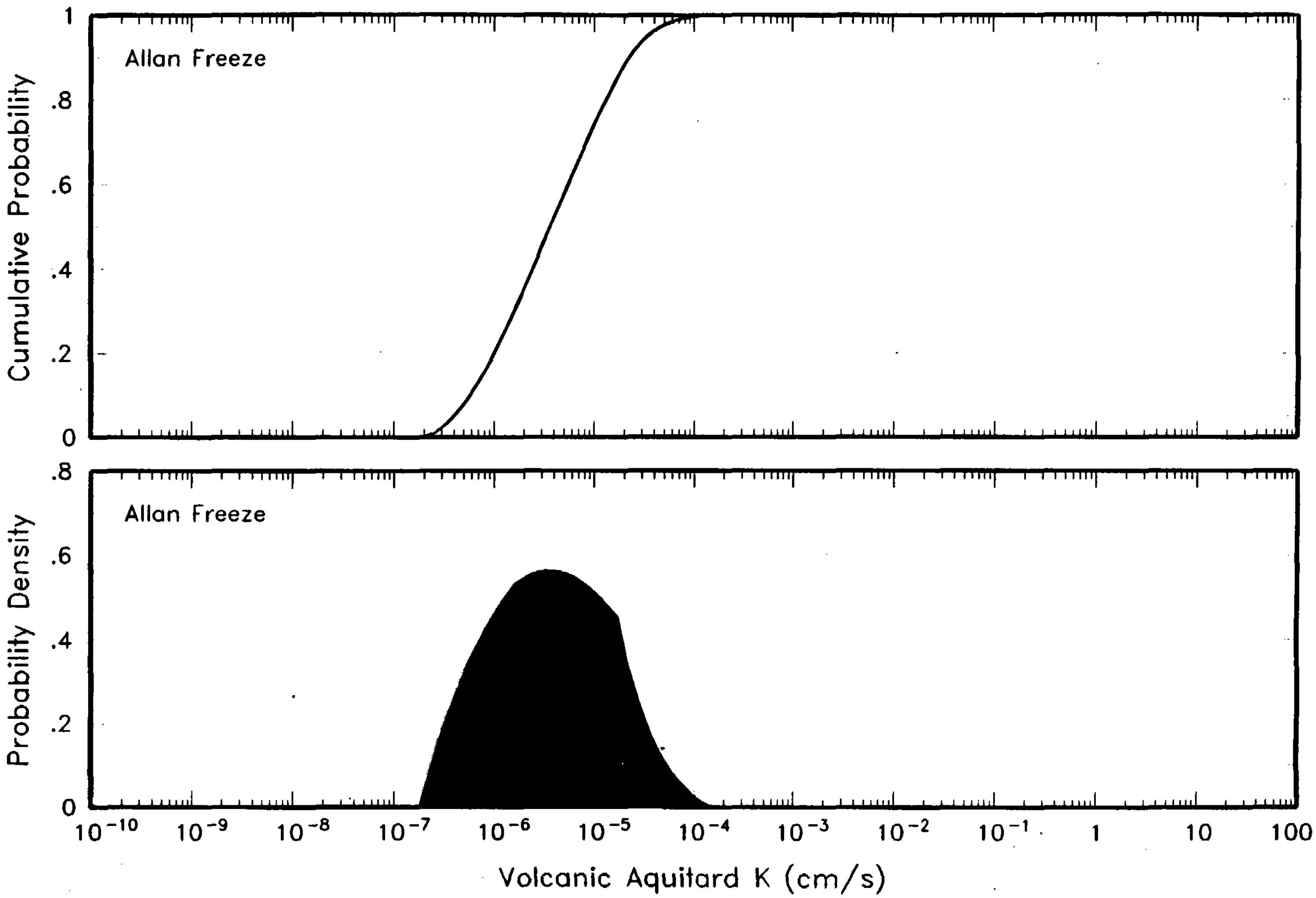

Figure 3-1f Distribution for volcanic aquitard hydraulic conductivity assessed by Allan Freeze

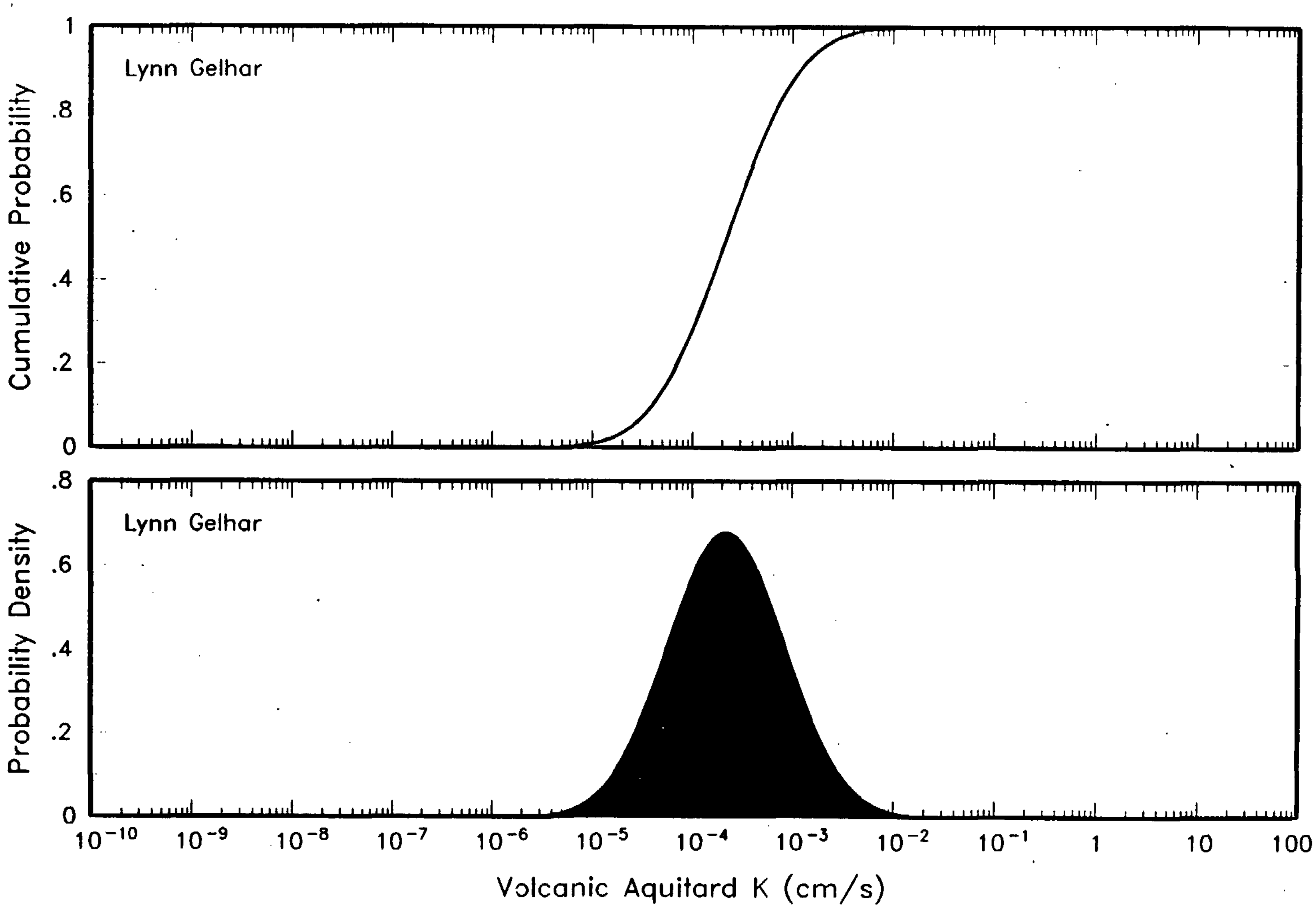

Figure 3-1g Distribution for volcanic aquitard hydraulic conductivity assessed by Lynn Gelhar

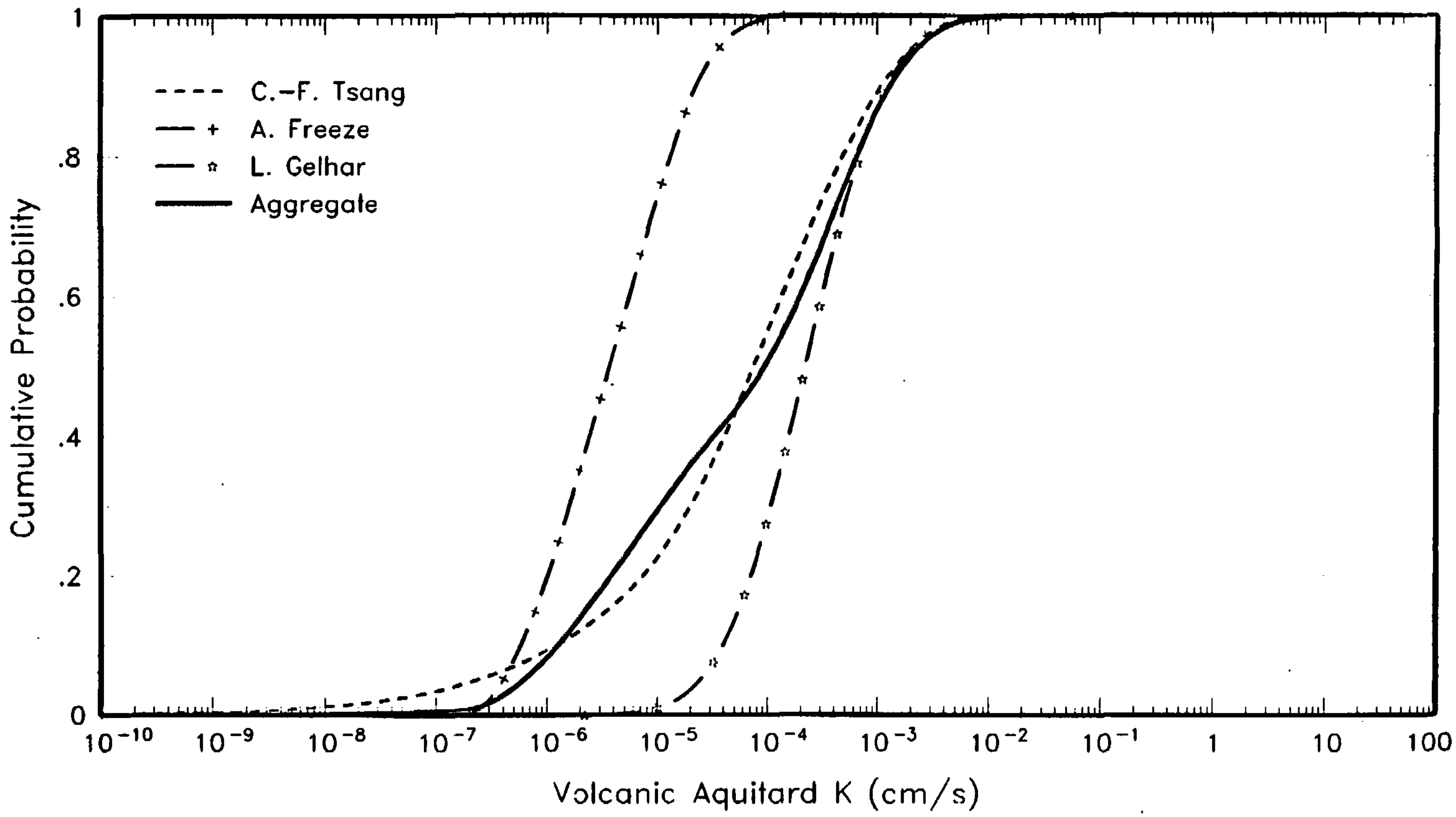

Figure 3-1h Individual and aggregate cumulative distributions for volcanic aquitard hydraulic conductivity

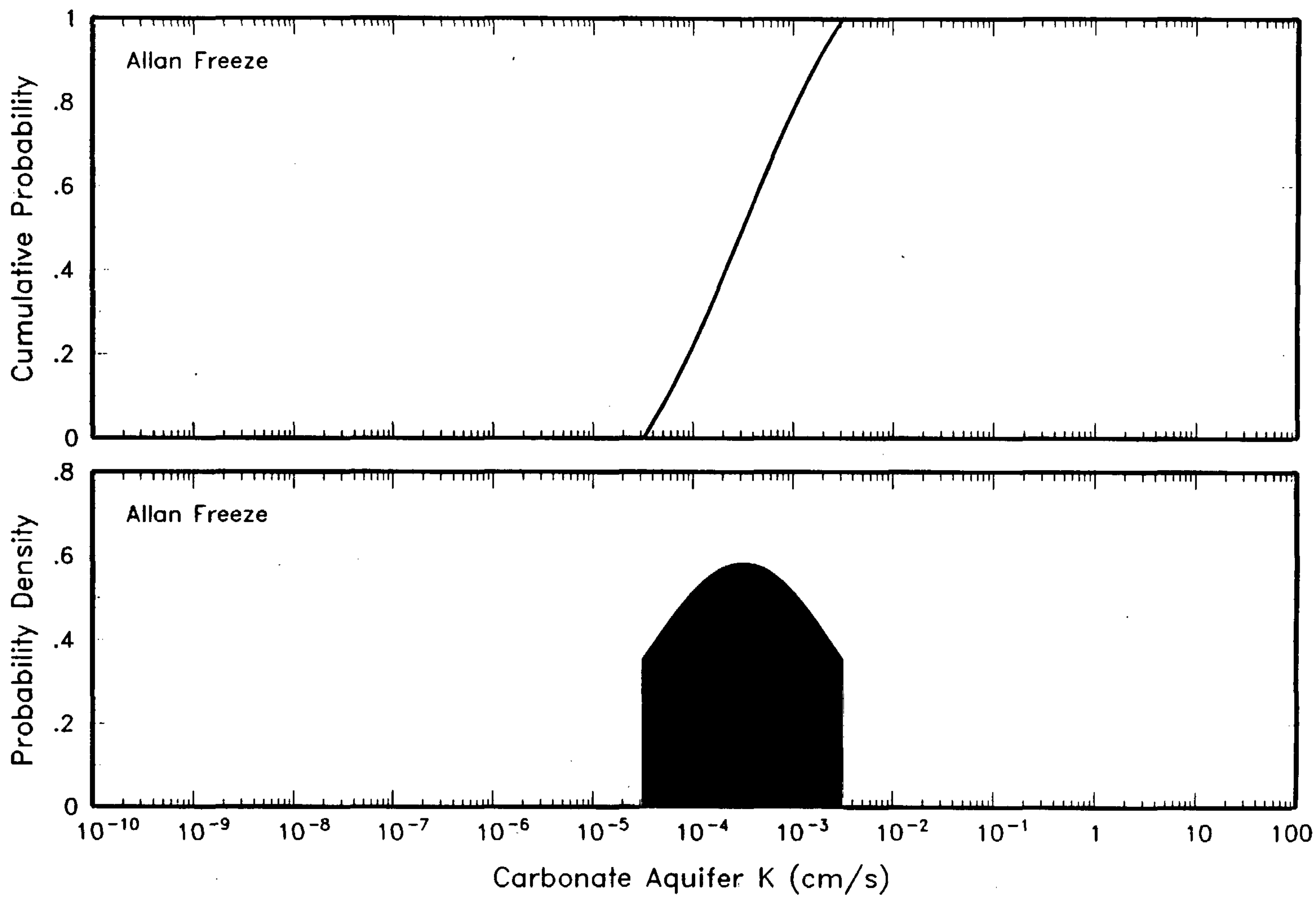

Figure 3-1i Distribution for carbonate aquifer hydraulic conductivity assessed by Allan Freeze

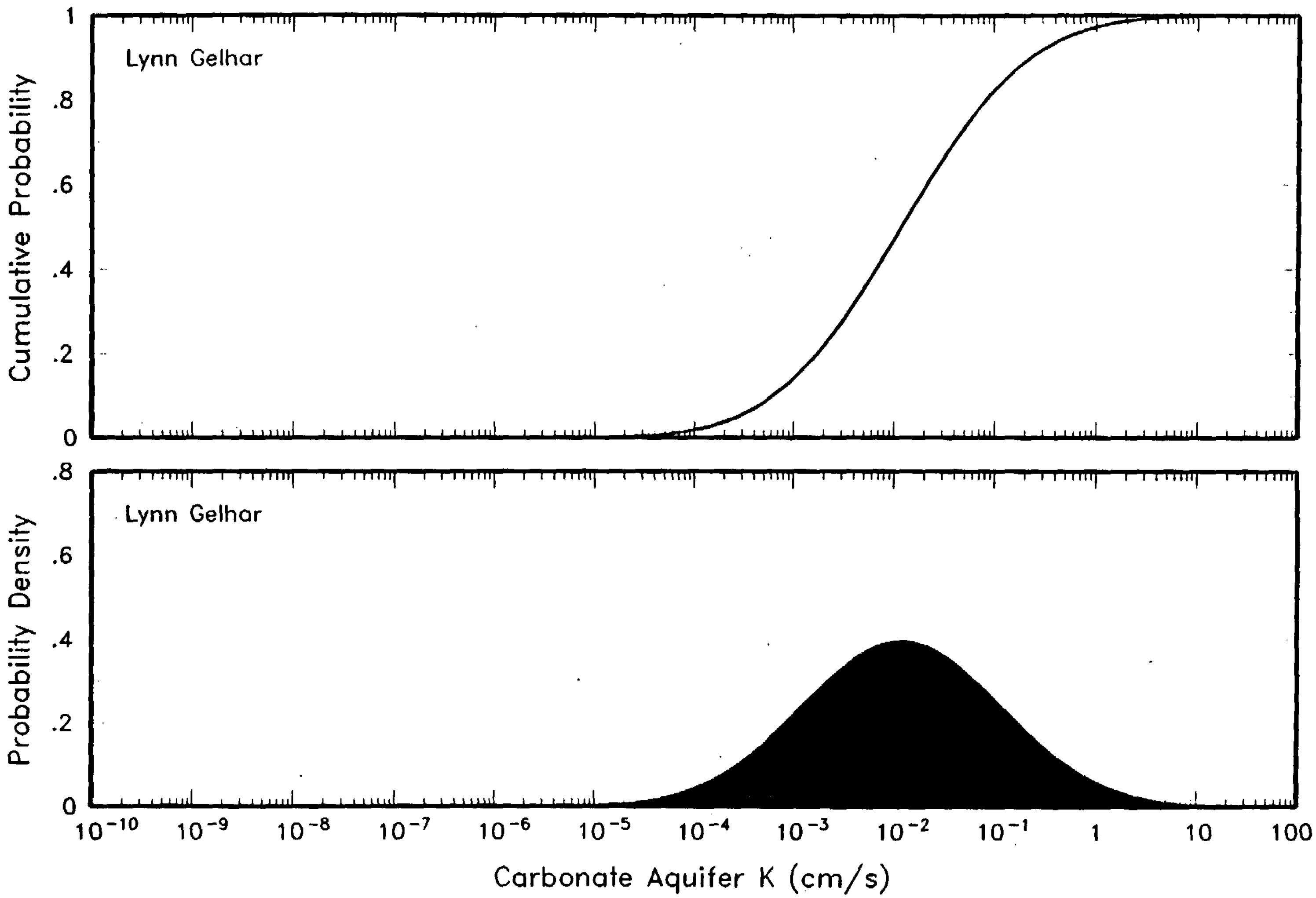

Figure 3-1j Distribution for carbonate aquifer hydraulic conductivity assessed by Lynn Gelhar

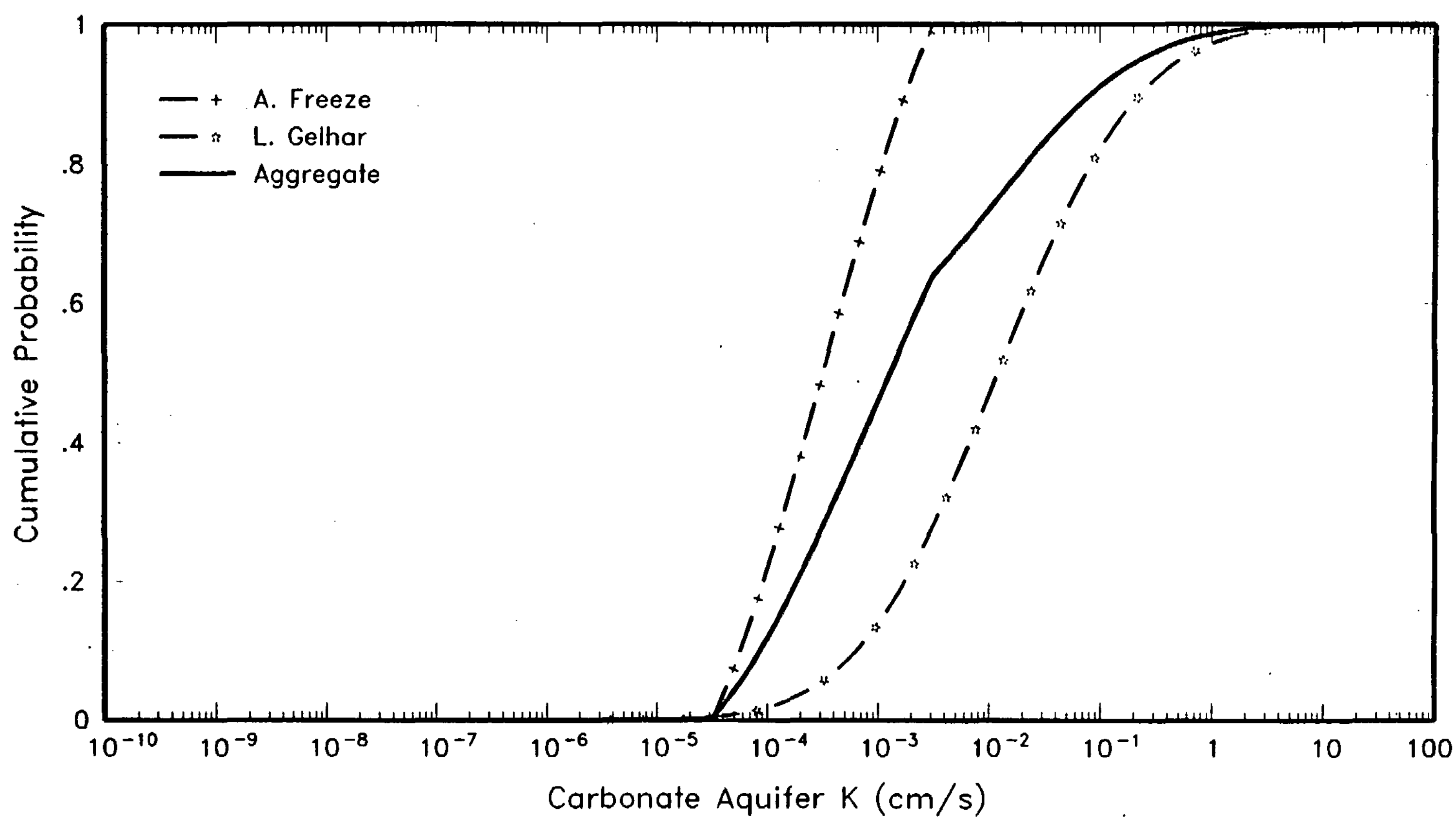

Figure 3-1k Individual and aggregate cumulative distributions for carbonate aquifer hydraulic conductivity

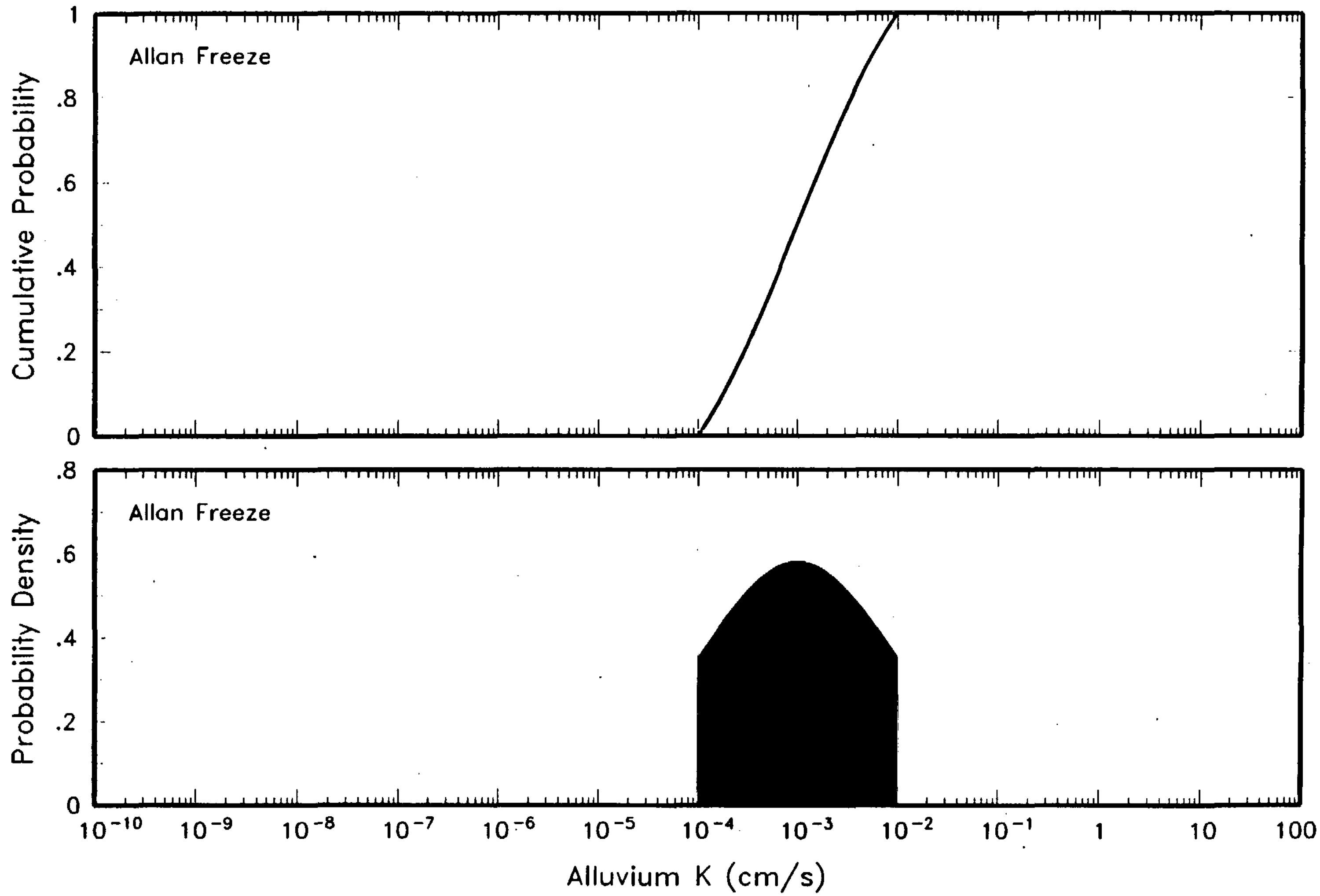

Figure 3-11 Distribution for alluvium hydraulic conductivity assessed by Allan Freeze

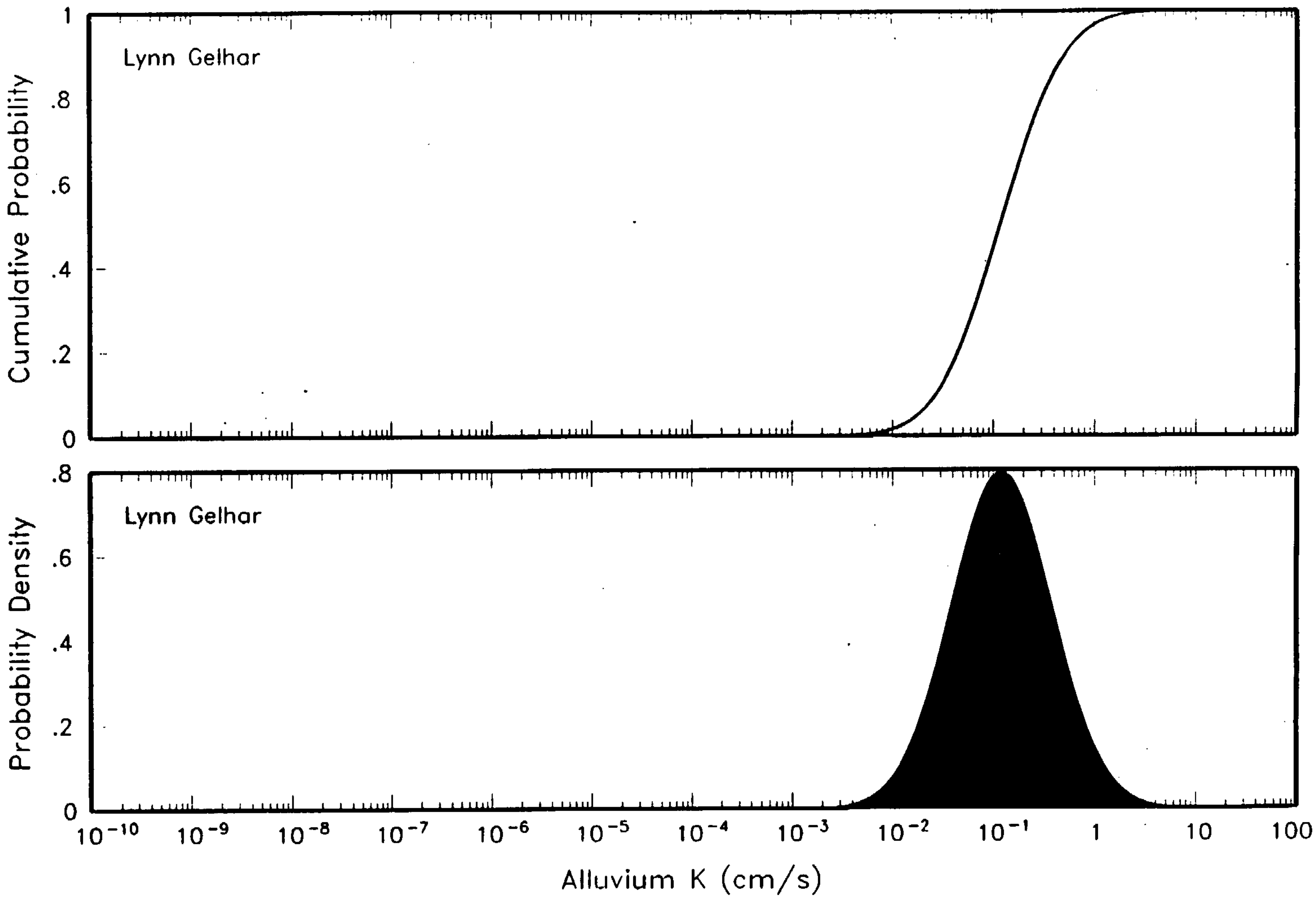

Figure 3-1m **Distribution for alluvium hydraulic conductivity assessed by Lynn Gelhar**

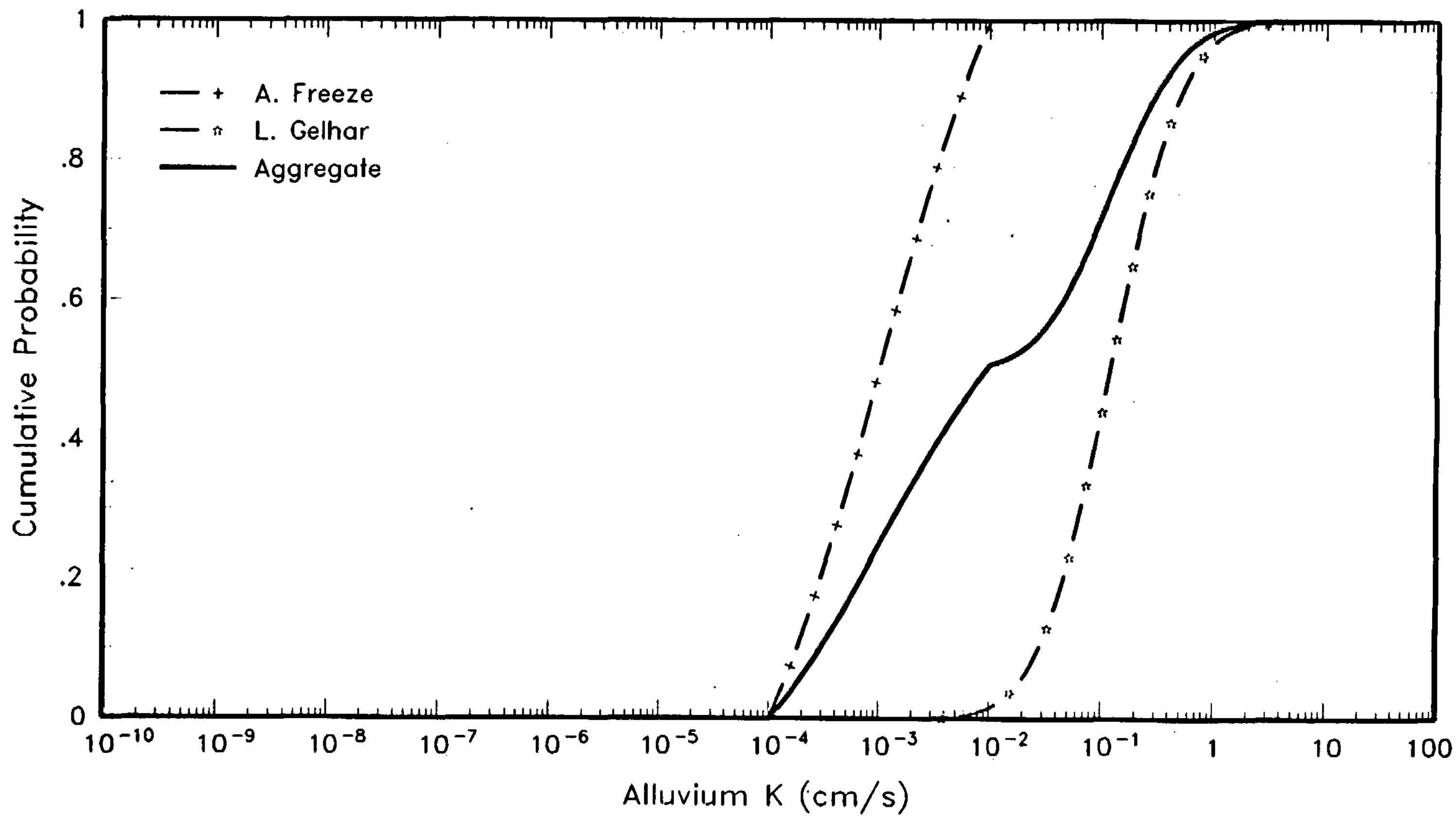

Figure 3-1n Individual and aggregate cumulative distributions for alluvium hydraulic conductivity

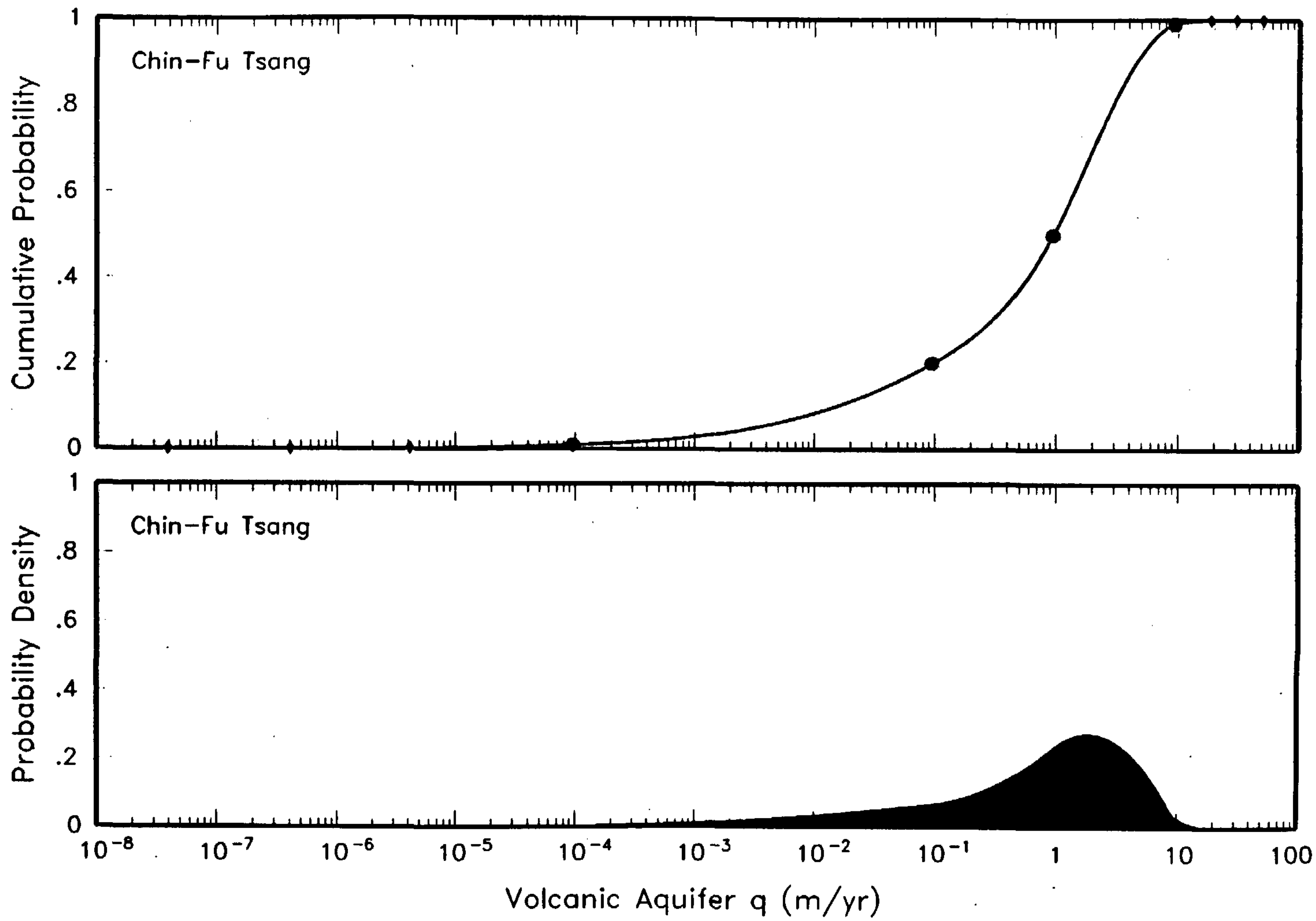

Figure 3-2a Distribution for volcanic aquifer specific discharge assessed by Chin-Fu Tsang

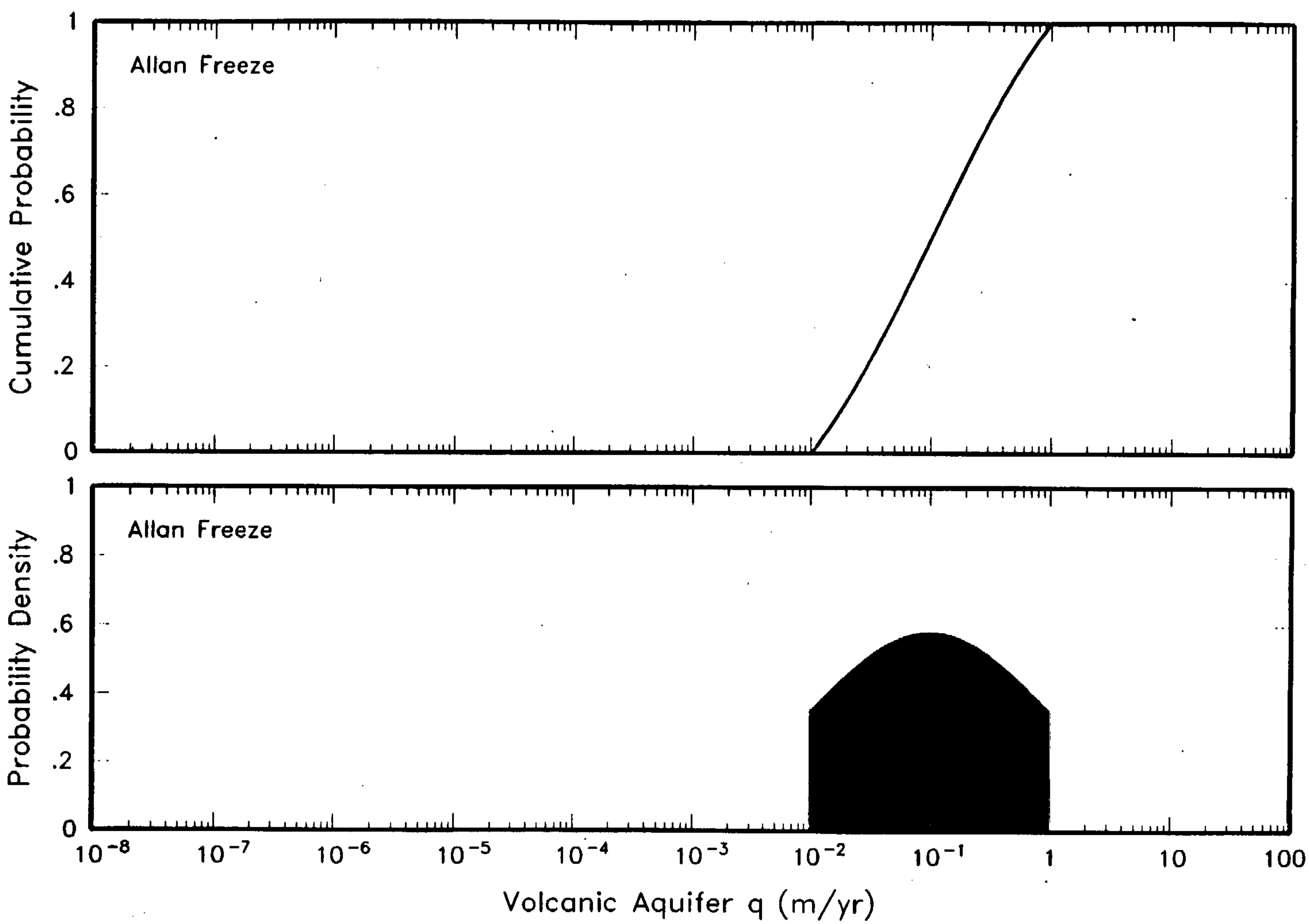

Figure 3-2b Distribution for volcanic aquifer specific discharge assessed by Allan Freeze

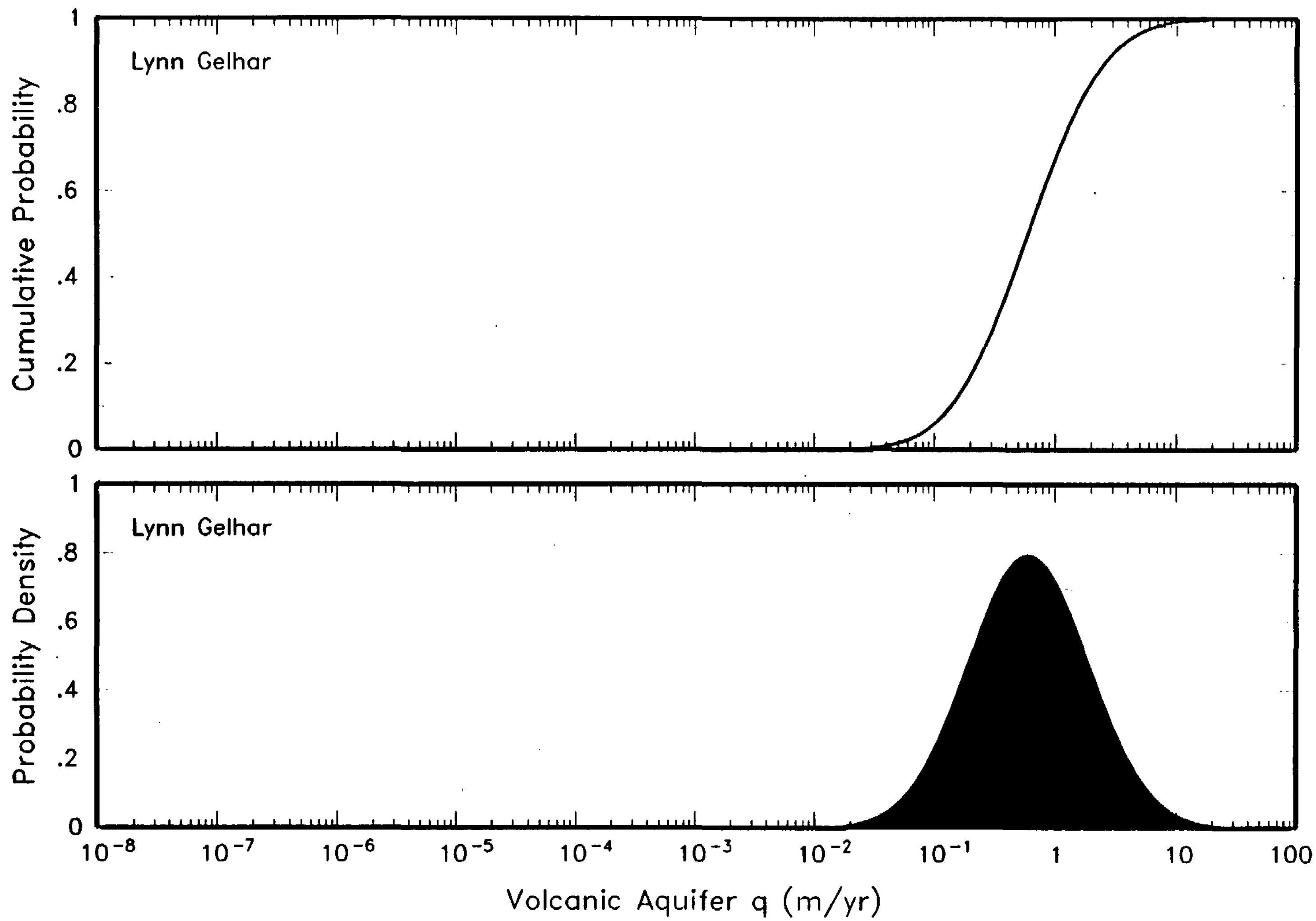

Figure 3-2c Distribution for volcanic aquifer specific discharge assessed by Lynn Gelhar

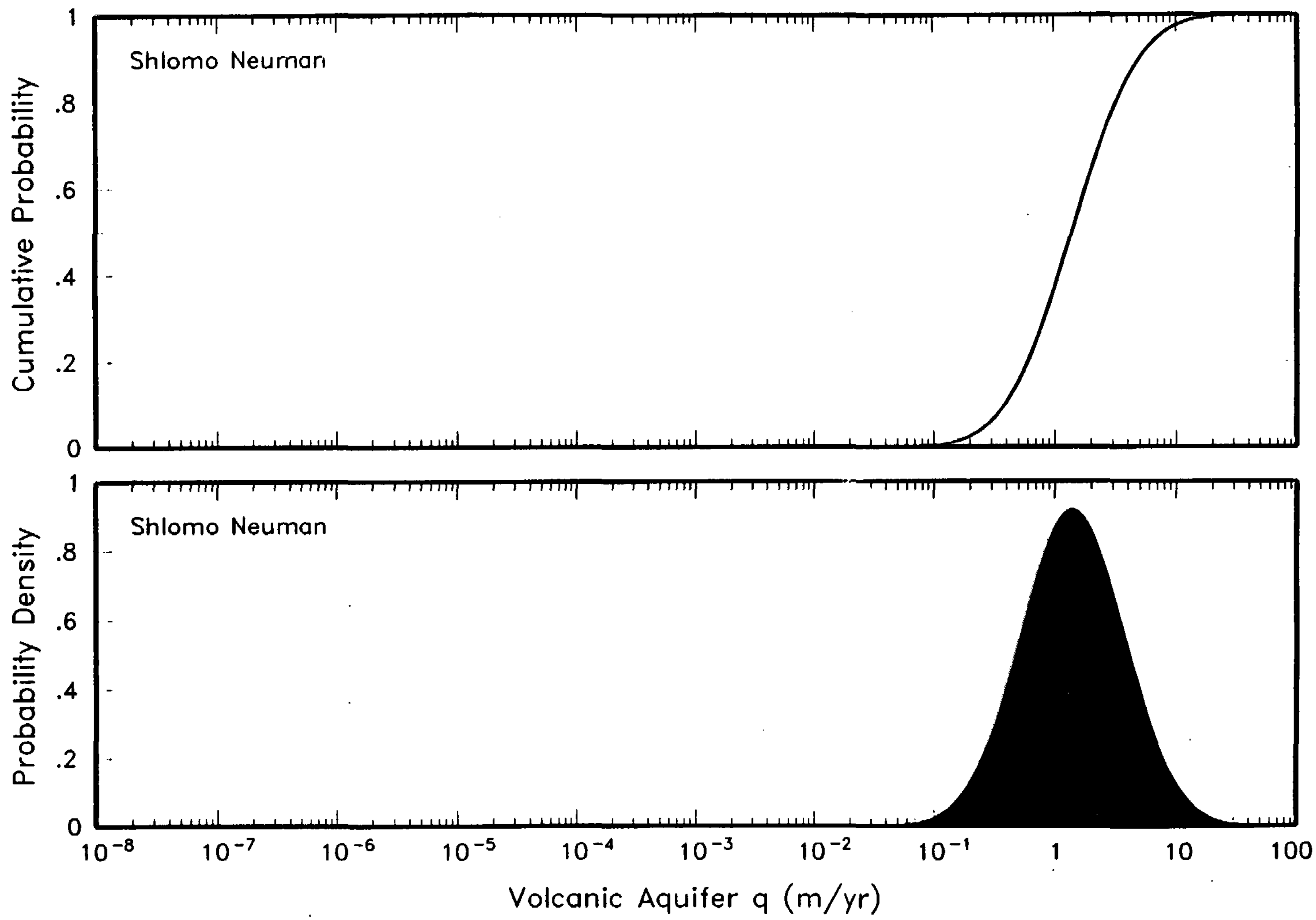

Figure 3-2d Distribution for volcanic aquifer specific discharge assessed by Shlomo Neuman

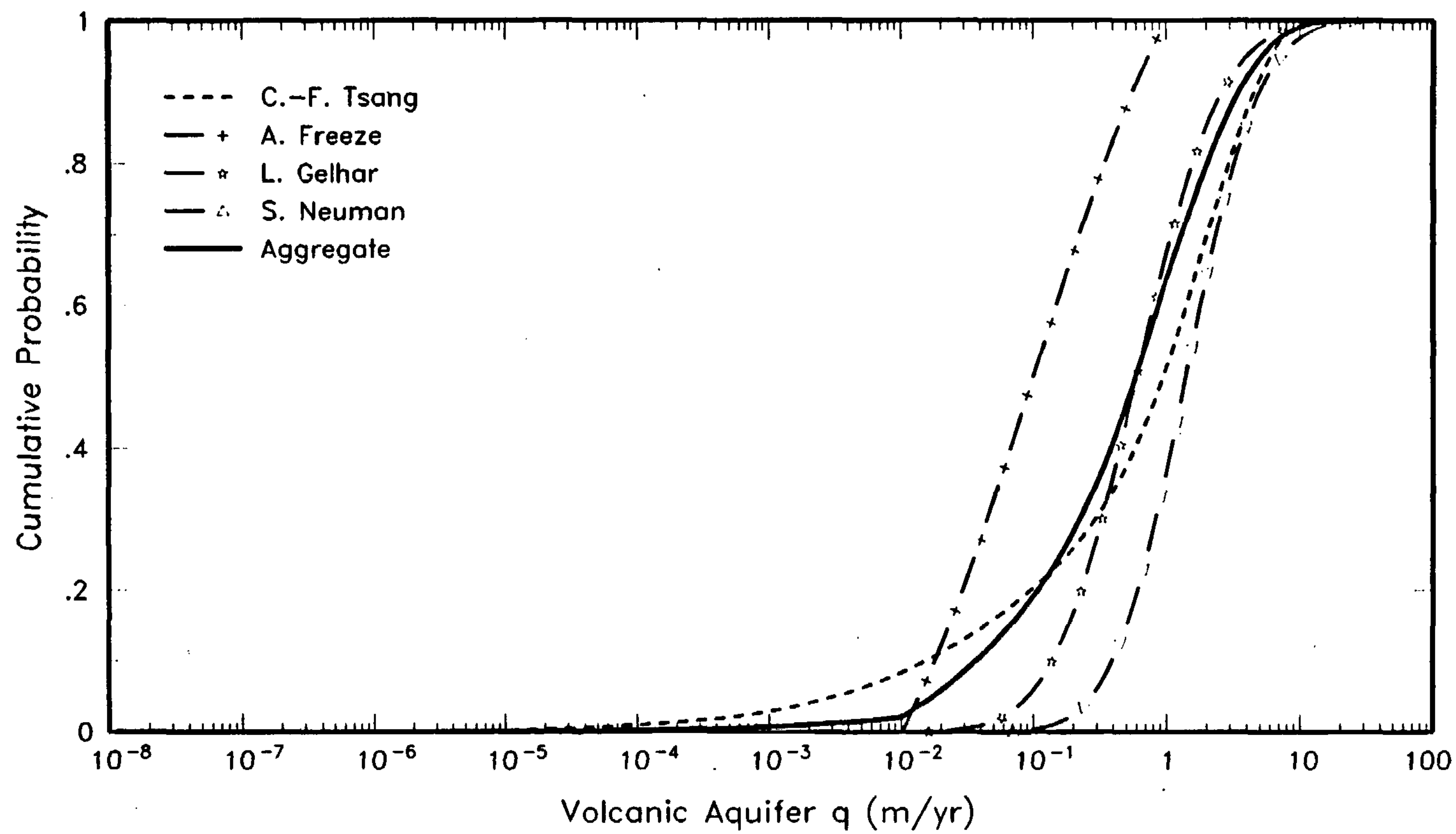

Figure 3-2e Individual and aggregate cumulative distributions for volcanic aquifer specific discharge

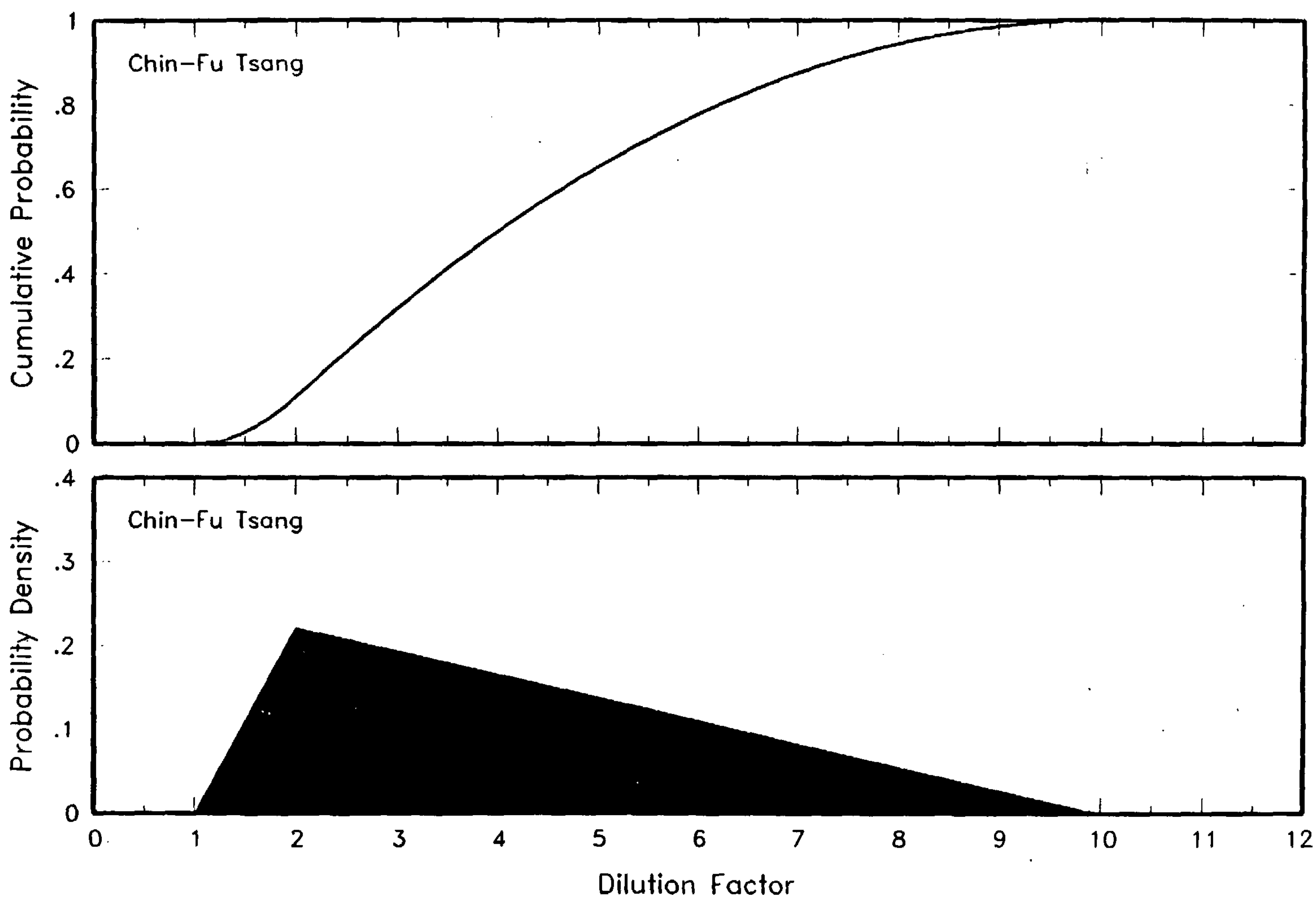

Figure 3-3a Distribution for dilution factor assessed by Chin-Fu Tsang

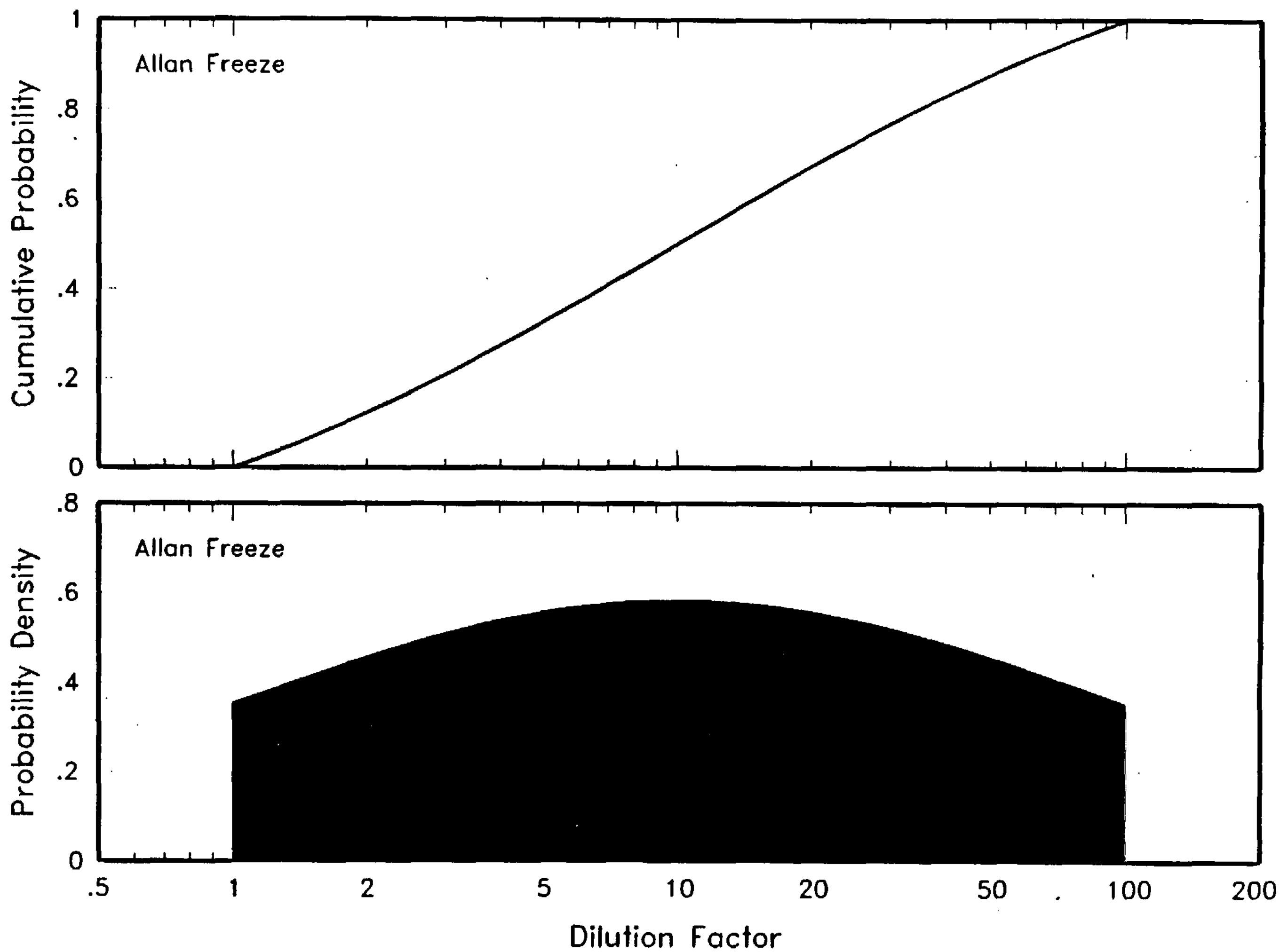

Figure 3-3b Distribution for dilution factor assessed by Allan Freeze

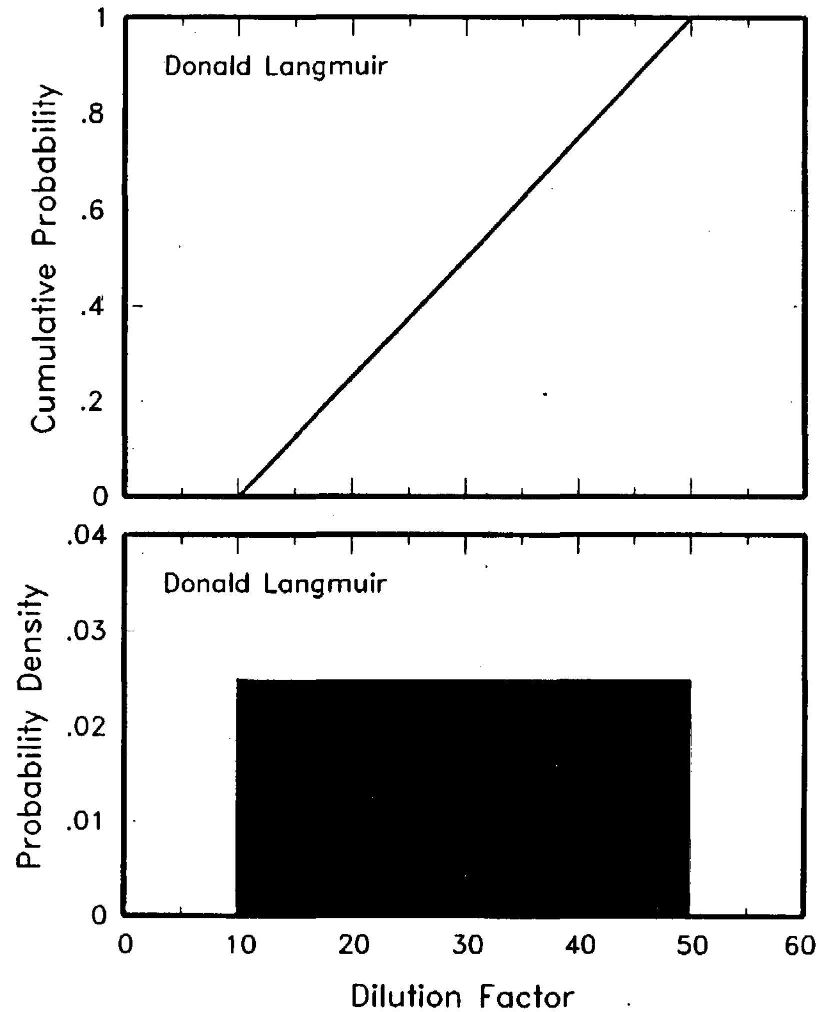

Figure 3-3c Distribution for dilution factor assessed by Donald Langmuir

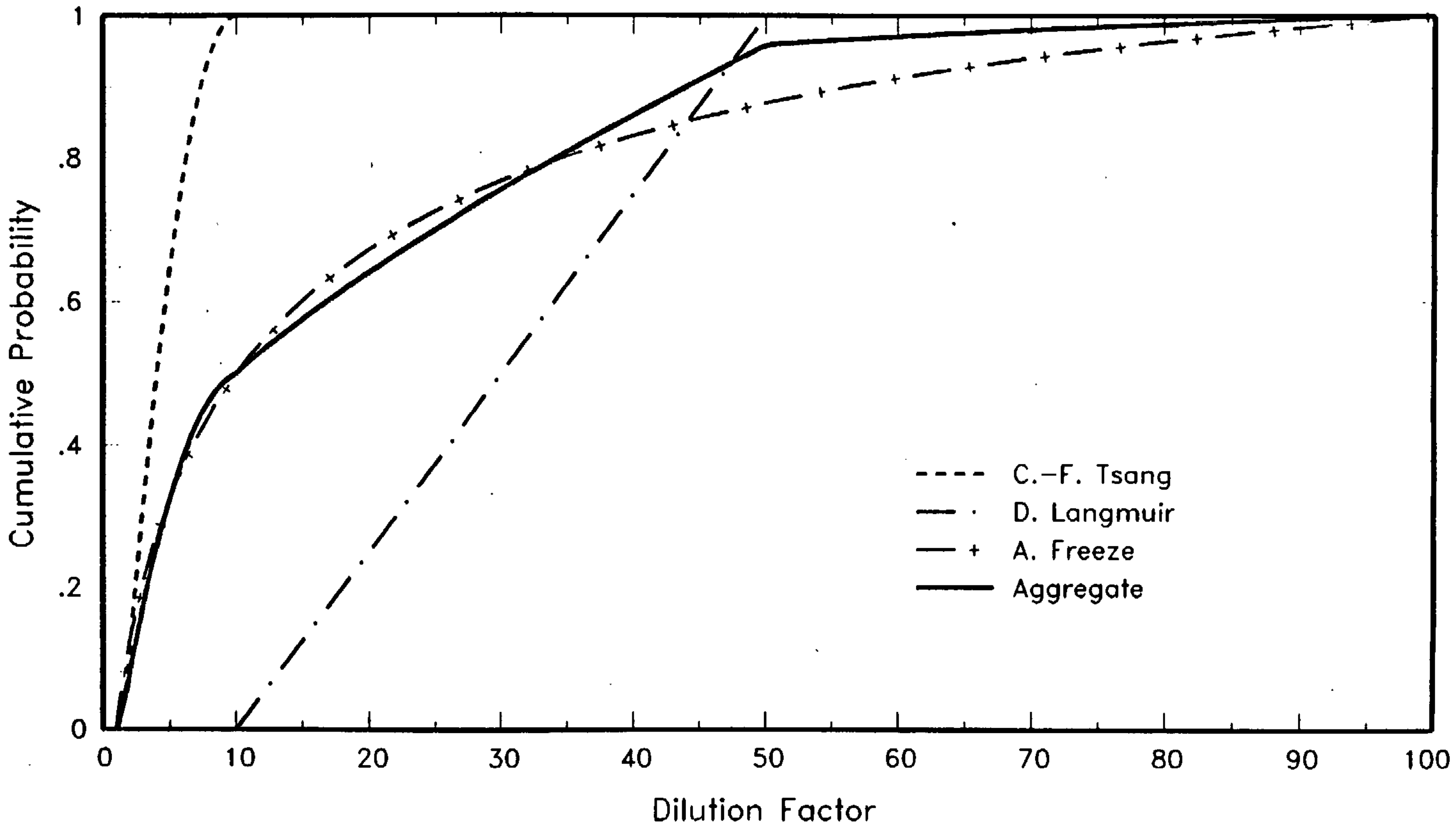

Figure 3-3d Individual and aggregate cumulative distributions for dilution factor

4.0 SUMMARY AND CONCLUSIONS

The Saturated Zone Flow and Transport Expert Elicitation (SZEE) is one of a series of projects that call on the elicitation of experts to characterize the knowledge and uncertainties in key inputs to the Yucca Mountain Total System Performance Assessment (TSPA). The objective of the SZEE project was to characterize the uncertainties associated with certain key issues related to the saturated zone system in and downgradient of the Yucca Mountain area. An understanding of saturated zone processes is critical to evaluating the performance of the potential high-level nuclear waste repository at Yucca Mountain.

A major goal of the project was to capture the uncertainties involved in assessing saturated zone processes. So that the analysis included a wide range of perspectives, multiple individual judgments were elicited from members of an expert panel. The panel members, who were experts from within and outside the Yucca Mountain project, represented a range of experience and specialization. A deliberate process was followed, consistent with procedural guidance regarding expert elicitation methodologies, to facilitate interactions among the experts, train them to express their uncertainties, and elicit their interpretations. The resulting assessments and probability distributions, therefore, provide a reasonable aggregate representation of the knowledge and uncertainties about key issues regarding saturated zone flow and transport.

The principal steps followed in the SZEE project were:

- Development of Project Plan
- Selection of the Expert Panel
- Data Compilation and Dissemination
- Meetings of the Expert Panel
- Elicitation of Experts
- Feedback of Preliminary Results
- Finalization of Expert Assessments
- Preparation of Project Report

The SZEE experts evaluated several key technical issues related to saturated zone flow and transport. A brief summary of the expert interpretations is given below.

Overview: Conceptual Model of Saturated Zone Flow

The experts' conceptual models deal with issues that are important to saturated zone flow and transport in the area beneath the site and downgradient to distances of 5 to 30 km, which are presumed distances to potential receptor locations. The experts concluded that the dominant direction of flow from the Yucca Mountain potential repository site in the saturated zone is southeast to Fortymile Wash and thence south to Amargosa Valley. All of the experts expressed a belief that the downgradient flow paths from Yucca Mountain likely occur within the lower volcanic aquifer and, farther south, within the valley fill alluvium, but likely do not involve the carbonate aquifer.

In general, the experts assessed the regional hydrologic environment as complex and as characterized by high permeabilities. Faults and major fractures are important components of this flow regime, and the hydrogeologic units are more important for identifying the nature of fracturing and faulting than for their matrix characteristics. Members noted that most of the flow appears to be channeled in preferential flow paths, which, based on flowmeter data, appear to represent only 5 to 20 percent of the thickness of the hydrostratigraphic units.

Several experts noted that although the regional and site-scale hydrologic models are being used to account for available data sets, they are not yet at a sufficient degree of development to provide accurate predictions of certain key parameters such as the flux beneath the site.

Large Hydraulic Gradient

In general, the experts narrowed down the various hypotheses for the cause of the feature to two basic models. In the "saturated zone" model, the feature is interpreted to be the result of a water-table slope within a fully saturated flow system and is related to topography, recharge patterns, and geology. In the "perched water" model, the flow system consists of an upper saturated zone underlain by a wedge of unsaturated rocks over the regional water table. Across the panel, the perched zone model was slightly preferred based on available data. We note, however, that the differences between the perched and the saturated models is merely the degree of saturation of the "wedge" between the upper and lower water tables.

Finally, the experts concluded that the probability of any large transient change in the configuration of the large hydraulic gradient (e.g., a sudden "breakthrough" of the feature) due to earthquake or other mechanism is extremely low. Further, long-term transient readjustment of gradients was given a very low probability.

Flux Beneath Yucca Mountain

An important input to the TSPA is the magnitude and orientation of flux at the top of the saturated zone beneath Yucca Mountain. All of the experts addressing this issue provided their assessments of flux as an estimate of specific discharge, q, which is related by Darcy's Law to hydraulic conductivity and hydraulic gradient. Because the application of the assessed hydraulic parameters is at the scale of the current site-scale model, the parameters are given as averages over the scales of the various hydrogeologic units.

The experts based their assessments of hydraulic conductivities for the hydrogeologic units on data sets from single-hole and multiple-hole tests and on their experience at other locations. In general, the heaviest reliance was placed on the C-well multiple-hole pumping tests. Hydraulic conductivity estimates for the hydrogeologic units are shown in Figure 3-1.

The assessed hydraulic gradient in the site vicinity is approximately 0.0003 to the southeast. The cumulative distribution functions (CDFs) for specific discharge are shown in Figure 3-2.

Influence of Climate Change

The experts generally agreed that the position of future water-table changes related to future climate change are best estimated by evaluating past water-table changes associated with previous glacial periods. The geochemical and paleodischarge evidence for past elevations of about 80 to 120 m above their present level was generally considered reasonable by the panel. Some of the experts noted that a particular purpose of the regional hydrologic model—once properly calibrated—should be to provide estimates of the influence of climate change on the hydrologic system. Regarding changes in the flow system, it was concluded that during wetter glacial periods, changes in the flow system could lead to more transients, perhaps changes in flow direction and hence greater dilution, and changes in levels of flux.

Conceptual Models of Saturated Zone Transport

The primary transport mechanism for contaminants from the repository is advective transport, particularly along preferential flow paths. This transport was envisioned by most of the experts as occurring along flow tubes that emanate from beneath the repository and proceeding downgradient, traveling within the volcanic aquifer and the alluvium, with little or no flow in the carbonates. Disregarding mixing within an extraction well, the experts concluded that the likely mechanisms for dilution of the contaminant plume are molecular diffusion and advective dispersion. They identified few mechanisms that would lead to substantial mixing, such as turbulent eddies, transients, or fingering. In general, the experts rejected a "stirred tank" model that assumes mixing at the water table of contaminants from the unsaturated zone with groundwater traveling horizontally in the saturated zone. The vertical width of the plume was estimated to be on the order of a few tens of meters, with dilution restricted to that which occurs through vertical dispersion. The experts generally concluded that there will be only small amounts of lateral and vertical dispersion along flow paths from the repository to distances of 5 to 30 km from the site.

Dilution Factor/Dispersivity

The experts provided their assessments expressed as either a "dilution factor" or as estimates of dispersivity. "Dilution factor" is defined as the ratio between the initial contaminant concentration and the highest concentration at a point some distance from the source. The assessment of dilution factors, given by Drs. Tsang, Langmuir, and Freeze, are shown in Figure 3-3. The values range from 2 to 100, with a median estimate of about 12. Dr. Gelhar provided estimates of longitudinal and transverse dispersivity for distances of 5 and 30 km.

Effective Fracture Density

Effective fracture density is defined as the average spacing of significant fractures that carry flow. The estimates, which range from 10 to 100 m, were based primarily on the frequency of major fractures mapped in the Exploratory Studies Facility, detailed surface geologic mapping, and indications of flowing zones in pump tests.

Hydrochemical Transport Parameters

The principal transport parameter used by the TSPA are sorption coefficients (Kd) for radionuclides. Dr. Langmuir addressed the issue of the applicability of laboratory-derived Kd values by providing a distribution of "effective Kd" values that consider the potential for various conditions and reactions along the flow path. In this way, the effective Kd values can consider the laboratory sorption values as well as field conditions that would cause them to be higher or lower, or to increase or decrease the range of uncertainty in Kd values. Dr. Langmuir concluded that in the Yucca Mountain region the effective Kd values generally will be higher than the laboratory values. He provided his assessments of effective Kd values for neptunium and uranium for the various hydrogeologic units.

Thermohydrology

Panel members assessed the potential effect on the saturated zone from thermal elevation due to repository heating. Although the experts generally concurred on the possible effects on the saturated zone, they were somewhat divided on the relative importance those effects might have. Potential effects from the expected increase in temperature at the saturated zone beneath the repository are changes in viscosity, precipitation and dissolution of minerals, and reduction in the width of the vertical plume due to buoyancy.

Colloids

Dr. Langmuir summarized his assessment of the fate of colloids. Many will be filtered out in the backfill or invert within the drift. Degradation colloids (such as Pu oxides) and radiocolloids will be undersaturated with respect to groundwater as soon as they move away from the waste. They therefore will tend to dissolve in the groundwater, and once in solution tend to be adsorbed by rock surfaces in fractures and especially in the matrix. Actinides on the surfaces of geocolloids will tend to desorb with groundwater flow, and to be readsorbed by surrounding rock surfaces that have the same surface bond strengths toward the actinides but have unoccupied surface sites and orders of magnitude more reactive surface area.

Water-Table Changes from Disruptive Events

All of the experts addressing this issue concluded that changes to the water table associated with earthquakes will be neither significant nor long-lived.

Anisotropy

Those experts who addressed this issue expressed their belief that there would be significant horizontal to vertical anisotropy at these scales in response to layering of the system. Horizontal to vertical anisotropy ratios range from 3:1 to 100:1. Anisotropy in the horizontal plane is suggested by the pattern of drawdown associated with the C-wells, the experts concluded.

Recommendations for Reducing Uncertainty

The experts provided their judgments regarding activities that could be conducted to reduce uncertainties in key issues related to the saturated zone. Suggestions included both additional data-collection activities and modeling/analysis activities. The suggestions are presented in the elicitation summaries (Appendix D) and summarized in Table 3-2.

APPENDIX A

BIOGRAPHIES
OF
MEMBERS OF THE EXPERT PANEL

BIOGRAPHIES OF MEMBERS OF THE EXPERT PANEL

Dr. R. Allan Freeze is President of R. Allan Freeze Engineering, Inc., based in White Rock, BC, Canada. He consults widely for private-sector clients and government agencies on projects involving groundwater supply, groundwater contamination, geotechnical seepage, and nuclear waste disposal. Before establishing his consulting practice, Dr. Freeze worked for Environment Canada in Calgary, AB; the IBM Thomas J. Watson Research Center in Yorktown Heights, NY; and the University of British Columbia in Vancouver, BC. During his 18-year career at U.B.C., he was Director of the Geological Engineering Program for six years and Associate Dean of Graduate Studies for three years. During his academic career, Dr. Freeze published more than 100 research papers. He has received the Horton and Macelwane awards from the American Geophysical Union, the Meinzer Award from the Geological Society of America, and the Theis Award from the American Institute of Hydrology. He is a fellow of the Royal Society of Canada. He is a former editor of the journal *Water Resources Research*, and is former President of the Hydrology Section of the American Geophysical Union. He is co-author, with John Cherry, of the widely used textbook Groundwater. Dr. Freeze earned a B.S. (1961) in geological engineering from Queen's University in Ontario, Canada, and an M.S. (1964) in geological engineering and Ph.D. (1966) in Civil Engineering from the University of California at Berkeley.

Dr. Lynn W. Gelhar is Professor of Civil and Environmental Engineering at the Massachusetts Institute of Technology. His current research focuses on stochastic theories of transport processes for unsaturated flow, fractured media, chemically heterogeneous media, variable viscosity fluids, biodegradation, multiphase flow, controlled field experiments on macrodispersion in aquifers and unsaturated flow, large-scale supercomputer simulation of flow and transport in heterogeneous porous media, and stimulation of in situ biodegradation using gas injection. He is the author of the textbook Stochastic Subsurface Hydrology, published by Prentice-Hall, Inc., and has authored more than 140 technical publications. He has extensive consulting experience with government and industry on aspects of groundwater hydrology, dealing particularly with problems of hazardous and radioactive waste disposal. Dr. Gelhar has been principal investigator on more than 30 research projects and has served on several multidisciplinary review teams, for instance reviewing environmental aspects of the Hanford site in Washington, the proposed WIPP radioactive waste disposal site in New Mexico, and the nuclear weapons test site in Nevada. Through consulting activities he has been involved in efforts to clean up uranium mine mill tailings sites and in several aspects of the high-level waste facility proposed for the basalt at the Hanford site in Washington. In 1982 Dr. Gelhar received the American Geophysical Union's Horton Award, and in 1983 was elected a fellow in the

American Geophysical Union. In 1987 he received the O.E. Meinzer Award from the Geological Society of America. He has been a visiting professor at universities and institutions throughout the world. Dr. Gelhar earned B.S. (1959), M.S. (1960), and Ph.D. (1964) degrees in Civil Engineering from the University of Wisconsin.

Dr. Donald Langmuir has been a full professor at the Colorado School of Mines since 1978. He is now Professor of Chemistry and Geochemistry, Emeritus, and President of Hydrochemical Systems Corporation. He performs research in environmental geochemistry and has taught graduate courses in introductory geochemistry,. environmental chemistry, and advanced aqueous geochemistry, with an emphasis on subsurface aqueous systems. During the past 31 years, Dr. Langmuir has published more than 150 papers, abstracts, and books, including the textbook Aqueous Environmental Geochemistry,published in 1997 by Prentice Hall. He has been elected a fellow of the American Association for the Advancement of Science and of the Mineralogical Society of America, and has served as chairman of the Environmental Committee of the Geochemical Society. He was also associate editor of *Geochimica et Cosmochimica Acta*, the journal of the Geochemical Society, and served on the editorial board of *Interface*, the journal of the Society of Environmental Geochemistry and Health. He has served on or chaired more than 20 expert panels. Dr. Langmuir currently is a senior advisory scientist to the Chemical and Science Technology Division of Los Alamos National Laboratory. In 1989, Dr. Langmuir was nominated by the National Academy of Sciences and appointed by President Reagan to serve as a member of the U. S. Nuclear Waste Technical Review Board. He was reappointed to that position for a second four-year term by President Bush, serving until 1997. As a consultant, Dr. Langmuir has worked on about 75 projects for clients throughout the United States and abroad. He has had extensive experience solving problems related to surface and groundwater pollution caused by the disposal of municipal and industrial wastes and by mining. He also has 20 years of experience solving problems related to the geologic disposal of nuclear wastes. Dr. Langmuir has served as an expert witness in numerous court cases. Dr. Langmuir received his A.B. (1956, with honors), M.A. (1961), and Ph.D. (1965) degrees in geochemistry from Harvard University.

Dr. Shlomo P. Neuman is Regents' Professor of Hydrology and Water Resources at the University of Arizona in Tucson. His research group conducts field, theoretical, and computational investigations of flow and transport through unsaturated fractured tuffs. Related research includes development and application of geostatistical methods for the spatial analysis of hydrogeologic data; development and application of stochastic methods to describe mathematically fluid flow and solute transport when the properties of soil and rock vary randomly in space and with the scale of observation; and development of a comprehensive modeling strategy of flow and transport under uncertainty for performance assessment of nuclear waste, decommissioning, and uranium recovery sites.

Dr. Neuman also helped develop computational algorithms and computer programs to predict subsurface flow and solute concentrations under uncertainty and to assess associated prediction errors; to estimate parameters for flow and transport models under uncertainty; and to use such computational models to help assess subsurface contamination, identify contaminant sources, design groundwater monitoring networks, and aid the design of remedial operations. Dr. Neuman has summarized his scientific contributions in more than 200 professional publications and has received many awards and honors, including an honorary appointment as professor of Nanjing University in China. He was elected a member of the National Academy of Engineering and a fellow of both the American Geophysical Union and the Geological Society of America. He is a certified professional hydrogeologist. Dr. Neuman received a B.S. in geology (with a minor in physics) from Hebrew University in Jerusalem (1963). He received an M.S. (1966) and Ph.D. (1968) in engineering science (civil/geotechnical) from the University of California at Berkeley.

Dr. Chin-Fu Tsang is a senior staff scientist with Lawrence Berkeley Laboratory's Earth Sciences Division, where he has pursued a variety of research interests for almost 30 years. After working in geothermal reservoir dynamics, he began to focus on heat exchange processes for underground thermal energy storage and on dynamic borehole fluid logging methods. Since 1987, he has been active in coupled thermo-hydro-mechanical processes associated with nuclear waste repositories, and in the numerical stochastic modeling of flow and transport in heterogeneous systems having a large variance and a spatial correlation length comparable to flow distances. For the latter, his work has emphasized the effects of channelized flow on both saturated and unsaturated media. Dr. Tsang has joined in international research efforts in hydrogeology, playing a key role in such international projects as HYDROCOIN and INTRAVAL. He currently is Chair of the Steering Committee for the International DECOVALEX project [1992-1998]. The project, based in Sweden, brings together researchers from eight countries to advance the state of science in coupled processes. He also established a Russian-American Center for Contaminant Transport Studies in Berkeley in 1993. Dr. Tsang has published more than 250 reports and invited conference presentations, including more than 90 papers in refereed journals. He is a co-author of the popular Water Resources Monograph 10, Groundwater Transport, published by the American Geophysical Union in 1984, now in its fourth printing. He has co-edited six other books in areas such as flow and contaminant transport, fractured rock, deep well injection, and coupled thermo-hydro-mechanical processes. Dr. Tsang has been invited to lecture at the Russian Academy of Sciences, the Academia Sinica, University of Paris, Moscow State University, Weizmann Institute of Science, the Japanese Ministry of Trade and Industry, and the NATO Advanced Study Institutes. Dr. Tsang received a First Class Honors B.S. in physics from the University of Manchester, England (1964) and a Ph.D. in Physics from the University of California at Berkeley (1969).

APPENDIX B

REFERENCES DISTRIBUTED TO MEMBERS OF THE EXPERT PANEL

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APPENDIX C

WORKSHOP AND FIELD TRIP SUMMARIES

SUMMARY
WORKSHOP ON SIGNIFICANT ISSUES AND AVAILABLE DATA

SATURATED ZONE EXPERT ELICITATION PROJECT

June 4 to 6, 1997
Denver Federal Center
Denver, Colorado

The Workshop on Significant Issues and Available Data was the first of three workshops to be conducted for the Yucca Mountain Saturated Zone Flow and Transport Expert Elicitation (SZEE) project, sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The goals of the workshop were to (1) introduce the expert panel to the SZEE project; (2) summarize the significant issues related to previous modeling of the saturated zone flow and transport system, and to incorporation of that modeling into previous total system performance assessments; and (3) summarize the available data sets developed to characterize the saturated zone in the Yucca Mountain region. The workshop of two and one-half days provided an opportunity for the members of the expert panel to gain a first-hand understanding of the data, their uncertainties, and the course of the rest of the project.

Copies of the overhead transparencies and slides shown during the workshop are available in the SZEE administrative files.

DAY 1 - WEDNESDAY, JUNE 4

Dr. Thomas Bjerstedt (DOE) welcomed attendees to the workshop on behalf of the U.S. Department of Energy. Dr. Kevin Coppersmith (Geomatrix) then welcomed participants and provided an overview of the steps to be followed, and the participants, in the SZEE project. He introduced the members of the methodology development team (MDT), the group that plans and conducts the project activities. MDT members include: Dr. William (Bill) W. Arnold (Sandia National Laboratories), Dr. Kevin J. Coppersmith (Geomatrix Consultants), Dr. Dwight Hoxie (U.S. Geological Survey), Mr. Russ Patterson (DOE), Ms. Martha Pendleton (M&O/ Woodward-Clyde Federal Services [WCFS]), Dr. Roseanne C. Perman (Geomatrix Consultants), and Mr. Patrick (Pat) Tucci (USGS), Dr. Peter A. Morris (Applied Decision Analysis), and Dr. Robert (Bob) Youngs (Geomatrix Consultants). Dr. Coppersmith discussed the process followed to select the members of the expert panel, and introduced the panel members: Dr. R. Allan Freeze (R. Allan Freeze Engineering, Inc.); Dr. Lynn W. Gelhar (Massachusetts Institute of Technology); Dr. Donald Langmuir (Colorado School of Mines, Emeritus); Dr. Shlomo P. Neuman

(University of Arizona); and Dr. Chin-Fu Tsang (Lawrence Berkeley National Laboratory). Workshop observers were asked to introduce themselves; a number of organizations were represented, including the U.S. Nuclear Regulatory Commission, the Nuclear Waste Technical Review Board, the Center for Nuclear Waste Regulatory Analyses, and the U.S. Geological Survey. Dr. Coppersmith discussed the expert roles of evaluator and proponent; outlined the meetings planned for the SZEE project; discussed the elicitation interviews, feedback, and the documentation process; and described other recent or ongoing expert elicitation studies for the Yucca Mountain project. Dr. Coppersmith reviewed the ground rules for workshops and described the purpose and approach for the first workshop.

A series of three talks were presented by members of the MDT to provide an overview of the Yucca Mountain project, the SZEE project objectives from a performance assessment perspective, and an overview of the saturated zone (SZ) flow system at Yucca Mountain as studied and modeled by the USGS. Martha Pendleton provided an overview of the objectives and strategies for the Yucca Mountain project. She described a number of features of the site characterization project, including the evolving waste containment and isolation strategy, analyses of disruptive processes and events, and the overall project objectives, including the 1998 Total System Performance Assessment (TSPA) -Viability Assessment (VA). The SZEE will support the TSPA-VA by assisting in defining likely alternative conceptual models for saturated zone flow and transport, and defining reasonable parameter ranges that include, where possible, probability distributions for those parameters. Bill Arnold discussed SZ flow and transport in the context of TSPA, discussing previous TSPA analyses and SZ model abstractions. He described the key issues in SZ flow and transport based on performance criteria used in prioritizing issues. His presentation concluded with a discussion of the role of the SZEE in quantifying uncertainty in key processes and parameters, which will include assistance in defining parameter uncertainty distributions and in defining the "reasonableness" of current SZ flow and transport models.

In the third and last MDT presentation, Pat Tucci provided an overview of the status of understanding of the SZ flow system at Yucca Mountain. He showed maps of the regional geographic features and described the regional hydrogeologic setting (including the overall water flow patterns and areas of discharge and recharge) and hydrogeologic units. He then focused on the hydrogeologic setting of the Yucca Mountain site, briefly describing the geologic units; major geologic features; potentiometric surfaces; and the large, moderate, and small hydraulic gradients. Mr. Tucci discussed the SZ flow modeling, including previous models, current modeling efforts, and the USGS regional and site-scale SZ models. The USGS models, and in particular the data inputs to the models, were the subject of subsequent workshop presentations (alternative models and interpretations are the focus of Workshop #2). Claudia Faunt (USGS) ended the first day's sessions by discussing the USGS regional and site hydrogeologic framework. She described the scope of the study, the centralized data base and data sources being used, the process followed to construct the 3-D framework model, and the hydrogeologic units used in the model. She showed a number of maps, cross sections, and fence diagrams displaying various model attributes.

Dr. Coppersmith opened the workshop to comments from observers. There was general discussion of the complexity of the SZ groundwater flow system at Yucca Mountain and how data could best be presented to facilitate the expert panel's understanding of the system.

DAY 2 - THURSDAY, JUNE 5

The second day of the workshop began with three talks in a session on "Hydraulic Characteristics." Claudia Faunt gave the first presentation on published regional and site hydraulic data. She described the available hydraulic conductivity, permeability, and porosity data and how the data were combined into a series of distributions representing a range of parameter values. Amjad M.J. Umari (USGS) gave a presentation on "Hydraulic and Tracer Testing at the C-Well Complex." He described the series of tests to measure pressure, temperature, and other properties conducted at the C-hole complex on the east side of Yucca Mountain near Bow Ridge. The hydraulic and tracer tests that have been conducted, their results and uncertainties, and the hydrogeologic intervals delimited by packer placement were discussed. He concluded that the tests at the C-well complex have successfully characterized hydraulic and transport properties of high-flow zones. Grady M. O'Brien (USGS) gave the third talk in the session, titled: "Single-borehole Aquifer Tests and Water-level Frequency-Response Analysis." He described the analytical approach, data quality, and uncertainties. The results of the frequency-response analysis include parameter ranges for vertical hydraulic conductivity, specific storage, and porosity.

The next session was titled "Water-Level Data and Trends." Frank D'Agnese gave an overview presentation on the Death Valley regional potentiometric surface. Robert Graves (USGS) gave a presentation on water-level data and trends at Yucca Mountain. He described the terminology used for the various types of wells and described the monitoring program and measurement corrections. He reported observed trends in 1985-1995 water-level data that include no apparent seasonal effects and no effect from regional groundwater withdrawals. The final talk in the session was given by John Czarnecki (USGS). He described the large hydraulic gradient defined in the region by two wells north of Yucca Mountain and several wells to the south. He discussed the water-level data at well USW G-2, and the possible evidence for perched water when compared with UZ-14. Dr. Czarnecki demonstrated that different conceptual models of the water table could be developed by selectively removing specific wells.

Following a lunch break, three talks were given in a session on "Recharge." The first talk, by Dr. Czarnecki, focused on the regional recharge patterns. Using data from Pahute Mesa south into the Amargosa Valley, he suggested that water from Pahute Mesa possibly does not flow to Yucca Mountain. Dr. Chuck Savard (USGS) described studies to estimate groundwater recharge in a 30-km area of Fortymile Wash, east of Yucca Mountain. He estimated streamflow volumes, infiltration loss volumes, and groundwater recharge volumes for four reaches of the wash to obtain relative recharge volumes and the groundwater recharge rate. Dr. D'Agnese gave the third talk, focusing on regional recharge estimates using a modified Maxey-Eakin approach. He discussed this approach, and the high, moderate, and low classes of recharge that can be developed for the region.

The last session of the day was on "Discharge." Dr. D'Agnese described regional evapotranspiration (ET) estimates using remote sensing and 3-D GIS data. Annual ET rates in Pahrump Valley were estimated based on vegetation types, and recharge rates estimated at discharge areas in the region. Detailed maps of potential recharge have been developed. Dr. Czarnecki, in his third talk of the day, described the Franklin Lake playa, a discharge area where different techniques have been used to estimate ET rates. He described his field studies, showed typical moisture content profiles, and discussed the hydrochemistry of the groundwater. Dr. D'Agnese then gave his fourth talk, the final talk of the day, on regional springs and their discharge rates. He described pumpage inventories conduced for the Pahrump Valley area, and noted that pumping in the Ash Meadows area in the 1960s and 1970s nearly dried the local springs, but was suspended because of the threat to endangered animal species.

Dr. Coppersmith opened the meeting for comments from observers. Discussions centered around key issues of highest uncertainty (including recharge, effective porosities, and transmissivity), and the different sensitivities of inputs to SZ models versus the TSPA model.

DAY 3 - FRIDAY, JUNE 6

The first session of the day, "Hydrochemistry," comprised three talks. William Steinkampf (USGS) described the geochemical data collected during the 1980s from a variety of types of wells for the Yucca Mountain project. He stated that many of the samples used may have been contaminated by detergents used in drilling fluids, as indicated by lithium concentrations, and cautioned that isotope data from these samples may not be accurate. Zell Peterman (USGS) gave the next talk on available and anticipated isotopic data. He described the sampling and "mapping" tasks of the SZ hydrochemistry program. Observations include that groundwater composition is laterally heterogeneous on the scale of kilometers, and that discrete domains (e.g., the Fortymile Canyon domain) can be defined. Origins of these heterogeneities include local recharge, variable ages, and laterally variable flux. Ed Kwicklis (USGS) gave a talk on radiocarbon data and analysis. He analyzed ^{14}C ages to provide an indication of groundwater flow directions, travel times, and recharge areas. NETPATH was used to obtain the initial ^{14}C activity of carbon in groundwater, using calculated contributions from different carbon sources. The corrected ^{14}C ages show consistent spatial patterns of groundwater of different ages in the Yucca Mountain area.

A talk on paleodischarge was then given by James B. Paces (USGS). He described studies conducted at paleodischarge localities in the Crater Flat and Amargosa Valley areas. In these studies, various age-dating techniques were applied to a range of materials, and paleoenvironments were reconstructed using assemblages of organisms. Available data indicate that regional, saturated-zone groundwater most likely supplied discharge during pluvial periods, indicating that the water table was elevated as much as 100 m ($\pm$ 20 m) above its present-day surface in southern Crater Flat.

A session on heat flow contained talks by William Dudley and John Sass (both USGS). In the first talk, John Sass reviewed the thermal regime of the southern Great Basin and heat flow at and around the Nevada Test Site. He described the geothermal data collection program at Yucca Mountain and the results of this program. He also discussed his interpretations of important anomalies such as the heat-flow deficiency beneath the Yucca Mountain site and the unique temperature logs in UE-25p#1 and USW G-2. In the second talk, William Dudley emphasized the thermal evidence for structural controls on SZ groundwater flow paths. He described the "fault-drain" model for the cause of the large hydraulic gradient, Solitario Canyon and Midway Valley faults as flow pathways rather than barriers, an alternative interpretation of the UE-25p#1 temperature log, and a proposed hydrologic explanation for the large heat-flow anomaly at UE-25a#3 in the Calico Hills.

Richard Forester (USGS) gave a talk about climate change. Using information on environmental preferences of tree species, ostracods, diatoms, and other organisms, he has studied climatic patterns of the past to predict patterns into the future. His studies suggest that the climate pattern could be shifting into colder, wetter winters.

Groundwater transport issues were described by the next three speakers in a series of talks on radionuclide sorption and solubility. Ines Triay (LANL) divided her presentation into three parts. In the first part, entitled "Status and Priorities Regarding Sorption of Long-Lived Radionuclides," she discussed the mineralogy of tuff samples and chemical analyses of water samples from Yucca Mountain. In the second part, "Radionuclide

Transport through Fractures," she discussed experimental studies that used natural rock fractures in fractured tuff, column experiments, and diffusion cells using fractured tuff. The final part of her talk was titled "Radionuclide Migration Under Diffusive Conditions." Experimental techniques and diffusion results of tuffs under varying degrees of saturation were described.

David Vaniman (LANL) gave the next presentation on "Saturated-Zone Mineralogy at Yucca Mountain." He discussed how X-ray diffraction is used to assess mineral types and abundances, zeolites and SZ flow, and mineral stabilities in the SZ. Arend Meijer (LANL/GCX, Inc.) gave the final presentation of the workshop on "Redox Potential (Eh) Studies." He described important redox-sensitive radionuclides, available data, and the new measurements planned. If reducing conditions exist in the SZ, neptunium-237 and technetium-99 could be stabilized.

Kevin Coppersmith discussed future project activities, including the itineray for the upcoming field trip and plans to distribute sample questions for the elicitations. He opened the workshop to comments from observers. Neil Coleman, NRC, stated that he would like to see the proposed elicitation questions when they are distributed to the expert panel. The workshop was adjourned.

SUMMARY
YUCCA MOUNTAIN FIELD TRIP

SATURATED ZONE EXPERT ELICITATION PROJECT

July 21, 1997

The field trip to Yucca Mountain and the surrounding region was organized to enable the SZEE expert panel members to observe the general setting of Yucca Mountain, surface bedrock exposures, paleodischarge sites, and local recharge and discharge features. The primary goal of the field trip was to provide expert panel members with an opportunity to observe first-hand those features that could help them better understand the saturated zone. The field trip was led by U.S. Geological Survey scientists who have conducted research in the region: John Czarnecki led the group throughout the day; discussions at specific stops were led by Mike Chornack (Raven Canyon), M.J. Umari (C-Wells), and Chuck Savard (Fortymile Wash.) The informal atmosphere and small size of the group allowed extensive debate and discussion.

Horsetooth Paleodischarge Site

This site contains extensive diatomites that were deposited from about 17,000 to 11,000 years before present, probably from a volcanic/alluvial aquifer that produced standing water. The present depth to the water table at this location is estimated to be about 100 m.

Raven Canyon

This stop was made to examine bedrock from the lower volcanic aquifer that composes the upper part of the saturated zone beneath the potential repository at Yucca Mountain: the Tram, Bullfrog, and Prow Pass tuffs of the Crater Flat Group. Fracture data have been collected at this locality to support fracture-flow modeling for groundwater modeling studies at Yucca Mountain.

Yucca Mountain Crest

After entering the Nevada Test Site through Gate 510, the group travelled to the crest of Yucca Mountain. The geography and geology were summarized, including the location of major landforms and structural features such as faults. The regional water flow pattern from Yucca Mountain toward the Amargosa Valley was discussed.

Fran Ridge Pavement
This stop was made to observe the Topopah Spring Tuff pavement. This rock unit is being considered for the potential repository horizon rock. Abundant carbonate fillings in fractures were observed in the exposed bedrock.

Adjacent to the Fran Ridge pavement is the site of a large block-heater test being conducted by Lawrence Livermore National Laboratory. The group looked at the test apparatus, and a researcher working at the site described the current status of the test.

C-Well Complex
The C-wells comprise three boreholes developed to conduct a series of tests to characterize hydraulic and transport properties of specific hydrogeologic intervals. M.J. Umari described the sampling equipment and procedures and the studies being conducted at the site.

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A brief stop was made at this well site. Water in this well, which originates in the Paleozoic aquifer, is essentially sodium bicarbonate water.

Fortymile Wash
The group travelled to the top of Alice Ridge for a scenic view of Fortymile Wash. Chuck Savard described the studies to estimate groundwater recharge in Fortymile Wash and pointed out the different reaches defined in the wash and the locations of gauging stations. After leaving Alice Ridge, the group stopped briefly in Fortymile Wash to observe the wash and examine photographs of the wash before and after a major flow event in 1995.

Well J-13
A brief stop was made at the site of well J-13, a major water supply well. The principal production occurs at a depth of about 300 m in the Topopah Spring Member of the Paintbrush Tuff; minor production occurs from the thick, overlying alluvium. Extensive chemical analyses of J-13 water have been conducted.

Ash Meadows
After exiting the Nevada Test Site through Gate 510, the group travelled to Ash Meadows and stopped at several springs. Water comes to the surface in Ash Meadows in more than 30 seeps and springs. The source for most of these waters is the Paleozoic carbonate aquifer. The group observed Fairbanks, Rogers, and Longstreet springs.

Devils Hole

The final stop of the trip was at Devils Hole, one of the few locations in the world where an accurate, long-term record of paleoclimate data is available. Studies that have been conducted at Devils Hole were discussed.

Franklin Lake playa was visible in the distance, and John Czarnecki briefly described the work he has conducted there. Following this discussion, the field trip ended, and the group returned to Las Vegas via Pahrump.

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SUMMARY
WORKSHOP ON ALTERNATIVE MODELS AND INTERPRETATIONS

SATURATED ZONE EXPERT ELICITATION PROJECT

July 22 and 23, 1997
Holiday Inn-Emerald Springs
Las Vegas, Nevada

The Workshop on Alternative Models and Interpretations was the second of three workshops being conducted for the Saturated Zone Flow and Transport Expert Elicitation (SZEE) project sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The purpose of the workshop was to review the key issues and uncertainties associated with the saturated zone in the Yucca Mountain region in support of the 1998 Total System Performance Assessment (TSPA)-Viability Assessment (VA) for the potential repository site. The workshop involved two days of technical presentations and discussions of alternative interpretations and approaches related to modeling regional groundwater flow, site-scale flow, and groundwater transport in the saturated zone. The workshop followed a one-day field trip during which the expert panel members had an opportunity to visit many of the localities described during the workshop.

Copies of the overhead transparencies and slides shown during the workshop are available in the SZEE administrative files.

DAY 1 - TUESDAY, JULY 22

Dr. Kevin Coppersmith (Geomatrix), SZEE project manager, introduced the workshop. He reviewed the purpose of the workshops and field trip: to assist the experts in evaluating the uncertainties associated with the saturated zone at Yucca Mountain. He emphasized the role of the expert panel members as *evaluators* who provide objective characterization of uncertainties and evaluate the relative credibility of alternative models and interpretations. Dr. William (Bill) Arnold of Sandia National Laboratories (SNL) then outlined the key issues to be addressed by the SZEE panel members (a list of these issues had been provided to the expert panel prior to the workshop). He emphasized the ultimate goal of evaluating the performance of the potential repository, and the criteria likely to be used to evaluate that performance. He summarized the processes most relevant to performance, and the key technical issues surrounding them.

The first session comprised nine talks on Modeling Regional Groundwater Flow. Frank D'Agnese of the U.S. Geological Survey (USGS) gave an overview of the first five talks, identifying the objectives and scope of the USGS regional modeling study and of the uncertainty analysis. Mary C. Hill (USGS) gave the first talk, "Model Calibration: Approach (Effective Calibration; Effective Use of Data)." She emphasized starting simply and adding complexity to describe this very complex system. Frank D'Agnese (USGS) next gave a talk titled, "USGS Model Construction, Calibration, and Evaluation." He described the development of subregions for use in the model: defining local, subregional, and regional flow paths and boundaries, recharge and discharge areas, and hydraulic conductivities. He discussed variations in alternative conceptual models, along with the uncertainties in estimated parameters and prediction. He also identified model constraints and areas where the models need improvement.

After a brief break, D. Cooley of the USGS gave a talk on general issues involved in modeling: defining uncertainty in model inputs/outputs, and identifying confidence intervals and prediction intervals. Given the nonlinear nature of the groundwater model for the Death Valley region, he prefers the so-called likelihood method of establishing confidence intervals over the Monte Carlo or Bootstrap methods. The next presentation, by Claudia Faunt (USGS), addressed the hydrochemical evaluation of flow paths in modeling groundwater flow in the Death Valley region. The work she has participated in is not specific to Yucca Mountain, although funded by the DOE. The computer program MODPATH has been used to compute three-dimensional pathways and to track particles backward from discharge areas to recharge areas in six localities. She displayed some of the results of the study in piper diagrams and cluster analyses.

After a break for lunch, Frank D'Agnese continued the first session with a presentation titled, "Simulated Effects of Climate Change on the Death Valley Regional Groundwater Flow System." His team utilizes the current regional steady-state model to simulate past (glacial) and future (warming) climate scenarios and their effects on the potentiometric surface. He also discussed the limitations of simulations, concluding that they are no more accurate than the present-day model. Rick Waddell (HSI/Geotrans) continued the session with two presentations. The first described the groundwater modeling program developed for the Nevada Test Site. Its purpose is to guide efforts to collect and evaluate data pertinent to migration of radionuclides produced by underground tests. A detailed, three-dimensional model has been developed, and flow paths identified. His second presentation focused on tracer experiments, which are designed to collect information on radionuclide mobility and the transport properties of fractured volcanic rocks. The test examined the ground zero area for the 1990 Bullion event. The transport model they developed based on data from three wells predicted a breakthrough of tritium, but that has not been observed yet.

After a brief break, Neil Coleman (U.S. Nuclear Regulatory Commission [NRC]) gave a talk titled, "Issue Resolution: Status Report on Methods to Evaluate Climate Change and Associated Effects." The NRC status report concluded that the timing of the last glacial cycle has been identified accurately, but that major problems surround attempts to predict future climates. They recommend that performance assessments include consideration of a return to full pluvial climates (cooler and wetter than current conditions), which could present conditions challenging to repository performance. Gordon Wittmeyer (Center for Nuclear Waste Regulatory Analyses [CNWRA]) closed the session with a presentation titled, "Conceptual Models of Saturated Zone Flow and Transport Used by the U.S. NRC in Total System Performance Assessments." He reviewed mathematical and conceptual models and the technical uncertainties related to flow and transport in the saturated zone. He described how the NRC/CNWRA will quantitatively evaluate how changes to the basic conceptual models of saturated zone flow and transport affect estimates of total system performance.

The second session, Site-Scale Groundwater Flow Modeling, was opened by Claudia Faunt, who spoke on the hydrogeologic framework for the site-scale flow model for the Death Valley region. She described constructing a three-dimensional model of flow based on a geologic map, hydraulic properties of the geologic units, and computer interpolation. Refinements of this model and alternative models are being considered.

The first day ended with comments from observers. Comments ranged from requests for clarification of how zones were defined and heterogeneities considered, to depictions of the steep hydraulic gradient, to concerns for the people and animals of the Death Valley region.

DAY 2 - WEDNESDAY, JULY 23

The second day continued the discussion of Site-Scale Modeling of Groundwater Flow. George Zyvoloski (LANL) began with a talk titled, "Saturated Zone Grid Generation and Numerical Model." He described work to date in data collection and code development in support of three-dimensional modeling of saturated zone flow and plans for future simulations. Because heterogeneities are difficult to capture, the model will employ unstructured grids (finite-element-type modeling). John Czarnecki (USGS) gave the next presentation on a three-dimensional, finite-element groundwater flow model for the saturated zone at Yucca Mountain that is a collaborative effort between the USGS and LANL. He provided preliminary data from the efforts at model construction, calibration, and evaluation. The plan is to use the model to simulate transport within hydrogeologic units and to estimate permeabilities of 16 hydrogeologic units. One of its purposes is to estimate the magnitude and direction of groundwater flow from the potential repository to the accessible environment. He offered several possible explanations for the large hydraulic gradient observed in the area. Dr. Czarnecki emphasized that the site model is not strongly linked to the regional model, since the site model matches specific data from wells in the site area.

Bruce Robinson (LANL) began the next session, on Transport Modeling, by describing preliminary results concerning transport from site-scale modeling. Transport is modeled using a reactive, finite-element solution. Preliminary results, based on a coarse grid, indicate where a finer grid is needed. Plans call for joining the transport models for the unsaturated and saturated zones. A primary conclusion of the study to date is that the saturated zone can provide significant dilution of radionuclides from the unsaturated zone, particularly that part of the inventory that travels rapidly through the unsaturated zone. After a brief break, Jake Turin continued this session with a talk titled, "Reactive Tracer Testing at the C-Wells." Paul Reimus is the Principal Investigator for this work. In this study, injection and pumping wells were used to track the movements of injected tracers. Multiple pathways were found that had different transport characteristics, but all pathways showed evidence of matrix diffusion and sorption, which appear to be effective slowing and dilution mechanisms. Additional tests at the C-wells are planned, and results will be integrated into ongoing modeling efforts.

Bruce Robinsons's second presentation, "Matrix Diffusion and Dispersivity," ended this morning's session. Mr. Robinson cited evidence for matrix diffusion. His group's work at LANL indicates that dispersivity is a key parameter, and lateral dispersion is a sensitive parameter that should be considered in the performance assessment. They, too, have found that sorption in the SZ leads to dilution and delayed arrival of radionuclides.

After a break for lunch, the workshop attendees reconvened to begin the final session, Conceptual Models of Groundwater Flow Processes. Linda Lehman (State of Nevada) opened the session with a discussion of the compartmentalization of the SZ system. Potentiometric surface data show embayments coincident with the Sundance and Drill Hole Wash faults; her group believes that a shear zone or transform fault system represents a strong control on groundwater flow. William Dudley gave the next presentation, "Alternative Models for the Large Hydraulic Gradient." He reviewed the numerous past and current explanations offered for the large gradient and listed the features and observations that may be significant to identifying the cause(s). He described consistency of various models with available data sets and identified models that he rejected, unlikely models, marginally viable models, and several of the more probable models.

John Kessler (EPRI) gave a presentation on "Saturated Zone Flow and Transport Modeling for EPRI's TSPA, Phase 3." EPRI, based on the work of Ed Sudicky and Franklin Schwartz, developed two models for the saturated zone: one near-field (to 8 km downstream), and one far-field (to 25 km downstream). He identified factors important to SZ modeling (factors that affect peak concentrations or arrival times): the assumption of a homogeneous, isotropic medium; an understanding of bulk hydraulic conductivity, porosities, and sorption coefficients; inclusion of a sufficiently large model domain; and inclusion of transverse dispersion (if the source size is small). George Barr (SNL) next gave a presentation titled, "Origin of the Local 3-D SZ Model." His presentation focused on the local isothermal SZ model he has developed. He described the data and alternative models considered in the development of the model, the current status of the model, and caveats, including uncertainties such as faults, fracture distribution, and compartmentalization.

Bill Arnold gave the final presentation of the workshop: "Distribution of Permeability and Channelization of SZ Flow and Transport." He described alternative conceptual models for permeability distribution in fractured tuffs of the saturated zone and their implications for radionuclide transport. An important conclusion from his work is that flow channelization probably occurs over a number of scales in the SZ, and that degree of welding can be used as an indication of flow channelization along stratigraphic units.

There were no comments from workshop observers, and Dr. Coppersmith adjourned the workshop.

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SUMMARY
WORKSHOP ON PRELIMINARY INTERPRETATIONS

SATURATED ZONE EXPERT ELICITATION PROJECT

August 11-12, 1997
Embassy Suites - South San Francisco, California

The Workshop on Preliminary Interpretations was the last of three workshops conducted for the Saturated Zone Expert Elicitation (SZEE) for the Yucca Mountain project, Nevada. The purposes of this workshop were to (1) provide an opportunity for members of the expert panel to present and discuss their preliminary interpretations and uncertainties regarding issues key to flow and transport in the saturated zone; (2) provide feedback to the panel members regarding their preliminary interpretations before the elicitations; and (3) provide panel members with elicitation training to help them quantify their uncertainties.

Copies of the overhead transparencies and slides shown during the workshop are available in the SZEE administrative files.

DAY 1 - MONDAY, AUGUST 11, 1997

Kevin Coppersmith (Geomatrix) began by describing the purpose and approach of the workshop, the goal of which is to enable each expert to understand the interpretations of others and be able to re-examine his own thinking based on new information and ideas. Dr. Coppersmith stated that this is a working meeting, with preliminary ideas subject to change, free-form discussion of alternative views, and hand-drawn graphics. The workshop was structured to address each of five key issues by having two panel members present their interpretations, and all members then discuss the issues.

Peter Morris (Applied Decision Analysis and MDT member) used the rest of the morning to introduce probability assessment in order to prepare the experts for the upcoming elicitation interviews. His guidance focused on using probability to quantify uncertainty, representing uncertainty using probabilities, and assessing probabilities.

After the lunch break, Bill Arnold (Sandia National Laboratories) introduced key issues to be addressed in the elicitation interviews. He outlined 12 issues, including dilution of radionuclide concentration at the interface between the saturated and unsaturated zones, dispersive mixing of groundwater flow, potential interaction between flow/transport in fractures and matrix, flowpath of the radionuclide plume, applicability of C-well test data to site-scale modeling, estimates of regional recharge and discharge used in modeling, use of geochemical data, effects of future climate change on transport of radionuclides, potential rises in water table beneath the potential repository, and conceptual model and significance of the large hydraulic gradient; described the four hydrogeologic units of interest (volcanic aquifers, volcanic aquitards, carbonate aquifer, and alluvium); and identified the parameters to be estimated, including flux beneath the repository expressed as specific discharge (ambient and pluvial), hydraulic conductivity of the four hydrogeologic units of interest, and changes in water table elevation. Transport parameters to be elicited also were discussed, including horizontal and transverse dispersivity, sorption coefficients (Kd) for the four units, and effective fracture density. It was noted that the experts would also be asked to provide their recommendations for future activities that could serve to reduce uncertainties in the key issues and parameters.

Then Pat Tucci (USGS) summarized the databases available to help the experts understand the issues associated with formulating a conceptual model of flow in the saturated zone beneath and downgradient of Yucca Mountain and a model of solute dilution downgradient of the potential repository.

Two experts gave their interpretations of the first of the five key issues to be addressed at this workshop, "Flux in the Saturated Zone Beneath the Site." Allan Freeze first presented his preliminary concept of the site's hydrogeologic framework, estimates of hydraulic conductivity, estimates of porosity, configuration of the water table, and analysis of flow net, leading up to estimates of advective flux expressed as specific discharge, his uncertainties, and the possible effects of changes produced by climate or the thermal influence of repository itself on the saturated zone. In his discussion, Dr. Freeze noted that fault planes may act as both barriers or conduits to groundwater flow and that single-well measurements probably are biased toward lower conductivities than those at the field scale.

The second talk on the issue of flux was given by Lynn Gelhar. He described regional and site-scale models of groundwater flow and site data, focusing on uncertainties in data and their possible resolution. To him, the important quantity for understanding flux was "specific discharge" rather than linear velocity. Dr. Gelhar found both the current regional model and site-scale model not useful for predicting advective groundwater flux immediately beneath the potential repository. He identified efforts that might improve both models. He provided his assessment of specific discharge and discussed his approach to evaluating the uncertainties in his estimate. After a short break, attendees reconvened to discuss among the entire panel the issue of flux in the saturated zone beneath the site. The first day of the workshop closed with comments from observers.

Comments included a discussion of the potential effect that faults and other geologic structures could have on the groundwater flow system.

DAY 2 - TUESDAY, AUGUST 12, 1997

The second day of the workshop was devoted to presentations and discussions related to the other four key issues. The day opened with presentations on Issue Number 2, "The Large Hydraulic Gradient, Its Causes and Implications." Shlomo Neuman gave the first presentation. He described what he terms an apparent large hydraulic gradient, various alternative conceptual models for its existence, and a basis for selecting from among the proposed models. He cited observations and data in support of his preferred choice, a perched system model, and commented on the alternative models. The next speaker was Allan Freeze, who described two alternative models for the large hydraulic gradient (LHG), which he described as "a steep slope in the water table." He examined the two explanations—a saturated flow system or a perched flow system—and identified features and observations that supported each. He favored a saturated system model to explain the large hydraulic gradient, but concluded that the implications of the LHG for the TSPA are similar whichever model is chosen. In either case, Dr. Freeze stated, "It is not a cause for alarm"; the LHG is simply a manifestation of a local flow system controlled by interactions between topography, geology, and recharge. He believed that the TSPA is much more sensitive to the effects of repository heating on the hydrologic regime and future increases in pumping from the Amargosa Desert. After discussing the issue of the LHG, the experts took a short break.

Issue Number 3, "Hydraulic Properties," was addressed after the break. Chin-Fu Tsang presented his preliminary comments. He described three-dimensional modeling performed by LBNL based on C-well pumping tests. He discussed the role of faults, high-conductivity pathways, and vertical flow. He also examined alternative approaches and models. Next, Lynn Gelhar addressed the results of recent hydraulic and tracer-test data from the C-wells, concluding that data from single-hole hydraulic tests were not directly useful for quantifying large-scale hydraulic properties, because single holes cannot tap heterogeneities. He also expressed concern that aquifer testing in the C-wells utilizes two-dimensional homogeneous, isotropic curves to convey a three-dimensional heterogeneous and/or horizontally anistropic system. Dr. Gelhar identified additional tests (a long-term aquifer test, more tracer tests in C-wells, and additional long-term tests at the C-wells) to determine large-scale hydraulic properties. He also called for large-scale forced-injection pumping well tracer tests to separate dispersion and matrix diffusion effects. He stated that he is not yet convinced that there is evidence for matrix diffusion. After this issue was discussed, participants took a break for lunch.

The workshop reconvened after lunch to address Issue Number 4, "Hydrochemistry and Transport Parameters" of the saturated zone. Don Langmuir presented his preliminary interpretations, concluding that the DOE approach to estimating the quantity of radionuclides that could be released and transported to the accessible environment through the saturated and unsaturated zones is highly conservative. The possible benefits of sorption, solubility, and redox reactions to reduce concentrations of radionuclides have not been sufficiently emphasized, he believed. He viewed an analysis of transport processes and parameters that considers only sorption as inadequate, because sorption only delays the peak release of long-lived radionuclides; solubility, if applicable, could greatly reduce or eliminate such releases. Dr. Langmuir emphasized a distinction between matrix flow and fracture flow—adsorption and reduction reactions, he said, are most likely to occur in the matrix, but shallow wells that penetrate volcanic rock (especially fractures) will not show evidence of slower flow (lower Eh). Chin-Fu Tsang gave the second presentation on this issue. He identified a need for the TSPA to define how the transport parameters will be used—at what scale, whether averaged over the area or assigned to individual faults—in order to identify the critical parameters and subjects that need additional research. He discussed analytical results of data from the tracer tests and alternative approaches: the multiple path model, fracture network model, channeling, and source term at the interface between the saturated and unsaturated zones. After the experts discussed this issue, there was a short break.

After the break, the workshop reconvened to discuss Issue Number 5, "Dilution Parameters and Spatial Distribution of Flow." Shlomo Neuman gave the first presentation, describing the current approach from TSPA-95, then his own viewpoint. He proposed applying Monte Carlo simulation to laboratory test data in order to simulate field-scale distributions. Dr. Neuman emphasized that dispersion cannot be interpreted as dilution, except in special cases. A large dispersion coefficient may be required to account for the uncertainty, he believed. Matrix diffusion, he stated, may enhance the mixing and spread of radionuclides but that there are few other mechanisms for enhancing dilution. Dr. Neuman also pointed out that there is highly localized flow in the volcanic and carbonate aquifers, which provides a low potential for dilution. Dr. Neuman emphasized that dispersion is scale-dependent and that dispersion coefficients reflect the degree of resolution rather than the amount of true dilution.

Don Langmuir gave the last presentation on this issue and for the workshop. He examined a statement from an EPRI report (12/96) that "physical processes such as dispersion (assumed minimal) and dilution will reduce groundwater radionuclide concentrations by approximately 50 times or less at 25 km, depending on the assumed depth of mixing and future climate and infiltration rates." He identified three types of groundwater in the area: alluvial, volcanic rock, and the deep regional carbonate aquifer—each having distinctive chemistries. He found that the general occurrence of volcanic rock groundwater is consistent with the proposed groundwater flow system in the volcanic rocks under Yucca Mountain. Maps showing detections of isotopes indicate sources of groundwater and recharge to the volcanic aquifer, which can provide insights into mixing and dilution of radionuclides. After the experts discussed this issue, comments and questions from observers were considered.

Dr. Coppersmith concluded the workshop by reviewing the schedule for the rest of the project and reviewing the procedures that would be followed in the upcoming elicitation interviews. Following this discussion, the workshop was adjourned.

APPENDIX D

ELICITATION SUMMARIES

ELICITATION SUMMARY
R. ALLAN FREEZE

OVERVIEW: CONCEPTUAL MODEL OF SATURATED ZONE FLOW

In my opinion, there is nothing about the saturated zone flow system in the Yucca Mountain region that would preclude the application of standard hydrologic tools in evaluating key aspects of the system, including flow directions and fluxes. Volcanic regions are complex, which leads to uncertainty in detail, but there are no fundamental conceptual uncertainties involving the nature of the flow system. I prefer to use a flow-net conceptualization to assess the flow field, to determine flow tubes, to evaluate the potential for hydraulic focusing, and ultimately to estimate the off-site advective flux rates in the aquifers beneath Yucca Mountain. In my opinion, the presently available data are sufficient to carry out this task.

The primary feature of the Yucca Mountain site is the high permeability of its hydrogeologic environment. The three-dimensional hydrogeologic framework consists of two important components: the hydrostratigraphic units, and the structural features. The hydrostratigraphic units are horizontally layered, reflecting the mode of deposition of the volcanic units. Because this is a fracture-dominated flow system, the lithologies are important primarily in terms of the control they provide on the nature of fracturing.

Which hydrostratigraphic units are important depends on the scale being considered—the regional scale, site scale, or detailed scale. At the regional scale, the important units are the valley fill, the volcanic rock aquifers and aquitards, the carbonate aquifer, the clastic aquitards, and the basement rocks. These hydrostratigraphic units are incorporated into the regional scale model, which has horizontal grid spacings of 1500 meters. At the site scale, the important units are the geologic units (Bullfrog tuff, Prow Pass tuff, Calico Hills Formation, etc.) and the hydrogeologic units (upper volcanic aquifer, upper volcanic confining unit, carbonate aquifer, etc.). These units are incorporated into the local scale model at a grid spacing of 1000 meters or less. At the detailed scale, the tuffs can be subdivided into ash-flow tuffs and bedded tuffs. The ash-flow tuffs have welded members that are fractured, low-porosity, high-conductivity aquifers. The nonwelded members are sparsely-fractured, moderate-porosity, low-conductivity aquitards. Zeolitized parts of the tuffs are very-sparsely-fractured, high-porosity, very-low-conductivity aquitards. The bedded tuffs tend to be very-sparsely-fractured, high-porosity, moderate-conductivity aquitards.

A number of factors can contribute to heterogeneity of the hydrostratigraphic units. The geologic units consist of multiple flows, each of which may exhibit non-welded tops and bottoms and welded middles. The degree of welding can vary laterally and vertically within a single unit. Similarly, devitrification and zeolitization can be heterogeneously distributed.

Faults and structural features also are important to the three-dimensional hydrogeologic framework at several scales. At the regional scale, there are deep, low-angle thrust faults in the carbonate aquifer, which are more highly fractured and brecciated on the upper plate. Several large-scale N-S normal faults exist in the Yucca Mountain region, including the Solitario Canyon, Ghost Dance, and Bow Ridge faults. These faults disrupt the hydrostratigraphic units and create steps in the water-table configuration. Medium-scale NW-SE faults such as the Yucca Wash, Drill Hole Wash, and Sundance faults also disrupt the flow system, as do local faults at the site scale. The result is a hydrogeologic environment consisting of offset rectangular blocks that may or may not maintain hydrologic continuity across fault zones. At the detailed scale, within these blocks, fracture systems are often strata-bound, so that the fracture density depends on the unit in which the fractures are developed.

Faults at all scales may exhibit layering parallel to the fault plane within a tabular fault zone. Deformation on the upper plate (hanging wall) is usually pronounced, exhibiting fracturing and brecciation that leads to high hydraulic conductivity. The lower plate (footwall) often contains fault gouge, leading to low hydraulic conductivity. This high-K/low-K layering can enhance conductivity along and parallel to a fault zone, and can cause low conductivity perpendicular to it. The high conductivity parallel to the fault zones makes most faults preferential pathways for flow. The N-S fault set may have greater conductivities than the NW-SE fault set. The degree to which faults block hydrostratigraphic continuity depends on the degree to which fault gouge develops on the footwalls, which in turn may depend on the lithology of the units traversed by the fault. The spatial distribution of conductivities resulting from the interaction of hydrostratigraphic units and faults may best be described by Bill Dudley's "plaid" conceptual model.

Spatial variabilities in hydraulic conductivity occur throughout the flow system, and focusing and channelization are important. On a regional scale, the volcanic rocks thin to the south, the Calico Hills Formation thins to the south within the volcanic rocks, and the carbonate aquifer is shallower to the south. The valley fill alluvium is present only in the south and it probably decreases in K to the south. Within the volcanic rocks, the hydraulic conductivity likely decreases with depth because of lithostatic loading; it appears to increase to the south because of an increase in tectonic fracturing and a decrease in the extent of alteration.

Flow surveys in wells and groundwater temperature anomalies confirm the existence of high-conductivity pathways. Near-vertical fault-controlled pathways probably are throughgoing. The continuity of horizontal hydrostratigraphically-controlled pathways is enhanced by the strong stratigraphic continuity within the units, but is limited by offsets of the units across fault zones. The evidence at the C-wells test site suggests that only 10-20% of fractures deliver significant flow, and that a large proportion of the flow may be carried by a very few of these fractures.

Large-scale horizontal-to-vertical anisotropy is expected in the region in response to stratigraphic layering. There may also be small-scale vertical-to-horizontal anisotropy within individual units because of cooling joints and columnar jointing.

The water-table configuration is relatively well understood in Yucca Mountain and south of it. It seems well established that flow is to the southeast and to the south. Likewise, it is nearly certain that flow comes up from the carbonate aquifer. Thus the lower volcanic aquifer and the alluvium are likely the most important hydrostratigraphic units relative to flow and transport in the saturated zone downgradient from the repository. Regional flow tubes exit Yucca Mountain to the SE within the volcanics, then pass into the alluvium along the eastern boundary of Alkali Flats-Furnace Creek Ranch groundwater subbasin. Local flow tubes within the repository blocks are likely to be quite erratic because of the differences in proximity to high-K fault zones between flow tubes, and the many different lithologic rock types at the water-table horizon.

There is a strong potential for focused flow within the system due to: (1) the draining action of high-K fault zones, (2) the flow tubes created by the intersection of fault zones and high-K stratigraphic horizons, (3) the geometry of the Yucca Mountain flow system as it impinges on the adjacent flow system east of Yucca Flats, (4) the influence of a possible high-K channel within the alluvium under Fortymile Wash, and (5) the influence of pumping well capture in the Amargosa Desert.

There is no evidence of significant natural short-term transients near Yucca Mountain, so a steady-state analysis is appropriate (as currently is incorporated into both regional- and local-scale models). Seasonal pumping demands and long-term increases in pumping in the Amargosa Desert may create transients, but response in the high-K units there should be rapid. In the longer term, climatic variations may cause long-term changes in the flow system that deserve consideration.

LARGE HYDRAULIC GRADIENT

The so-called large hydraulic gradient (LHG) is actually a steep water-table slope north of Yucca Mountain. There is a concomitant area south of the site that has a flat water-table slope. Because both elevation and recharge increase to the north, an increase in water-table elevation is expected. In my mind, the only issue associated with the large hydraulic gradient is why the water-table slope shows such a pronounced break just north of the site rather than a more gradual slope. Large hydraulic gradients are a common feature in the region, and they probably share a common cause.

Two credible interpretations can be made of the available information regarding the LHG: a saturated flow system or a perched flow system. It is not possible to determine which is the case, because the three-dimensional distribution of hydraulic head in the vicinity of the LHG north of Yucca Mountain is poorly known due to sparse data. The hydraulic gradients in the three-dimensional flow system likely have both lateral and vertical components and may be quite complex. If the system is fully saturated, then the configuration of the water table beneath the land surface will be a function of topography, recharge patterns, and geology (including hydrostratigraphic units and structural features). The topographic gradient increases to the north in the vicinity of the LHG; it is on the order of 0.016 southeast of Yucca Mountain and 0.037 to the north. Recharge also increases north of the LHG; it is estimated to be less than 1 mm/year to the south and as much as 10 mm/year to the north. Water-table offsets associated with faults (e.g., the Solitario Canyon fault) are thought to be common in the area; perhaps geologic control of this type may contribute to the steepness of the water table across Yucca Wash.

The alternative interpretation to the saturated flow system model is a perched flow system consisting of an upper saturated zone underlain by a wedge of unsaturated rocks (which probably are close to saturation) over the regional water table. I prefer not to use the ill-defined term "semi-perched," but consider any case where a saturated zone lies above an unsaturated zone to be a perched system. Perched flow systems are a common feature in the region. They usually develop on hillsides in horizontally stratified systems that have large differences in hydraulic conductivity between units. They are usually manifested as springs and seepage areas at elevations well above the regional water table.

Several features and observations favor the saturated-flow-system interpretation of the LHG. Large water-table slopes apparently are associated with low-conductivity features in the saturated zone elsewhere in the region (e.g., the Eleana Formation northeast of

Yucca Mountain, the Solitario Canyon fault). Some of these hydraulic gradients are unlikely to be perched (e.g., Amargosa Desert to Death Valley through the Funeral Mountains). There are even higher heads north of the LHG (e.g., 1187 m in Upper Fortymile Wash, and 1400 m on Paiute Mesa); these values would easily fit into a saturated regional flow interpretation without the need for unsaturated explanations. There are upward flows from the carbonate aquifer into the volcanics south of the LHG; the higher heads at depth that give rise to these flows imply a saturated connection with the high heads north of the LHG. There are no regional springs associated with the LHG, as might be expected for perched conditions.

The close hydraulic contours exhibited across the LHG imply the presence of a unit having low hydraulic conductivity, which could be either a near-vertical low-conductivity structural feature (Figure AF-1a), or a near-horizontal low-conductivity stratigraphic unit (Figure AF-1b). In support of the latter possibility, it is worth noting that the base of the Calico Hills upper volcanic confining unit is at 730 m elevation, which coincides with the water-table elevation south of the LHG. The LHG could also be caused by the northward pinchout of a deep high-conductivity drain (Figure AF-1c). The concept of a "deep drain" south of the LHG is supported by the presence of the carbonate aquifer and NW-SE trending faults.

Several features and observations can be interpreted to favor the perched-flow-system interpretation of the LHG. Water levels in USW UZ-14 were 967 m during drilling and pump testing, and 778 m after casing off a higher zone and completing the well in the Bullfrog tuff. A drop in the water levels of USW-G2 from 1029 to 1020 m since 1982 suggests draining (although it could also be caused by simple equilibration in a low-K formation). Apparent partial saturation in the Calico Hills Formation is indicated in USW-G2 on the basis of geophysical logging of the borehole. Perched conditions are also suggested by the decrease of thermal gradient profiles over time in USW-G2. The prevalence of perched conditions in the region is supported by the identification of perched zones in the unsaturated zone beneath Yucca Mountain.

Based on the evidence, I place a higher credibility in the "saturated flow system" interpretation (probability 70%) than the "perched flow system" interpretation (probability 30%). Given that the saturated zone model is correct, the controlling feature can be either a horizontal or a vertical feature, or both. I believe that it is likely that both types of features are present and assess the relative degree of control to be 65% for horizontal features and 35% for vertical features.

The available head data, although sparse, can be interpreted to favor the saturated explanation. Figure AF-2 illustrates the flow net that can be constructed in the vicinity of the LHG from just two controlling head values: the 750-m hydraulic head measured in UE25p#1 at depth in the lower carbonate aquifer (LCaA), and the 1020-m elevation of the water table in USW-G2. In this scenario, the control on the LHG is the upper volcanic confining unit (UVCU). The flow net not only provides an explanation of the LHG; it also manifests many of the hydrogeologic features known to exist at the site (downward recharge of the volcanic aquifers from above, upward flow from the carbonate aquifer, etc.). The flow net is schematic and preliminary; it is presented here solely to illustrate the degree of control exerted on the flow net by even a few data points. I would encourage the Yucca Mountain study team to construct a more sophisticated flow net using more complete data.

In my opinion, settling the LHG controversy is not critical to the project. The only outstanding question is whether the UVCU is fully saturated or only nearly-so. The implications for TSPA are similar for both the saturated and the perched flow system models. Whether the saturated or perched model is correct, the LHG is simply a manifestation of the local flow system controlled by interactions between topography, geology, and recharge. It is not a cause for alarm. The likelihood of a "breakthrough" of groundwater "dammed" behind the LHG is zero, and the likelihood of major, long-term transient readjustment of gradients is very small. Perhaps the principal benefit to be gained in understanding the LHG is to further our knowledge of the regional hydrologic framework. The implications to saturated zone flux beneath Yucca Mountain are minimal. Gradients southeast of Yucca Mountain in flow tubes draining Yucca Mountain are little affected by these alternative conceptual models. Other issues appear to have a much greater impact on the TSPA than the LHG. These include the impacts of repository heating on the UZ/SZ hydrologic regime and increased future pumping in the Amargosa Desert. The current regional and site-scale numerical models do not appear to be well-suited for further analysis of the LHG issue. It may be better assessed offline.

HYDRAULIC CONDUCTIVITY AND FLUX BENEATH YUCCA MOUNTAIN

The horizontal flux vector in the uppermost part of the saturated zone beneath Yucca Mountain is needed for the TSPA. Ultimately, it will be needed both for current conditions and for conditions that may arise in response to climate change or the impact of repository heating on the saturated-zone hydrologic regime. Climatic changes are considered in a later section; repository impacts were not addressed in this elicitation.

My approach to estimating fluxes is traditional: (1) establish the three-dimensional hydrogeologic framework; (2) carry out flow-net analysis to identify flow tubes; (3) develop hydraulic conductivity estimates; and (4) use Darcy's law to calculate specific discharge values. We begin by first considering hydraulic conductivity values (and their uncertainties) for the following hydrogeologic units: valley-fill alluvium, volcanic aquifers, volcanic aquitards, and the carbonate aquifer. The "volcanic aquifer" considered is the lower volcanic aquifer, which consists of the Prow Pass, Bullfrog, and Tram formations. Of these units, the lower Bullfrog unit is the most transmissive in the site area. I also include consideration of the hydraulic conductivity associated with the permeable portions of fault zones. I have compiled the ranges of reported hydraulic conductivity values for the various units based on estimates from the regional and local hydrogeologic framework models, calibrated local and regional numerical flow models, available field measurements, and other interpretations (Table AF-1). The available information is a combination of point values (from single-hole measurements), and local averages (from multiple-hole tests such as the C-wells, and from model calibration of the hydrologic models). The available data are biased in favor of high-K units.

I am assuming that the appropriate scale of application for the hydraulic conductivity estimates that I provide here is that of the elements of the current site-scale model (1500 x 1500 x 100 m). Hence, the hydraulic conductivity values are local averages, and the total spread in uncertainty in the values is much less than would be assessed if a distribution of point-scale values were provided.

Based on my review of the estimates and my own experience at other locations, I provide the following estimates of hydraulic conductivity for the various hydrogeologic units. In all cases, the distribution is a truncated lognormal distribution, and values are given in centimeters per second (cm/s):

HYDRAULIC CONDUCTIVITY, K (cm/sec)

Hydrogeo-Logic Unit	Lower Bound	-1/2 Std Dev	Median	+1/2 Std Dev	Upper Bound
Alluvium	10^{-4}	3×10^{-4}	10^{-3}	3×10^{-3}	10^{-2}
Volcanic Aquifers	3×10^{-5}	10^{-4}	3×10^{-4}	10^{-3}	3×10^{-3}
Volcanic Aquitards	For each realization, set K for the aquitards equal to the K-value of the volcanic aquifers divided by a factor X, where X is uniformly distributed between 20 and 180, with median 100.				
Carbonates	3×10^{-5}	10^{-4}	3×10^{-4}	10^{-3}	3×10^{-3}
Fault Zones (permeable portion)	For each realization, set K for the fault zones equal to the K-value of the volcanic aquifers multiplied by a factor Y, where Y is uniformly distributed between 2 and 18, with median 10.				

The hydraulic conductivity values quoted in the above table for the volcanic aquifers are at a scale that includes the influence of minor faults and major fractures. There may be interest within TSPA (for consideration of matrix diffusion and sorption effects) in the K-values for unfractured matrix blocks (or more realistically, for matrix blocks influenced only by local minor fractures). The data are sparse, and I am not prepared to develop a full probability distribution function (PDF), but I would expect the median value to lie in the range 10^{-7} to 10^{-5} cm/s, with a wide spread of point values.

The saturated zone flux at the water table beneath Yucca Mountain is assessed in terms of specific discharge of the lower volcanic aquifer, which is the predominant hydrogeologic unit at the water table beneath the site. Specific discharge, *q*, is defined as:

$$q = Ki$$

where *K* is the hydraulic conductivity and *i* is the hydraulic gradient. In the vicinity of the repository, the hydraulic gradient is relatively low (0.0003), and there is not much uncertainty in its magnitude. The uncertainty in hydraulic conductivity is considerably greater and, because *K* and *i* are correlated, it is assumed that the uncertainty in *K* dominates the uncertainty in specific discharge. The probability distribution that is developed to characterize the uncertainty in *q* is based on the assumption that the flow tubes beneath the site traverse the volcanic aquifer (median K = 3×10^{-4} cm/sec) for parts of their pathway, and permeable fault zones (median K = 10 times median K of volcanic aquifer) for other parts of their pathway.

The following truncated lognormal distribution describes my characterization of the specific discharge, q_{SZ}, beneath the site in meters per year (m/y):

	Lower Bound	-1/2 Std Dev	Median	+1/2 Std Dev	Upper Bound
q_{sz} (m/yr)	10^{-2}	3×10^{-2}	10^{-1}	3×10^{-1}	10^{0}

As a reality check, I also considered the average linear velocity in the saturated zone in the vicinity of the site. Average linear velocity, *v*, is given by the expression:

$$v = q/n$$

where *q* is the specific discharge and *n* is average porosity. For the alluvium in the Amargosa Desert, assuming hydraulic conductivity equal to 10^{-3} cm/s, porosity equal to 0.20, and a gradient of 0.002, the expected value of the average linear velocity is 3.15 m/y. For the volcanic-aquifer/fault-zone region beneath the site, depending on the selected porosity values and the percentage of flow tubes in each unit, the expected value of the average linear velocity is in the range of 1 to 10 m/y. This leads to the following truncated lognormal distribution for average linear velocity, v, in the volcanic-aquifer/fault-zone region, in m/y:

	Lower Bound	-1/2 Std Dev	Median	+1/2 Std Dev	Upper Bound
v (m/yr)	0.3	1	3	10	30

These estimates of linear velocity can be compared with published estimates from TSPA-95 for the volcanic aquifer, which quote a median value of 1.07 m/y and a standard deviation of 0.49. Overheads shown by Bill Arnold at SZEE Workshop 3, indicated a range of 0.1 to 10 m/y. Isotopic age dates east and southeast of Yucca Mountain indicate ages of 4000 to 7000 years (but may be affected by recharge from Fortymile Wash). Other ages for locations west and south of Yucca Mountain are in the range 6000 to 12,000 years. The implication of the age dates is that groundwater has migrated thousands of meters in thousands of years, leading to an estimated average linear velocity of 1 m/y.

The uncertainties that are reflected in the PDFs in this section include: (1) conceptual uncertainties, (2) uncertainties in the hydrogeologic framework, (3) measurement uncertainties, and (4) model output uncertainties. The first category includes uncertainties about fault-zone hydraulics. The second category recognizes uncertainties in water-table configuration, distribution of hydrostratigraphic units, and the nature and distribution of fault zones. The third category reflects uncertainty both in the measurements themselves (large open intervals, integrity of packed-off zones, etc.) and their interpretation (non-uniqueness of interpretation of pump tests, representativeness of measured values, etc.). The fourth category arises from questions regarding the representativeness of model discretizations and model calibrations.

INFLUENCE OF CLIMATE CHANGE

In terms of the likely nature of future climate change, I agree with the position taken by the Nuclear Regulatory Commission that the most likely future climate scenario is anthropogenic greenhouse warming for 3000 years, followed by resumed global cooling toward the next glacial epoch, which is predicted by the Milankovitch orbital theory of climate. In terms of recharge and discharge under a climate change, the regional model provides reasonable estimates because it is calibrated with discharge data. Discharge data are inherently better than recharge data in this regard, because it is very difficult to estimate regional infiltration.

Modeling of the last glacial period using the regional model is based on a cooler, wetter climate that has mean annual precipitation 2 to 4 times current rates, which leads to an increase in the Death Valley water budget from 400,000 to 700,000 m^3/yr, and a rise in the water table at Yucca Mountain of 50 to 100 m. As a reality check on these model results, evidence from past glacial periods suggests that water-table rises beneath Yucca Mountain have ranged from 60 to 130 m.

I assume that future glacial climates are likely to be similar to those of the past. Based on the information summarized above, I estimate that the water table rise, Δwt, in meters, beneath Yucca Mountain during future glacial climatic conditions can be represented by the following truncated normal probability distribution:

	Lower Bound	-1 Std Dev	Median/Mean	+1 Std Dev	Upper Bound
Δwt (m)	25	50	75	100	150

Under glacial climatic conditions, I would expect increased flux beneath the site. First of all, the water-table rise would probably be greater north of Yucca Mountain than at the site itself, thus increasing the gradient. Second, a higher water table beneath Yucca Mountain would mean that more of the Topopah Springs tuffs would be saturated, and this unit has a higher hydraulic conductivity than much of the lower volcanic aquifer.

The following truncated lognormal distribution expresses my assessment and uncertainties regarding the ratio between the specific discharge under glacial conditions, q_{gl}, and under ambient conditions, q_a:

	Lower Bound	-1/2 Std Dev	Mean	+1/2 Std Dev	Upper Bound
q_{gl}/q_a	1	2	3.2	5.5	10

This estimated ratio is supported by water balance simulations using the regional model. These simulations show a change in discharge of approximately a factor of 5 for past glacial conditions.

SATURATED ZONE TRANSPORT: DISPERSION, DILUTION, AND MIXING

Conceptual Model

The primary mechanism of transport in the saturated zone downgradient from the repository is advective transport with the flowing groundwater. The release of radionuclides to the saturated zone beneath the repository can be viewed as release from a point source, multiple point sources, or an area source. Over long periods (thousands of years), conceptualizing the source as an area source (reflecting, I suppose, the existence of multiple point sources) is probably most appropriate, particularly given the discretization of the existing models. Advection most likely occurs along preferential flow paths and, as discussed previously, several factors would lead to focusing the flow. Therefore, I envision the downgradient flow paths as flow tubes heading to the southeast from the repository and turning south at Fortymile Wash. As discussed earlier, upward flow from the carbonates seems to be well established. Thus, I would expect the flow paths to occur within the volcanic aquifer until they enter the alluvium, with little or no flow from Yucca Mountain in the carbonate aquifer.

Some dilution of the contaminant plume will occur through longitudinal dispersion and through lateral and vertical transverse dispersion. I anticipate that lateral and vertical dispersion are likely to be small. Retardation of the radionuclides will occur from matrix diffusion and sorption. Within the welded tuffs, essentially all of the flow will occur within fractures and essentially none within the matrix. Sorption, matrix diffusion, and retardation in these units will be minimal. Matrix diffusion within the zeolitized and bedded tuffs may be more effective because there is likely to be sufficient contact with the matrix for sorption to occur in these units.

Few mechanisms would lead to substantial mixing of the plume. It is almost certain that the flow system occurs as laminar flow without turbulence. The only process that has the potential for significantly changing the position of flow tubes emanating from Yucca Mountain—and thereby causing mixing or lateral spreading to occur— are climatic transients. Water table rises may lead to changes in gradients and consequent changes in flow directions. However, because the time frames associated with climatic change are long, the flow field may have ample time to adjust slowly to the changed conditions.

There will also be mixing in the wellbore of water-supply wells in the Amargosa Desert, but I cannot conceive that this would be allowed as a dilution mechanism for TSPA purposes. However, if future groundwater exploitation were to increase substantially, and if such pumping rates were spatially and temporally erratic, then there might also be considerable mixing in the capture zones of those wells due to the pumping transients.

Dilution Factor

Rather than try to estimate dispersivity, a theoretical construct with which I am not very comfortable, I prefer to estimate a "dilution factor," which expresses the ratio between the initial contaminant concentration at the source and the highest concentration at another point some distance from the source. It encompasses all processes that lead to dilution, without highlighting "dispersion" as the controlling mechanism. It is based on both the hydraulic and the geochemical evidence.

I make the following assumptions: (1) the source is tens to hundreds of meters in dimension; (2) it is a steady, non-decaying source; (3) concentrations are measured at the center of the plume at a distance of 25 km from the source; and (4) concentrations are measured thousands of years after the initiation of release at the source. With these assumptions, I present the following truncated lognormal distribution to express my estimate of the median dilution factor and its associated uncertainty:

	Lower Bound	-1/2 Std Dev	Median	+1/2 Std Dev	Upper Bound
Dilution Factor	1	3	10	30	100

In my opinion, the dilution factor is the most uncertain parameter we have been asked to assess. If source areas are site-wide and transients are minuscule, then essentially no dilution will occur (dilution factor = 1). If source areas are point-like and glacial transients are significant, concentrations could be diluted up to 100-fold (dilution factor = 100). I have selected 10 as a median dilution factor, but have no great confidence in its representativeness.

Mixing Depth and Effective Fracture Density

Because of a lack of experience in using the concept of "mixing depth," I cannot comment on the appropriateness of the mixing depths that have been assumed in past TSPAs. However, it is easy to calculate the relative contribution that the vertical flow reaching the water table from Yucca Mountain makes to the horizontal flow at the water table. At 10 mm/yr vertical flux over a 1.5 x 1.5 km^2 repository area, the vertical flux is comparable to or larger than the lateral flow at 1 m/yr occurring through a 50-m-deep (the mixing depth that has been assumed) by 1.5-km-wide cross-sectional area. Therefore, it seems reasonable to conclude that flow tubes arising beneath the repository from downward infiltration through the unsaturated zone will remain fairly discrete, and there will be little mixing with the lateral flow tubes at the water table. Incoming lateral flow tubes will simply be pushed deeper by the Yucca Mountain recharge. I am not sure whether the mixing and dilution are likely to be higher or lower in fractured rock than in unconsolidated alluvium, but there are abundant data for contaminant plumes in alluvium that show long, continuous flow tubes with little lateral spreading over several kilometers, and little mixing with incoming lateral flow tubes from off site.

Effective fracture density is defined as the spacing between flowing fractures. Zero to 10 fractures/meter have been observed in the ESF, although I am not sure whether a similar fracture spacing exists in the lower volcanic aquifer. Certainly not all of these fractures would be effective. Truly effective fractures for flow are probably spaced at 10 to 50 m. Of these, only those in nonwelded, bedded, or zeolitized tuffs are likely to be "effective" from a dual-porosity, matrix-diffusion point of view.

HYDROCHEMICAL TRANSPORT PARAMETERS

The Kd values presented to us seem reasonable and in keeping with values reported elsewhere for similar radionuclides. I do not have sufficient expertise in this area to comment critically, or to provide probability distributions to represent my uncertainty. In this case, most of my uncertainty would come from ignorance, and distributions more reflective of realistic uncertainty ranges for TSPA use ought to come from the other panelists.

OTHER ISSUES

Thermohydrology

I believe that the impact of repository heating could be quite significant to saturated zone flow and transport. Boiling, buoyant convection, redistribution, and condensation of moisture in the unsaturated zone will lead to complex, transient patterns of perched saturation, fracture drainage, and increased recharge to the water table. Under one scenario presented to us, recharge to the water table could increase 100-fold relative to ambient conditions, and increased rates could persist for 1000 years.

The temperature effects are predicted to extend into the saturated zone. They potentially could create convection cells in the saturated zone and produce mineralogical alteration that could affect the permeability structure of the volcanic aquifers. These possible effects of repository heating on the saturated zone should be examined in further detail.

Water Table Changes from Disruptive Events

Disruptive events such as earthquakes or volcanism influence groundwater fluid pressures through their interaction with the subsurface stress field. I cannot comment on the possible impacts of volcanism, but earthquakes are known to produce short-lived spikes of increased fluid pressure in deep confined aquifers. The effects are due to deformations in fractured rocks engendered by changes to the stress field. They do not involve significant physical transfer of water and therefore are not likely to lead to large or long-lived changes in water-table elevation.

RECOMMENDATIONS FOR REDUCING UNCERTAINTY

Careful construction of flow nets in the vicinity of the large hydraulic gradient, using all available head data in a three-dimensional context, would aid in settling the LHG controversy. Uncertainties with respect to the LHG could be further laid to rest by two or three well-placed boreholes. However, ordinary drilling protocols will not suffice. It is difficult to determine whether low-K rocks are fully saturated (or just nearly so), and special protocols would be needed to obtain the necessary downhole information on saturation.

Uncertainties with respect to fault zone hydraulics could be reduced by careful mapping of fault properties in the ESF. (Properties measured in the unsaturated zone probably can be meaningfully projected into the saturated zone, if done with care.) Hydraulic tests (such as the C-wells pump tests) in the vicinity of a known fault might also clarify fault properties; as might further simulation and calibration of the new site-scale model.

Further well-controlled field tracer tests may help clarify the nature of dispersion, matrix diffusion, and sorption in the fractured volcanic rocks. It is necessary that laboratory Kd values be confirmed in situ.

Major underground testing (as recommended by the 1996 Thermohydrologic Peer Review Team) is still needed to clarify thermohydrologic processes associated with repository heating. Continued thermohydrologic modeling should be carried out to identify more fully the possible impacts on the saturated zone.

TABLE AF-1
ESTIMATES OF HYDRAULIC CONDUCTIVITY
(cm/s)

		Valley-Fill Alluvium	Upper Volcanic Aquifer (Topapah Springs)	Lower Volcanic Aquifer (Prow Pass, Bullfrog, Tram)	Eleana Formation	Lower Carbonate Aquifer	Fault Zones
Estimates	Local model HFM	$9.2 \times 10^{-5} - 6.0 \times 10^{-3}$	$9.6 \times 10^{-10} - 3.2 \times 10^{-2}$			$5.8 \times 10^{-7} - 2.6 \times 10^{-1}$	
	Regional model HFM	$1.2 \times 10^{-4} - 1.2 \times 10^{-1}$	$1.2 \times 10^{-4} - 1.2 \times 10^{-1}$	$1.2 \times 10^{-4} - 1.2 \times 10^{-1}$		$1.2 \times 10^{-4} - 1.2 \times 10^{-1}$	$9.3 \times 10^{-3} - 1.2 \times 10^{-1}$
Models	Calibrated local model	1.1×10^{-4}	2.6×10^{-5}	5.0×10^{-4}		5.5×10^{-3}	
	Calibrated regional model	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	1.2×10^{-9}	3.2×10^{-4}	2.3×10^{-2}
Measurements	Air injection tests		$10^{-5} - 10^{-2}$				
	Single borehole tests		$1.7 \times 10^{-4} - 3.2 \times 10^{-2}$	$4.3 \times 10^{-6} - 9 \times 10^{-4}$		2.2×10^{-4}	
	Pump tests, C-wells			$7 \times 10^{-4} - 7 \times 10^{-2}$			
	Packer injection tests, 25 p #1			$7 \times 10^{-6} - 8 \times 10^{-5}$			
Interpretation	Anisotropy, C-wells			10 – 100			

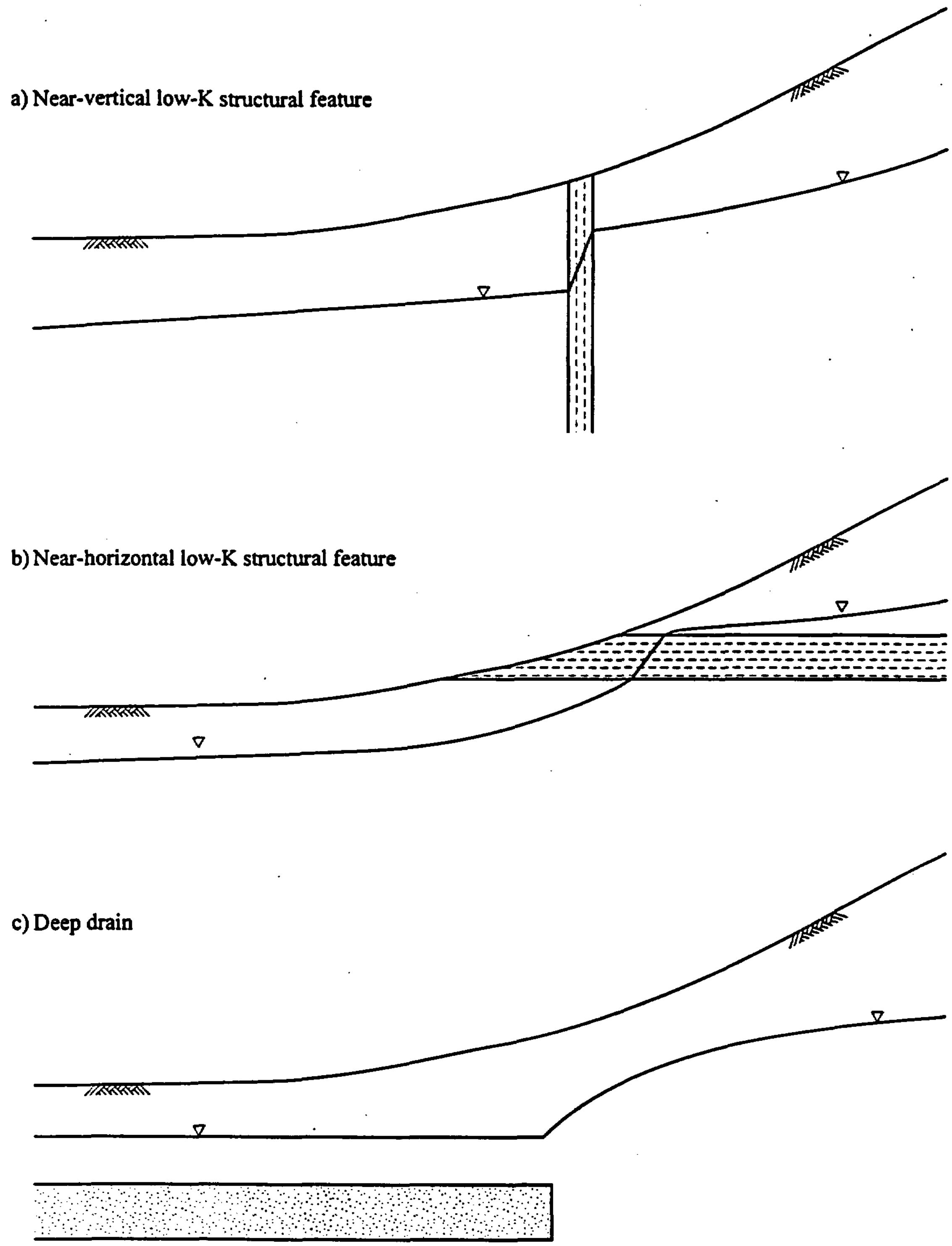

Figure AF-1 Alternative possible causes for the large hydraulic gradient (LHG), assuming a saturated flow system model rather than a perched flow system model.

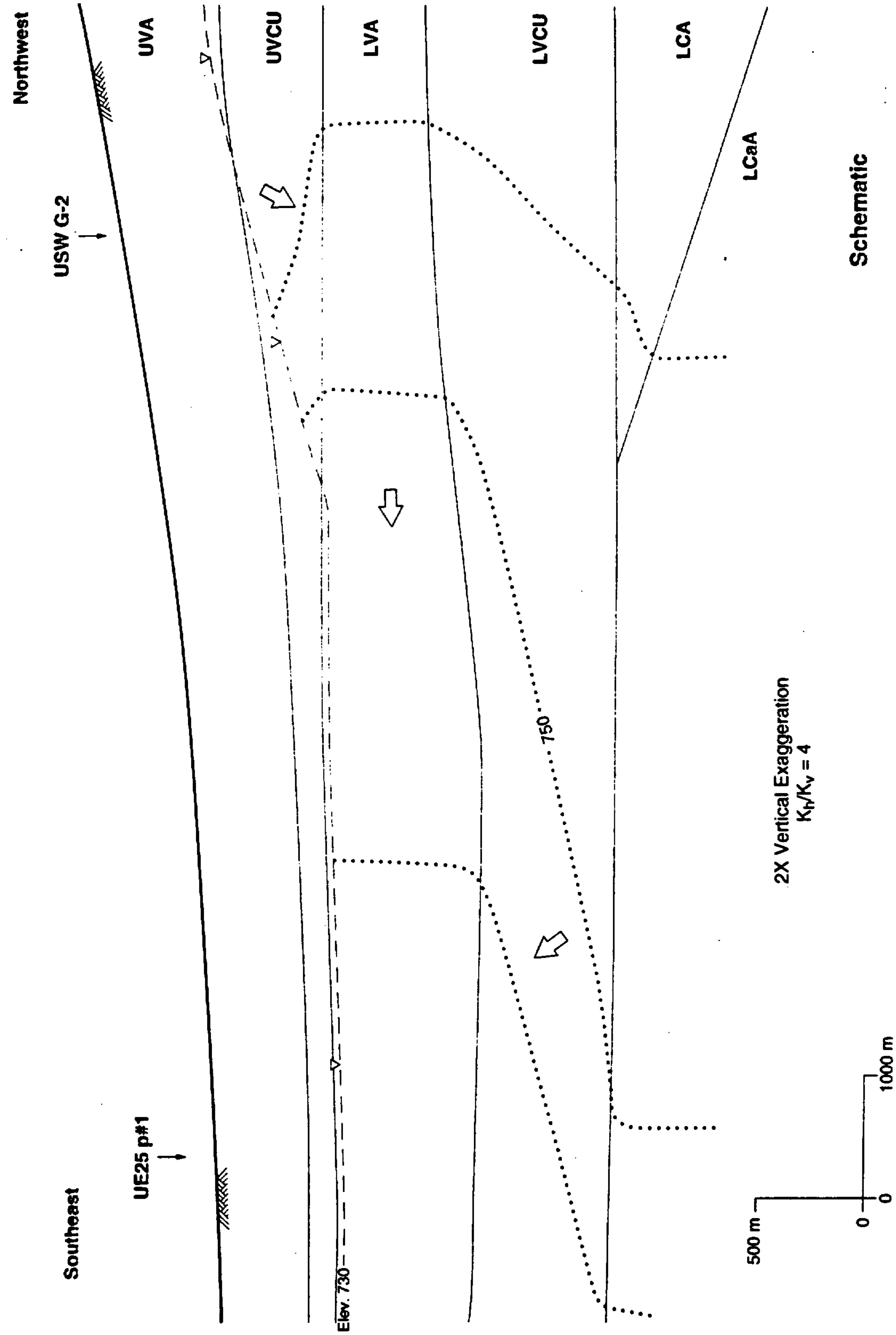

Figure AF-2 Flow net constructed in the vicinity of the large hydraulic gradient (LHG), from two controlling hydraulic head values at UE25p#1 and USW-G2.

ELICITATION SUMMARY
LYNN GELHAR

INTRODUCTION

The purpose of these introductory remarks is to offer some opinions, comments, and suggestions regarding the expert elicitation process. These remarks are intended to identify some possible limitations in the process and to suggest improvements that could address these limitations in future studies of this type. These remarks should not be construed as questioning the validity or utility of the current study. The overall premise of an expert elicitation process that addresses uncertainty rests on the notion of subjective probability; that is, the view that probabilities express a degree of belief. Many scientists question the utility of subjective probabilities as a basis for resolving scientific questions, taking the view that probabilities are evaluated from repeated observations of similar experiments. Although I see that subjective probability, as implemented in Bayesian methodology, may be a useful formalism for some engineering decision-making, I tend to favor the use of repeated observations to characterize probabilities. My perspective on probability influenced how I approached the assessments sought in the elicitation, as noted below. It is important to recognize that the scientific community is divided regarding the interpretation of probabilities and that this may affect the defensibility of the results from the expert elicitation process. In my view, it is important that subjective probabilities do not become a substitute for critical amd feasible data collection.

In light of the above discussion, my approach to assessing the issues was to rely primarily on specific information for the Yucca Mountain area, flavored by my experience with similar processes and geologic settings. From experience, I have seen that it is often difficult to extract reliable information from oral presentations and transparency copies; important details that may limit the validity of conclusions often are not recognizable. On the other hand, the presentations are important in revealing the researchers' perspectives on their work, and allowing an opportunity for discussion on and questioning of the work that may not be covered in written materials. I have placed the greatest weight on information for which detailed, reviewable written documents were available and which was also discussed specifically in oral presentations. I have placed less weight on material that was available in written documents but was not specifically presented by the researcher in one of the workshops. Information that was introduced only via oral presentation had only limited influence on my evaluations.

In view of the wide range of topics that our panel was asked to address, the very large amount of information that is pertinent to each topic, and the short time frame for the study, I believe that it would be appropriate to provide more of a focus for the workshops. I feel that more of an emphasis on the needs of the current TSPA activity could have provided a focus for the presentations; in essence each research group would be asked to show how their data, results and interpretations are used quantitatively to identify dominant processes and/or represent parameter uncertainty for TSPA. It seems a bit illogical not to seek a quantitative uncertainty assessment from project researchers, many of whom have a decade of experience with the site, and to rely more on a few "experts" whose experience with the site derives primarily from an effort to assimilate thousands of pages of documents in a few weeks. I raise this issue because of my experience serving on similar panels (though not a formal elicitation process) reviewing performance assessment modeling and associated uncertainties for the Nevada Test Site and for the proposed on-site disposal facility for low-level tank wastes at Hanford. In these cases, draft PA documents and appendices with data and interpretations providing the basis for the parameters and uncertainties therein were provided. I do not contend that this review structure produced a better result, but it certainly resulted in a more focused, efficient review process. For purposes of defensibility, it ultimately will be necessary to produce formal documentation showing how the field and lab data were used to determine the parameters and their uncertainties for TSPA at Yucca Mountain.

I believe that the availability of technical information may have been a limitation in the SZEE process. For example, key documents, such as the C-well hydraulic and tracer test reports, were not available until a few days before Workshop 3, when the panel was expected to provide preliminary assessments. This being the last meeting of the panel as a group, I feel that there may not have been adequate opportunity for the panel to interact regarding the findings of these key documents and other issues. The optimum arrangement would be to have detailed, reviewable written materials on a given topic available to the panel a week or two before that topic is to be discussed in a workshop, as this would facilitate more meaningful discussion and questioning. I also felt that the probability training session, although entertaining, was quite rudimentary and longer than necessary; some of this time would better have been spent allowing for interactions among the panel members regarding technical issues.

OVERVIEW: CONCEPTUAL MODEL OF SATURATED ZONE FLOW

Flowmeter logging of multiple boreholes is one of the most important pieces of semi-quantitative information for demonstrating the nature of flow in the volcanic aquifer near the site. This inflow logging shows that water is moving through only a small part of the overall vertical section and that, at different locations, these flowing zones do not occur in the same horizons within geologic units. The very low hydraulic gradient and the high transmissivity of the C-well aquifer test establish that the volcanic aquifer is highly transmissive downgradient of the site. There probably is a complicated flow network that is not simply related to lithology. The degree and scale of interconnectedness is unknown. The C-well data show a good deal of interconnection at the scale of the test (e.g., hundreds of meters). Permeability of the flow system cannot be related simply to lithology, as there probably are aquitards and aquifers within each unit. Borehole logging suggests that most of the flow travels through a few zones of higher transmissivity, rather than through the entire thickness of the unit. I would estimate that, on average, most of the flow occurs in less than 10 percent of the total thickness of the interval. Therefore, in modeling the system at a local scale, we may need to deal with velocities in local zones versus using a continuum model. If we are fortunate, the system that is not interconnected at a local scale (~100 m) may be interconnected at a larger scale (kilometers). It is tempting to adopt a standard mobile-immobile zone model in which solute exchange between the stagnant and flowing waters is controlled by molecular diffusion ("matrix diffusion"), but I am not convinced that this concept is appropriate at

Yucca Mountain and at many other sites where the notion is being applied. More likely there is a wide range of fluid velocities in each of the two zones. Consequently, transport is controlled by advective differences that overwhelm molecular diffusion effects, except in the unrealistic idealized case of no flow in one zone and a constant velocity in the other. Large-scale tracer tests would be valuable to address these questions.

It is not clear whether preferred flow paths (e.g., faults) must be discretely modeled. Channelization probably is involved, but may not be important at greater distances. Perhaps 5 percent of an aquifer might be accommodating flow, but it is not possible to map channels in detail. Perhaps a variety of models should be considered, ranging from a homogeneous continuum model to a highly channelized model, and the importance of their differences evaluated. In the flow system downgradient from the repository, it is difficult to see hydraulic evidence for channelization. Experience elsewhere has shown that large-scale lateral persistence of geologic features may not imply lateral persistence of hydraulics properties. Also, the hydraulic role of faults may be ambiguous; faults may be conduits for and/or barriers to flow. Large-scale (km) tracer tests are needed to examine the large-scale interconnected nature of the flow system. Other than perhaps the C-well data, we have few data regarding the importance of faults. The fact that responses in wells were observed out to distances of 3 km indicates that the aquifer in this area is highly transmissive, but it is not clear whether the high transmissivity is related to faults.

In evaluating recharge and discharge in the regional model, there are considerable uncertainties that will be difficult to reduce. In addition to the amounts of recharge and discharge, we don't know the internal distribution of permeability throughout the regional system. Consequently, there will be large, irreducible uncertainties in the flow paths and velocities predicted by the regional model. To evaluate whether the regional system is steady state, I would look at the response times and transmissivities. It is difficult to say whether Pleistocene transients still remain in the regional system, but I would expect that such transients are less significant in the site area because of the highly transmissive nature of the aquifer system there. The regional model is most important as a tool for evaluating the effect of climate change on the flow system. The model tells how a change in recharge would affect the regional system (e.g., flow directions), but it probably is not sufficient to impose flux conditions on the site-scale model. Prescribed fluxes are more likely to be usefully determined from site-scale aquifer pumping tests, such as the C-well tests. Regional modeling should not be dropped from the Yucca Mountain program, however, because of its importance as a tool to explore the effects of climate change.

Experience with dilute plumes at other sites suggests that the plume from the repository is not likely to move down deep into the aquifer system. The upward gradient inferred from the single carbonate aquifer well makes movement into that unit very unlikely under present conditions. Only for a site located at a water-table divide in a regional flow system would we expect the plume to be carried deep into the aquifer system; that is not the case at Yucca Mountain. There may be some tendency for the plume's movement to have a stronger downward component in the confining units in the volcanics, but in general the plume will stay shallow. Eventually, at distances of 20 to 30 km, the plume likely will be depressed somewhat below the water table because of the recharge occurring along the path of the plume. A continuum model for the alluvium probably is sufficient.

Based on a recharge of 15 mm/yr and a specific discharge in the aquifer of 0.66 m/yr beneath Yucca Mountain, the plume will extend about 25 m below the water table at the downstream edge of the repository (1 km wide). The water table is not a smooth surface; it is relatively flat in the high-permeability zones and steeper in low-permeability zones. The "mixing depth," as used in TSPA-95, is essentially zero, as there is no mechanism for mixing beneath the site at the water table other than that reflected by the small vertical transverse dispersion, which is already represented in the transport model. The influence of small intraformational heterogeneities downgradient from the source is incorporated into the dispersion terms. If there are identifiable large-scale permeability zones, these can be included in the models.

LARGE HYDRAULIC GRADIENT

The large hydraulic gradient (LHG) is not considered a crucial issue. If the issue relates only to the flow system north of the site, it would not be very important; it is more important to characterizing the downgradient flow paths. Both the "perched water" and the "saturated zone" models proposed to explain the feature (see discussion by S. Neuman and A. Freeze at SZEE Workshop 3) appear to be reasonable. Because of its parsimony, I would tend to favor the perched water explanation, assigning a weight of 0.6 to the perched model and 0.4 to the saturated zone model.

The importance of the LHG seems to be that it indicates perched water, which probably will be more extensive with climate change. The LHG as well as the evidence for perching beneath Yucca Mountain confirms the presence of low-permeability zones. I would be more concerned about the potential for increased perched water beneath the repository during climate change than the potential for a change in the LHG during climate change.

HYDRAULIC CONDUCTIVITY AND FLUX BENEATH YUCCA MOUNTAIN

Both the regional model and the site-scale models in their present forms are not useful for predicting groundwater flux beneath the potential repository. There are several sources of uncertainty and limitations to the models, which were discussed in detail at SZEE Workshop 3 (L. Gelhar presentation) and are summarized below. Therefore, my assessment of the magnitude and uncertainties in flux will come from my examination of the available data and from my experience elsewhere.

Some of the sources of uncertainty and limitations to the regional model include the following. The northeasterly extent of the basin is unknown, and the inflow and outflow to the basin are poorly defined. Water-level data are sparse within the basin except at Yucca Mountain, in the Nevada Test Site, and a few areas of groundwater development in valleys. The subsurface geology is ill-defined in many areas. The aquifer system is hydraulically heterogeneous; hydraulic conductivity (K) ranges over seven orders of magnitude. As a result, there is large uncertainty regarding flow pathways through the system. Actual hydraulic conductivity data with corresponding spatial locations are not used explicitly in calibrating the regional model; only maximum and minimum values are used. The problem of estimating hydraulic conductivity in this situation of unknown flux is essentially indeterminate, but parameter confidence intervals calculated via MODFLOWP are inexplicably narrow and quantitatively meaningless. Many of the predicted heads at Yucca Mountain are 20 to 60 m higher than observed. The model parameters are highly aggregated; only 4 homogeneous, isotropic K zones comprise the top layer of the model. The hydraulic conductivity $K_3 = 0.006$ m/day for the top (500-m) layer at Yucca Mountain (tuff aquifer) seems to be extremely low. Likewise, the hydraulic conductivity $K_1 = 0.275$ m/day for the basin fill and carbonates appears to be unreasonably low.

Some of the sources of uncertainty and limitations to the site-scale model include the following. The representation of the geology in the model may not be adequate; the spatial distribution of units occurring at the water table shows major inconsistencies with Figure 5 of Fridrich et al. (1994). The scheme used for assigning head boundary conditions is not defensible. Using the PEST parameter estimation code for only one parameter at a time will not provide meaningful estimates of uncertainties. No site-specific hydraulic conductivity data are used. The estimated hydraulic conductivity values of 0.1 m/day for basin fill and 0.026 m/day for the middle volcanic aquifer seem to be unreasonably low in comparison with the site data and with experience with similar formations.

To estimate flux, I rely primarily on data from the area of the C-wells (within ~1 km), which show transmissivities of ~1000 m^2/day. Judging from the detailed comparisons at the C-wells (Geldon, 1994), transmissivity values inferred from single-borehole hydraulic testing typically are two orders of magnitude lower than those found from aquifer pumping tests involving several observation wells. Apparently, scale dependencies would explain the differences between the single borehole tests and the aquifer tests. The single-borehole tests may not sample the larger-scale interconnectivity of the system; thus data from these tests are not considered in my assessment.

Specific discharge, q, is defined by:

$$q = KJ$$

where K is hydraulic conductivity and J is the hydraulic gradient. In the part of the Yucca Mountain site area immediately downgradient of the proposed repository, J = 0.0003; the gradient is fairly uniform, and there is not much uncertainty in this value. Hydraulic conductivity is much more uncertain and contributes to a large uncertainty in specific discharge. To estimate the speçific discharge for the volcanic aquifers, I use the estimate of K = 6 m/day for the Crater Flat tuffs (middle volcanic aquifer), which is based on the C-well aquifer tests (transmissivity = 3000 m^2/day, aquifer thickness = 500 m) to arrive at a specific discharge q = 0.0018 m/day (0.66 m/yr). Although the range of transmissivities in the C-well tests varies by only a factor of 2 to 3, I would expect plus or minus one order of magnitude uncertainty in the specific discharge as one moves away from the C-wells at a scale of ~5 km. I therefore would express the uncertainty in my estimate of the specific discharge for the volcanic aquifers, q_{va}, as a lognormal distribution having a geometric mean value of 0.6 m/yr, a $+2\sigma$ value of 6 m/yr, and a -2σ value of 0.06 m/yr ($\sigma_{\log K} = 0.5$, this is the base 10 log). Because the hydraulic gradient is essentially fixed, the uncertainty in hydraulic conductivity (geometric mean of 6 m/day) of the volcanic aquifer is also plus or minus one order of magnitude.

To look at velocities of migration within the volcanic aquifer, one can assume that the units are <10% transmissive (a range of 1% to 10% is warranted based on the measured contributions to flow in several boreholes) and that the average flow rate within the transmissive zones is ten times higher than the average flow rate for the unit. The flow in the remainder of the aquifer can be assumed to be essentially zero.

HYDRAULIC CONDUCTIVITY (m/day)

		-2?	Geometric Mean	+2?
Volcanic Aquifer		0.6	6	60
Volcanic Aquitards	10X- 100X less than volcanic aquifer (log is uniformly distributed)			
Carbonate Aquifer	0.1	10	1000	
Valley Fill Alluvium	10	100	1000	

The uncertainties in hydraulic conductivity for the four hydrogeologic units are given in the table above. It is difficult to decide how to use the single-well tests to assess the hydraulic conductivity of the volcanic aquitards or confining units. In order for there to be sufficient differences in conductivity that the units act as confining units, I would expect a difference of at least a factor of ten and perhaps as much as 100. (Assume a uniform distribution for the log of the ratio.) The carbonate aquifer appears to be very permeable based on well P-1, which shows an oscillatory response in the slug tests. Therefore, hydraulic conductivities of tens of meters per day are plausible, but uncertainty is high because of the difficulties interpreting the single test in the carbonates. Valley fill alluvium could easily be in the hundreds of meters per day, especially in the areas near the mountain front and Fortymile Wash where coarse sediments are expected. Measured hydraulic conductivities of the sand and gravel at Cape Cod range from 0.1 to 1500 m/day, although this is too wide a range for an "average" hydraulic conductivity. I would expect a trend in the conductivity values of the alluvium from higher values in the north, where it is coarser and near the range front, decreasing to the south. It is important to note that the hydraulic conductivity values given above are average values for the hydrogeologic unit and would include the conductivities for faults and other features within the unit. The range of point values within any given unit would, of course, be much wider than the ranges given above for the entire unit.

INFLUENCE OF CLIMATE CHANGE

The primary influences of climate change are a rise in water table and an increase in perched water conditions. The paleodischarge data suggest that past water table rises during glaciation have been on the order of 100 m in the region, which seems reasonable for Yucca Mountain. In modeling water-table rise using the regional model, uncertainties in recharge are significant: water-table rise could be as high as 200 m because of the uncertainties. Another important consideration regarding the response to climate change would be an increase in perched water conditions at the site. The perched water issue is not to be addressed in the site model, but may be covered in the unsaturated zone modeling not presented to our panel. The regional model also suggests that there will be more runoff in Fortymile Wash, perhaps with the water table rising to the surface in some parts of the wash. This could steepen the gradient and increase fluxes beneath the site.

I would not expect drastic changes in the gradient (perhaps 2 to 3 times), because I do not expect hydraulic conductivities to change. Likewise, I would expect the flux to fall within the range of estimates already given, but to be on the high side. This can be checked by assuming a 100-m rise beneath Yucca Mountain and a water table that reaches the surface at Fortymile Wash. In general, there may be changes in the direction of the hydraulic gradient, and there may be more fluctuations (transients) during glacial periods, both of which can affect dispersion. The observed differences in Cl^- in the matrix and in the fractures in the perched water zone (Rousseau et al., 1996, p. 187) are very important. Similar measurements below the water table would be extremely valuable in resolving the issue of the effectiveness of matrix diffusion in the field.

DISPERSION, DILUTION, AND SPATIAL DISTRIBUTION OF FLOW

Conceptual Model

It is important to consider that the scales of interest are 5 to 30 km (the possible distances to receptor wells). At these regional scales, it seems appropriate to use continuum models and exclude the localized effects of faults and other local heterogeneities. Typically, influence of heterogeneities with scales on the order of 1/10 or less of the dimensions of the plume can be adequately represented through dispersive terms. Based on the hydraulic testing in the C-wells, it seems likely that the aquifer system will be well connected at scales of about 1 km and more. The interconnection of flow paths at scales smaller than this can be described through traditional dispersive transport. Influences of larger-scale features such as confining units and faults will occur, but these features simply change the geometry of the plume rather than cause dilution (defined as a change in the maximum concentration). For example, as the plume experiences a large-scale change in hydraulic conductivity, the plume may stretch out but not undergo dilution.

Detailed tracer studies at Cape Cod (LeBlanc et al., 1991) show that maximum concentrations decreased by almost one order of magnitude at a mean plume displacement of 100 m, indicating significant dilution in the aquifer even in a relatively homogeneous system. The spatial second moments of the distribution of the concentrations grow linearly with mean displacement (Garabedian et al., 1991), but if the implied dispersivities are used to predict the maximum concentration, it will underpredict the observed maximum: Actual plumes are not smooth Gaussian distributions, but rather show irregular variations around the solution of the advection-dispersion equation using the macrodispersivities. This effect reflects the influence of small-scale heterogeneities in producing local variations in the concentration field around the smooth mean. The magnitude of the variations in concentration around the mean can be quantified using the concentration variance. Theoretical analysis of the concentration variance (Kapoor and Gelhar, 1994) shows that it is proportional to the mean concentration gradient; the coefficient of variation of concentration tends to be large at the fringes of the plume. This effect of concentration variability around the mean represents an additional source of uncertainty that is not accounted for in the classical advection-dispersion models being used to simulate contaminant transport for Yucca Mountain. The degree of dilution ultimately is controlled by local dispersion and molecular diffusion, but is strongly influenced by the fine-scale variations in the flow field. Very small-scale variations in flow create large concentration gradients and large surface areas over which local dispersion can act to more effectively decrease concentration differences.

Longitudinal and Transverse Dispersivity

Longitudinal macrodispersion is controlled primarily by the degree of variation in and correlation scale of the hydraulic conductivity. Temporal variations in the flow field, such as short-term or seasonal changes in hydraulic gradient, affect plume displacement, and ultimately can cause a significant increase in the transverse dispersivity (Rehfeldt and

Gelhar, 1992). The more fluctuation of the direction of the hydraulic gradient, the more transverse dispersion. The fluctuation in the direction of the gradient, as it interacts with the heterogeneity, is the most important control on transverse dispersivity. Transverse dispersivity is the strongest control on plume spreading and possible dilution for the Yucca Mountain situation, which involves a steady release of contaminant. Longitudinal dispersion will be important only at the leading edge of the advancing plume.

Field experiments summarized by Gelhar et al. (1992, Figure 1) found little difference in longitudinal dispersivity between porous media and fractured media; the relationship between longitudinal dispersivity and scale provides a basis for estimating longitudinal dispersivity along with the variance in the estimate. Figure LG-1 is a version of Gelhar et al. (1992, Figure 1), with several of the large-scale fractured rock sites explicitly identified. Weighing the applicability of various data points in the plot, I provide the following estimates of longitudinal dispersivity:

For 5 km:	**For 30 km:**
Assuming a lognormal distribution, Geometric mean = 50 m σ_{log10} = 0.5, therefore, -2σ = 5 m +2σ = 500 m	Assuming a lognormal distribution, Geometric mean = 100 m σ_{log10} = 0.75, therefore, -2σ = 3.2 m, +2σ = 3,200 m

Note that these estimates are for a nonreactive species and may be significantly larger for a sorbing species. Sorption heterogeneity affects only the longitudinal dispersivity and not the transverse dispersivities. The longitudinal dispersivity for sorbing contaminants could be 10 times or greater than for nonsorbing solutes, depending on the variability of the sorption coefficient and its correlation with hydraulic conductivity (Garabedian et al., 1988; Gelhar, 1993, Section 5.4, Equation 5.4.18; and Talbot and Gelhar, 1994). It is important to recognize that this process occurs even when there is not a correlation between sorption and conductivity. Significant enhancement of longitudinal dispersivity can result solely from independent (uncorrelated) variations of Kd; this was the case for the ten-fold increase found by Talbott and Gelhar (1994) for a low-level radioactive waste site. Such increased longitudinal dispersion can be important because it can greatly increase downstream concentrations in the case of contaminants undergoing radioactive decay.

To estimate transverse dispersivity, I consider the detailed tracer tests conducted at Borden and Cape Cod. At Borden there were apparently large fluctuations in the direction of the hydraulic gradient, but only scattered measurements of the gradient were made during the tracer test. Later detailed measurements (Farrell et al., 1994) were used to evaluate theoretical predictions of transverse dispersivity incorporating unsteady effects. At Cape Cod, the measured fluctuations in the direction of the hydraulic gradient during the tracer test were definitely smaller than at Borden (LeBlanc et al., 1991, Figure 5A); the standard deviation of the gradient direction was about 3° (Rehfeldt and Gelhar, 1992). The ratio of horizontal transverse to longitudinal dispersivity is about 1:10 at Borden and about 1:50 at Cape Cod. The two sites have comparable heterogeneity in hydraulic conductivity and longitudinal dispersivity; the difference in the transverse dispersivity is attributed to the greater fluctuations in direction of flow at Borden. The Condie site near Regina, Canada (Van der Kamp et al., 1994), is a unique case of a long (8-km) plume in a very steady flow system that shows very small transverse dispersivities (see Figure LWG-2). For Yucca Mountain, I looked at water-level data (Graves et al., 1997) for a group of three wells: H-3, H-4, and WT-1. Taking note of the disruption of the H-3 record in response to a packer change around December 1990, the data were analyzed in two segments; the standard deviation of the angle of the hydraulic gradient was 1.8°, indicating somewhat lower fluctuation (more steady) than Cape Cod. The trend implies that less fluctuation means less transverse dispersivity (e.g., the Condie site) rather than greater (e.g., the Borden site). An additional point for the vertical transverse dispersivity was extracted from a vertical chloride distribution measured in the volcanic aquifer system at Honolulu (Visher and Mink, 1964, Figure 16); the vertical dispersivity (0.2 m at a distance of 8.1 km) is much larger than at Condie, most likely because of greater unsteadiness associated with humid conditions and heavy utilization of the aquifer.

Looking at the plots of horizontal transverse dispersivity versus scale and vertical transverse dispersivity versus scale (Figure LG-2, revised Figures 4 and 5 from Gelhar et al., 1992, with additional data added at elicitation interview), there is a wide range of possible values and very few data. Based on my experience, and placing less weight on the low-reliability data points, I arrive at the following estimates for both 5 and 30 km.

Horizontal Transverse Dispersivity	Vertical Transverse Dispersivity
Assuming a lognormal distribution, Geometric mean = 0.5 m $\sigma_{\log 10}$ = 0.75, therefore, -2σ = 0.016 m +2σ = 16 m	Assuming a lognormal distribution, Geometric mean = 5 mm $\sigma_{\log 10}$ = 0.75, therefore, -2σ = 0.16 mm +2σ = 160 mm

In sampling the above distributions, one should assume a correlation between longitudinal and transverse dispersivity.

During wetter climates there will be more fluctuations in hydraulic gradients, which will likely lead to greater dispersion. I would expect increases of factors of 2 to 3 times in transverse dispersivity during wetter periods and no change in longitudinal dispersivity.

The C-well tracer tests provided only limited data on dispersivity. The dispersivities measured are not in the range of scales we are interested in. The interpretations of the tracer tests seems to raise more questions than they answer. Many crucial details are missing from the LANL report on the multi-tracer test. The change in the nature of the breakthrough curves between the USGS and LANL test is perplexing. The unreasonably high fracture porosities being calculated seem to indicate that the assumptions regarding the advective flow field are unrealistic. Three-dimensional and anisotropic effects likely are involved. I do not find the claim that a matrix diffusion effect has been demonstrated to be convincing. The differences between the Br and PFBA tracers breakthrough are small and are masked by the double-peaked behavior, and it has not been shown that these tracers behave ideally. The distinctive differences in breakthrough seen in the chalk tracer test analyzed by Moench (1995) are much more convincing regarding matrix diffusion effects. A recent reanalysis of the Grimsel multi-tracer test by Kunstmann et al. (1997) concluded that transverse dispersion was important, and the effects seen could not be attributed to diffusion into the porous rock matrix. They also found that tracer data found by reversing the flow field was helpful for determining transport parameters. For a complex flow system with multiple paths having different travel times, as apparently encountered in the LANL multi-tracer test, it is necessary to consider that some differences may be related to differences in transverse mixing between different flow paths. Clearly the issue of the importance of matrix diffusion remains unresolved. Larger-scale (up to 1-km well spacing) tracer tests are likely to be more useful in resolving this question and providing dispersivity data at the scale of interest to the project.

Width of Plume

The vertical width of the plume beneath the water table at the downstream edge of the repository can be estimated from the estimated recharge and the specific discharge in the aquifer. Assuming that the recharge reaching the water table is 15 mm/yr (0.015 m/yr), the horizontal specific discharge is 0.66 m/yr, the slope of a mean flow line relative to the mean water-table slope is 0.015/0.66 = 0.023, and the source is 1 km long, the bottom of the plume would be about 0.023 x 1000 m (source length) = 23 m thick. This is a relatively thin plume vertically. Note that this width is simply the advective downward movement of the plume boundary and is not the same as a "mixing depth," because the contaminants are not subject to mixing other than that due to the very small vertical dispersivity. The width of the mixed zone at the bottom of the plume is on the order of twice the square root of the product of the vertical dispersivity (5 mm) and the distance traveled (1000 m), or 4.4 m. Based on experience from many field sites, clean water infiltrating on top of a plume as it progresses downstream from the site definitely does not mix rapidly with the plume; vertical mixing is limited because of the very small vertical transverse dispersivity. A dispersive mixing calculation as described above shows that one would travel 8 km downgradient before the vertical mixing due to dispersion penetrates halfway (from above and below) through the initial 25-m vertical thickness to begin to decrease the maximum concentration.

Effective Fracture Density

There was no formal discussion of this issue, and no systematic information was provided on this. Consequently, it is difficult to provide a meaningful quantitative assessment. In my mind, the most pertinent information is again that from the borehole flow-logging. From Figure 15 of Luckey et al. (1996), we see that significant inflows occur at no more than 3 or 4 narrow horizons in each borehole. Given that the section (the lower volcanic aquifer) is about 500 m thick, an average spacing of these flowing (fracture?) zones is in the range of 100 to 200 m. I do not think one can judge much regarding flow by counting visible fractures.

Effective Porosity

Effective porosity, which is the porosity available for transport, integrates both the fractures and the matrix (for a continuum model). In view of the ambiguities in the multi-tracer test and the large differences between chloride concentrations observed in the fractures and the matrix in some saturated areas (perched zones) of the site (Rousseau et al., 1996, p. 187), I am skeptical about the applicability of this concept. Even if it is assumed that the effective molecular diffusion coefficent is relatively large (say 0.1 times the molecular diffusivity), based on the 100-m "fracture" spacing noted above, it would take more than 10^5 years for a solute to fully access the "stagnant" pore space between the flow zones. Furthermore, the data assembled in Figure 27 of Craig and Reed (1991) for H-6 shows that the matrix porosity is low in the horizons that contribute flow, indicating that matrix diffusion will not be very effective in storing solute from the "fracture." Given these observations, I see no justification for assuming that solutes will access the matrix porosity of the entire vertical section within the time frame of interest in TSPA. I would use fracture porosity here, but the very high values (nearly 10%) deduced from the tracer tests do not seem reasonable. Values of fracture porosity on the order of 10^{-3} seem plausible to me, but values could range over several orders of magnitude. For example, tracer tests in the basalt flow tops at Hanford produced effective porosity values as low as 10^{-5} (Leonart et al., 1985), whereas current interpretations of the C-well tests give values as high as 10^{-1}. It might be possible to develop plausible estimates that account for "matrix diffusion" effects by using lab data on matrix porostiy and effective molecular diffusion for the different rock types, but unfortunately the lab data were not presented in a way that makes that possible. Large-scale tracer tests are needed to resolve this issue.

There seems to be no site-specific information on effective porosity for the alluvium, but data for similar aquifers are widely available (Gelhar et al., 1992), permiting relatively tight estimates for this material. Based on experience with permeable granular sediments elsewhere, I would expect a mean of 0.25 and a coefficient of variation about 30 percent ($+2\sigma = 0.4$, $-2\sigma = 0.1$), with a truncated normal distribution (limited to the interval [0, 1]).

HYDROCHEMISTRY, TRANSPORT PARAMETERS

Regarding effective K_d sorption coefficients for fractures and matrix, I am unable to make meaningful estimates because of a lack of information. For field conditions, I do not see as much support for using the K_d estimates in the written report (Triay et al., 1997) as was portrayed at SZEE Workshop 1 (Triay presentation). The crucial question is how to representatively sample the system relative to what parts of the system will undergo sorption; this is not addressed in the LANL report. The report provides no explanation or justification for a sampling strategy that would be appropriate to represent the zones that are flowing. Batch tests on crushed rock may not be representative and may not provide minimum K_d values. If we assume that the lab tests are representative of the matrix, then we need to consider the likelihood that flow will reach the matrix. The cited moments and probability distributions (Table 26, Triay et al., 1997) are useless; one needs to know where the data came from, which units were sampled, the number of samples, how representative the samples are, etc. There seems to be a blind belief on the part of the LANL group that lab-determined values are directly usable in the field. I have similar concerns regarding the molecular diffusion data in the report; natural fracture surfaces were not tested. It would seem that effective field K_d values could be several orders of magnitude different (likely lower) than lab values. It is also important to know if there is a correlation between bulk hydraulic conductivity values and bulk or effective K_d values, because this can have a strong influence on longitudinal dispersion of sorbing solutes.

OTHER ISSUES

Thermohydrology

I would expect the thermal effect on the physical nature of flow and transport in the saturated zone to be modest. There may be a reduction in the vertical width of the plume due to buoyancy. Chemical changes may be more important, but I am unable to quantify them. I doubt that this effect is an overwhelming source of uncertainty in the saturated zone flow and transport problem. As I recall, this issue was discussed only as an aside in George Barr's presentation. No reviewable written material was provided on this issue, making it difficult to provide a meaningful assessment.

Water-Table Changes from Disruptive Events

There was no systematic discussion of such issues during the presentations; I do not feel that I have enough information to make a meaningful assessment.

Anisotropy

The C-well data suggest a ratio of ~1:10 horizontal anisotropy. I would expect a 1:10 to 1:100 vertical to horizontal anisotropy.

RECOMMENDATIONS FOR REDUCING UNCERTAINTY

The following lists items that are important to reduce the uncertainties regarding key processes and parameters.

1. Large-Scale Hydraulic and Tracer Tests

Probably the most important activity that would contribute to significant reduction of uncertainty would be additional large-scale, multi-hole hydraulic and tracer testing. These tests should be conducted in the area SSE of the site (south of the C-wells) to gain information along the flow paths from the repository. Hydraulic testing should be done with monitoring wells that range several km from the pumping well. Well spacing for the tracer testing should be on the order of 500 to 1000 m to allow sufficient distances to evaluate transport properties (effective porosity, dispersivities, matrix diffusion properties, sorption properties) at scales approaching those pertinent to PA modeling. The dipole (pumping-injection well) configuration is strongly recommended for the tracer test, because (1) tests at a given scale can be completed more rapidly; (2) it produces a flow field having a wide range of advective velocity, thus making it more feasible to separate the effects of dispersion and matrix diffusion; and (3) it can diagnose large-scale heterogeneity (fault zone?) effects. This test configuration was used successfully in tracer tests at the Grimsel site (Kunstmann et al., 1997). Multiple nonsorbing tracers having greater differences in molecular diffusion coefficient (Gupta et al., 1994; Sanford et al., in press, 1996; uranine (Moench, 1995) should be used. Reactive tracers should be selected to mimic the geochemical processes that are expected to control the sorption of key radionuclides. A formal external technical review group should be established to review the plans for the design and execution of the large-scale hydraulic and tracer testing program. The testing program likely will take several years and be very costly. It is important that the testing program be designed to avoid pitfalls and have the flexibility to adapt to the surprises that frequently are encountered in field experiments.

2. Re-evaluation of Single-Borehole Tests

The existing single-borehole data provide extensive spatial coverage of the site, but apparently there are some as-yet-unexplained complications in these tests and/or their interpretation, causing the results to fall two or more orders of magnitude below the hydraulic conductivities found from multi-well aquifer tests (Geldon, 1994). These tests should be re-analyzed using the latest techniques, possibly including three-dimensional numerical simulation with discrete fracture effects, to see whether a sound quantitative explanation can be found for the apparent bias in the original interpretations. If an appropriate correction can be devised, the single-borehole data would be very useful in defining the spatial distribution of hydraulic properties at the site.

3. Improvements of the Site-Scale Model

The grid used in the model should be refined to adequately represent the known hydrogeologic units and to resolve the expected plume structure (with small transverse dispersivities). The model grid should also be designed to simulate the C-well aquifer test and any future multi-well hydraulic testing at the site; the flux imposed by these tests would be the primary basis for calibrating the site-scale model.

4. Field Measurements of Ambient Matrix Diffusion Effects

Sampling and water analyses similar to those reported by Rousseau et al. (1996, p. 187) for the perched water at UZ-14 . If similar differences in water chemistry between fracture and matrix are seen at several locations, this would call into question the effectiveness of matrix diffusion under natural flow conditions. Diffusion cell lab test on natural fracture surfaces also are suggested.

5. Improved Interpretation and Documentation of the C-Well Multi-Tracer Test

Many important details of experimental and interpretative methodology are lacking from the draft report (Reimis and Turin, 7/31/97); if the results are to be accepted as technically sound, these details must be provided. As the material is now presented, it is not possible for the reader independently to assess the validity of the experimental results and their interpretation. The authors need to provide the details essential for independent evaluation. The material currently is in the summary style of a journal article, which is not adequate technical documentation for this important experiment. For example, explicit experimental evidence is needed to demonstrate that the two nonsorbing tracers behave ideally for the geochemical conditions corresponding to the field. The interpretative analyses implicitly neglect any effects of transverse mixing, but this process likely will come into play as soon as one adopts a model that contains multiple paths having different advective transport rates.

6. Improvements to the Report on the LANL Lab Sorption/Diffusion Testing

Although the draft report (Triay et al., 1997) contains many specifics about experimental equipment and procedures, it lacks crucial details about the overall experimental design and the justification in terms of field applicability. From the material presented, the reader is unable to determine where samples were collected, particularly in relation to the in situ hydrologic characteristics of the saturated zone. In order to judge the field applicability of the lab results, one must determine whether the lab data are representative of the very small portion of the rock through which water is likely to move. Borehole flow logging is the best indication of where flow is taking place. The flow properties are not necessarily related in a simple fashion to lithology/mineralogy, as seems to be the assumption of the report. Section VIII of the report on Applicability... does not address this crucial issue; it is largely a wish list for future work. There is no quantitative interpretation of the only experiments on a natural fracture (Section V(C)), and of the diffusion cell experiments (Section VI(B)).

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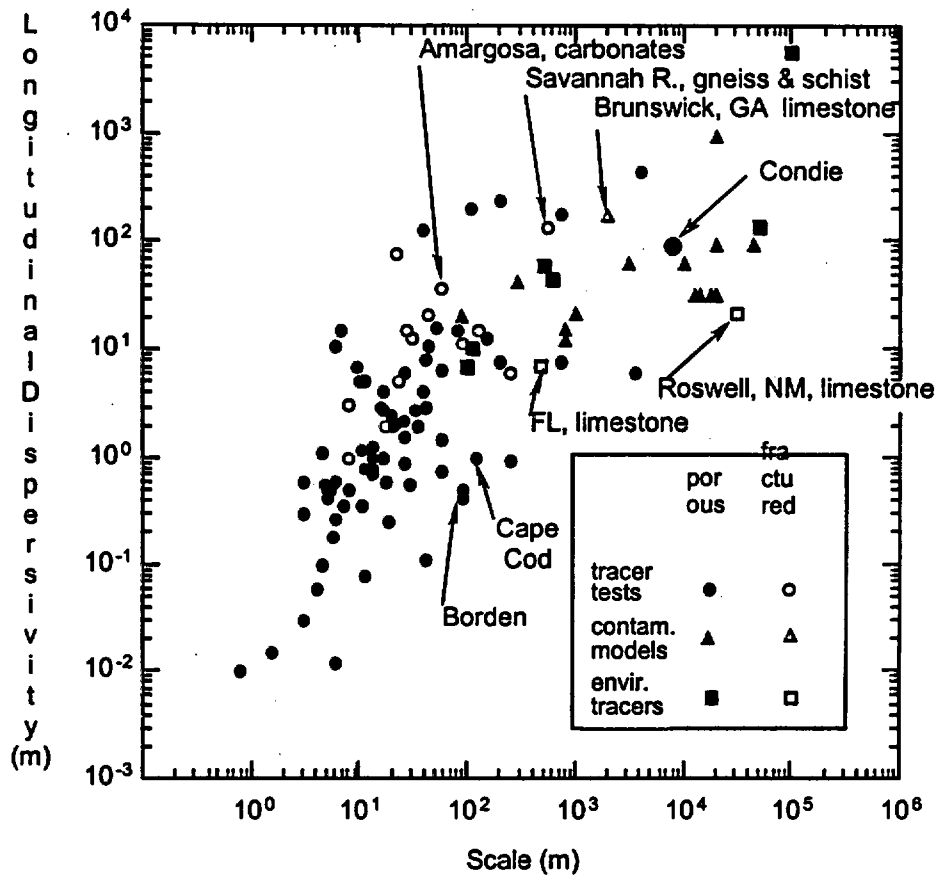
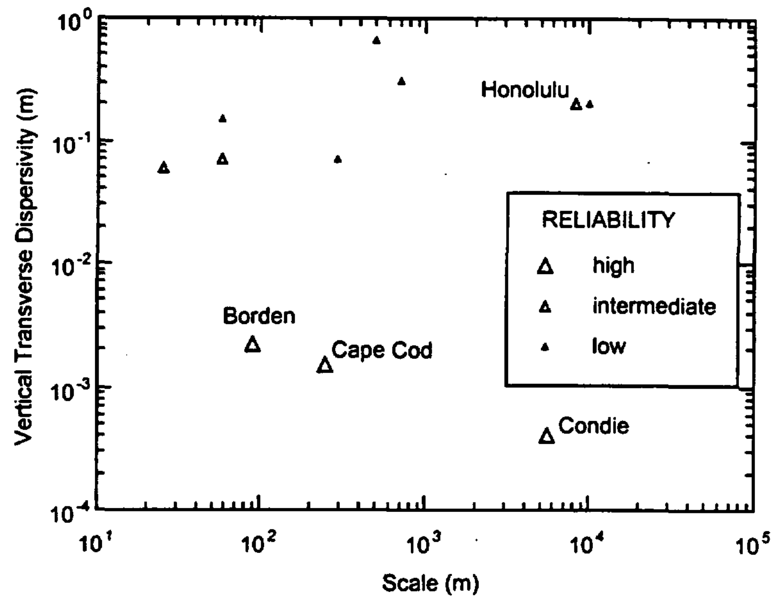


Figure LG-1 Longitudinal dispersity with large-scale fractured rock sites identified (from Gelhar et al., 1992, figure 1).



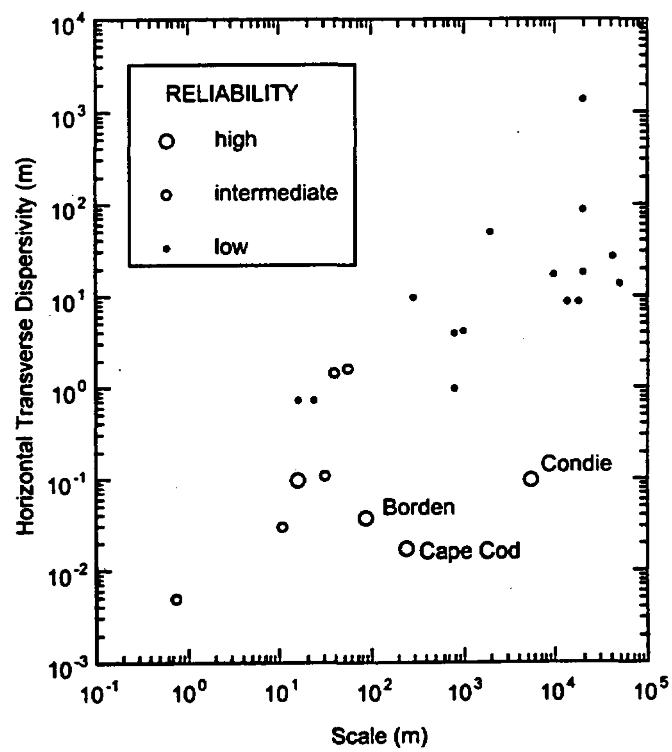


Figure LG-2a, b Horizontal and vertical transverse dispersivities (from Gelhar et al., 1992, figures 4 and 5).

ELICITATION SUMMARY
SHLOMO P. NEUMAN

OVERVIEW: CONCEPTUAL MODEL OF SATURATED ZONE FLOW

The Yucca Mountain area is part of a regional flow system commonly associated with the Death Valley groundwater basin. There is considerable information about the climate, topography, physiography, hydrography, and geology of the region, much of which has been assembled into a well-organized data base and a comprehensive three-dimensional geologic framework. With the aid of this information, it has been possible to delineate in a crude but plausible manner the lateral outline of the basin boundaries; the lateral and vertical extent of major hydrogeologic units in some areas of the basin; numerous faults and other structural features that impact the continuity of these units; depth to groundwater; the approximate location and extent of major groundwater recharge and discharge areas; and the location of focused discharge points such as springs and wells. Not surprisingly, data coverage is uneven across the basin, being relatively dense in some areas and sparse in other areas. Because the basin is structurally complex, it is difficult to interpolate or extrapolate subsurface information across it with confidence. As a result, there is considerable uncertainty about the presence, depth, and lateral continuity of key hydrogeologic units in many parts of the basin. This includes large areas north or upstream of Yucca Mountain, which may exert important control over subsurface flow under the mountain and farther downstream. In particular, little if anything is known about the hydrogeology of the Timber Mountain area between Pahute Mesa and Yucca Mountain, which may hold the key to a reliable estimation of fluxes under and downstream of a repository at the site.

Quantitative information concerning subsurface flow in the Death Valley groundwater basin is limited. Although the basin is considered to form a closed system, there may be flow into and out of the basin across at least some of its lateral boundaries. This is doubly true about the internal boundaries that are said to divide the larger Death Valley basin into smaller subbasins. Information about the hydraulic properties of hydrogeologic units in the basin is limited; much of the assembled data base contains laboratory and small-scale field measurements of permeability and porosity, which may not be representative of values required for flow and transport analyses on site and regional scales, especially where the rock is fractured. There is virtually no information about the hydraulic properties of faults and fault zones in the basin; available information about the pneumatic properties of some features has not yet been utilized in saturated zone analyses. In all current groundwater flow models, faults appear merely as offsets without being assigned their own hydraulic properties; yet we know from pneumatic pressure monitoring and air injection tests in the unsaturated Topopah Spring unit that vertical faults may be more transmissive than the surrounding rock in directions parallel to their plane of offset; more transmissive horizontally than vertically in the same plane; and less transmissive than the surrounding rock normal to this plane. Likewise, the Solitario Canyon fault is associated with a relatively steep drop in groundwater levels from west to east, which suggests that it acts as a barrier to flow in this direction. This fault is also associated with a temperature anomaly that appears to act as a conduit for vertical flow of relatively warm waters from the deep carbonate aquifer through an intervening aquitard to the lower volcanic aquifer. Indeed, there has been an interesting attempt by Bredehoeft (in press, 1997) to evaluate the vertical permeability of a fault that connects the deep carbonate aquifer with the overlying tuffaceous aquifer based on earth-tide water-level fluctuations registered in the carbonate aquifer within borehole UE-25pl, and then to calculate the corresponding upward flow rate based on a measured head drop of about 20 m between the carbonate and tuffaceous aquifers at the same location. His work suggests two ways in which the carbonate aquifer could act as a conduit for radionuclides emanating from a repository at Yucca Mountain: one is a reversal of the vertical gradient due to water withdrawal from the carbonate aquifer, the other is a similar reversal due to climatic change.

Recharge estimates appear to be most reliable where evaluated directly, as along parts of Fortymile Wash, and least reliable where based on the Maxey-Eakin method or modification thereof. The original Maxey-Eakin method predicts zero recharge in areas such as Yucca Mountain, where elevation and precipitation are below predetermined thresholds; we know today that recharge at Yucca Mountain is not negligibly small and can be locally high during major storm events. The modified Maxey-Eakin method applied to the Death Valley basin makes intuitive sense, but its reliability has never been ascertained against independent measurements or estimates in this or any other basin. Discharge estimates are most reliable in springs and wells where flow and withdrawal rates are measured. They are, however, much less reliable in areas such as Alkali Flats, where discharge occurs by evapotranspiration at uncertain rates across surfaces of uncertain extent.

Although depth to groundwater is known with reasonable accuracy at many locations, water-level variations with depth have been measured at only a few locations, as have hydraulic heads in the deep carbonate aquifer; in the Yucca Mountain area, this aquifer has been penetrated by only one well (UE-25pl). There is an open question about hydrogeologic conditions that control depth to groundwater in critical parts of the basin, including those on the north and west sides of Yucca Mountain. On the north side, hydraulic gradients appear to be anomalously high; alternative interpretations of this phenomenon will be discussed later. On the west side, hydraulic gradients are considerably higher than under much of the Yucca Mountain area, a phenomenon that generally is attributed to the Solitario Canyon fault and its surmised ability to act as a partial barrier to flow from west to east. Yet the hydraulic properties of this fault have never been measured. Thus flow rates across it cannot be calculated by means of Darcy's law, even though the corresponding hydraulic gradient is known. Hence there is presently no direct way to assess the ambient rates at which groundwater flows laterally from north and west into the Yucca Mountain area.

Farther downstream in the Yucca Mountain area, groundwater levels vary so slowly that any error in their measurement translates into a large error in the estimation of hydraulic gradients. In fact, groundwater elevation data in this area are sufficiently ambiguous to allow some hydrogeologists to contour them by means of smooth curves unaffected by faults, while allowing others to contour them so as to delineate embayments around the

Drillhole, Sundance, and an additional hypothetical fault. Hence, even though this area contains some of the most reliable estimates of rock hydraulic properties within the Death Valley basin, the available data are insufficient to compute ambient fluxes underneath Yucca Mountain with any reasonable degree of certainty. For this reason I consider it important to base calculations of groundwater flux in the Yucca Mountain area not only on site hydraulic data, but also on regional recharge and discharge data in a manner that renders all such calculations fully compatible and consistent with each other.

Site-scale and regional flow models developed for the saturated zone to date are consistent neither with each other nor with site measurements of rock hydraulic properties. The models differ in their hydrogeologic and gridding structures; in their prescribed or computed parameters; in conditions computed or prescribed along their interfaces; and in conditions computed or prescribed along their overlapping upper surfaces. The regional model consists of three layers that represent not hydrogeologic units but perceived (not clear how established) shallow, intermediate, and deep flow systems. The permeabilities ascribed to hydrologic units in both models, including calibrated values, are orders of magnitude lower than values determined in field tests, most notably pumping tests conducted in the C-cluster of wells. Yet these pumping tests are unique in providing by far the most reliable and relevant information about hydraulic behavior and parameters of several key hydrogeologic units at the site on scales that range from tens of meters to kilometers. The C-well tests suggest that the lower volcanic aquifer is hydraulically anisotropic in the horizontal plane; I suspect that this anisotropy is the hydraulic manifestation of faults that cross the test area and render the aquifer more transmissive parallel than perpendicular to the planes of the faults. Because the site-scale and regional flow models incorporate at most a few discrete faults explicitly within their respective grids, it would have been logical for them to incorporate the effect of all other faults implicitly by rendering all hydrogeologic units anisotropic in the horizontal and vertical directions, yet this was not done. The site-scale model was calibrated in a manner that fails to guarantee unique or meaningful results; calibration of the regional model has led to reliability estimates that seem to be unduly optimistic and hence of questionable validity. This is especially true when considering that uncertainty of the input data into these models has not been fully and convincingly quantified. Additionally, the models are too crude to provide reliable qualitative insight into, or quantitative information about, three-dimensional flow at the site or within the basin. I must therefore conclude that, in their present form, the site-scale and regional flow models are of very limited value.

The C-well hydraulic tests have proven that it is possible to conduct, within reasonable time frames and budgets, pressure interference tests between boreholes at Yucca Mountain that span multiple spatial scales of importance and relevance to the characterization and analysis of groundwater flow at the site. I propose to plan and conduct several additional tests of this kind, using existing boreholes, to better characterize the hydraulic properties of hydrogeologic units at the site; identify the hydraulic influence and properties of faults; and provide data against which it may be possible to calibrate a comprehensive, high-resolution groundwater flow model. I propose that such a model be developed and rendered compatible with all relevant site and basin-wide hydrologic and hydrogeologic data; that it have much greater spatial resolution in the horizontal and vertical directions than do the present site and regional flow models, especially in and downstream of the Yucca Mountain area; and that its development be coordinated with that of a similar-scale model recently constructed for environmental management of the Nevada Test Site. I propose that the uncertainty of all input data be quantified and that reliable prior information, especially that concerning hydraulic parameters from large-scale pumping tests, be formally included in the calibration process. A model that encompasses the entire basin has better-defined boundary inflows and outflows than does a site model with artificial boundaries, and is therefore better suited for calculation and calibration of water balance.

To further improve the prospects of constructing and calibrating a meaningful regional flow model, I recommend that the Yucca Mountain project strengthen its isotope hydrology program with the aim of obtaining more extensive and reliable information about groundwater ages and directions of flow throughout the basin.

It has been proposed that groundwater in the Yucca Mountain area occurs in "compartments" between which there is little or no hydraulic communication. Although the rates of hydraulic pressure propagation and flow may be slow across faults or units of low permeability, such flow does occur under most natural circumstances. In my view, the concept of isolated compartments in the area of Yucca Mountain is supported neither by theory nor by field evidence; the Death Valley basin forms an integrated flow system, all parts of which communicate with each other hydraulically at various rates.

The C-well pumping tests provided information not only about the overall transmissivity of the lower volcanic aquifer on scales of relevance to site and regional groundwater flow modeling, but also about its storativity and specific yield, as well as the transmissivity, horizontal and vertical hydraulic conductivities, storativity, and specific yield of its constituent units (Prow Pass, Bullfrog, and Tram) and the overlying Calico Hills aquitard. The tests appear to exhibit some "dual-porosity" behavior, which hydrogeologists commonly associate with a binary system of fractures and matrix, the former acting primarily as conduits for flow and the latter as fluid storage reservoirs. This interpretation seems inappropriate for the C-well tests. It appears more plausible to consider the rock as consisting of (porous and/or fractured) zones of relatively high permeability that form a (fully or partially interconnected) network within which are embedded blocks of less permeable (porous and/or fractured) rock, and to consider both components as capable of storing as well as allowing throughflow of fluid (in which case one speaks of "dual-permeability" behavior); flow through (rather than just in and out of) the less permeable blocks is especially likely to develop as the system approaches steady state. Rather than forming a binary system of high- and low-permeability components, the rock most probably contains a hierarchy of such components that spans a range of permeability values.

Tracer tests in the C-wells have yielded a porosity of 9% to 10%, which hydrogeologists so far have associated with fractures. I propose that this unusually high "fracture porosity" is in fact representative not only of fractures but also of matrix associated with the less permeable components of the hierarchy. The same may apply to transport, as discussed below.

LARGE APPARENT HYDRAULIC GRADIENT

An large apparent hydraulic gradient (LAHG) has been identified by water levels on the north side of Yucca Mountain. The LAHG is defined by only two boreholes on its north (G-2, WT-6) and three boreholes on its south (G-1, H-1, WT-16). There are no data to confirm that water level highs recorded in G-2 and WT-6 persist farther to the north, northwest, or northeast. The LAHG is on the order of (200 to 280 m)/2000 m, 0.01 to 0.14 in contrast to a moderate gradient of 0.02 to 0.04 across the Solitario Canyon fault, and small gradient of 0.0001 to 0.0004 south and east of the former. Regionally, steep hydraulic gradients tend to be associated with known geologic or topographic features such as edges of thick confining units, faults with major offsets, caldera boundaries, and mountain range fronts. A large gradient on the west side of Yucca Flat coincides with the edge of the Eleana Formation. The LAHG at Yucca Mountain is unique in that it does not correspond to any obvious geologic or topographic feature.

Several conceptual models have been proposed for the LAHG. These attribute the LAHG to (1) a perched system whereby water levels in boreholes G-2 and WT-6 on the north side of the LAHG reflect the upper volcanic aquifer, those on the south reflect the lower volcanic aquifer, and downward vertical leakage takes place from the former to the latter through the intervening Calico Hills aquitard; (2) a semiperched system that is similar to (1) but considers the Calico Hills aquitard to be saturated; (3) topographic control on the regional and local water table; (4) a drain model according to which the LAHG coincides with the effective northern limit of the deep carbonate aquifer and a fault buried under the Calico Hills Formation, marking the northern boundary of a buried graben; water drains through the fault downward from the volcanic system into the underlying carbonate aquifer, then returns in part by upwelling along the Solitario Canyon, Bow Ridge, and Paintbrush faults; (5) a spillway model in which a buried fault delineates the effective northern boundary of the lower volcanic aquifer, causing water to spill from the upper into the lower volcanic aquifer; (6) a model according to which a buried fault acts as a barrier to flow from north to south due to the juxtaposition of low- and high-permeability layers and/or the presence of low-permeability gouge material within the fault; (7) a reduction in permeability due to increased rock alteration and decreased fracturing to the north; (8) presence of the Eleana Formation, which causes the thinning of overlying volcanics and reduces flow rates from north to south; and (9) neotectonic phenomena such as rotational extension and/or increased stress to the north, causing elevated water levels in this region.

It is important to adopt an appropriate interpretive model for the LAHG so as to demonstrate an understanding of site hydrogeology and reduce uncertainty in both the qualitative (conceptual) and quantitative (computational) representations of flow and transport in the Yucca Mountain area. A defensible conceptual framework for the LAHG is especially important to correctly define inflow boundary conditions for the site groundwater flow model and to answer questions such as, "Is inflow into the Yucca Mountain area from the north significant and, if so, where does it occur and at what rates? Is flow from the north diverted into Crater Flat or along Fortymile Wash? If so, how and to what extent?"

Among alternative conceptual models for the LAHG, I favor those that are supported by the largest, most reliable and relevant set of observations and experimental data. Among all alternative models that conform to a given set of observations and experimental data, I favor the least complex (this is known as the principle of parsimony).

Based on these principles, I tentatively favor the perched system model because it is conceptually straightforward and, as shown below, is supported by numerous direct and indirect observations and/or data while contradicting none. The same is not true of any other model, with the possible exception of the semiperched concept, which is easy to accommodate jointly with the perched interpretation (more on this below). A single additional borehole, drilled strategically into the LAHG area and logged as well as sampled appropriately, should in my view suffice to confirm or deny that the LAHG is an artifact of perched conditions, as I propose. In the absence of new data from such a borehole, I tentatively associate a probability of 0.95 with the perched system model, 0.4 with the semiperched model, and 0.1 with all remaining conceptual models for the LAHG.

The following observations and data support, more or less in the order listed, a perched interpretation of the LAHG.

(1) Recorded water levels in G-2 and WT-6 are near the contact between the Topopah Spring basal vitrophyre and the underlying Calico Hills Formation; perched conditions are known to exist near this contact in other wells (UZ-14, NRG-7A, SD-7, SD9).

(2) Recorded water levels in G-2 and WT-6 (1,020 - 1,030 m) are not anomalous when compared to perched levels (from north to south) in UZ-14 (960 m), NRG-7A (860 m), SD-9 (890 m), and SD-7 (860 m).

(3) The upper volcanic confining unit is much thicker in G-2 (326 m) and WT-6 than in G-1 (156 m), H-1 (135 m), and WT-16 (see isopach map of Calico Hills Formation); these wells define the LAHG.

(4) Geophysical logs suggest that rock saturation along G-2 is at and/or slightly below unity at altitudes above 730 m, which coincides with the Calico Hills aquitard, but at unity in the underlying lower volcanic aquifer; water levels in G-1 (750 m), H-1 (731 m), and G-4 (731 m) farther south are just below the aquifer/aquitard contact (27 m, 5 m, and 2 m, respectively); thus, the top of the saturated zone in G-2 is not anomalous when compared to that in G-1, H-1, and G-4.

(5) Water levels in G-2 declined by 12 m between 1981 and 1994, while those in WT-6 rose by 4 m.

(6) Thermal gradients in G-2 decreased gradually with time.

(7) Pumping in April 1996 resulted in an asymptotic residual drawdown of about 0.5 m in G-2 by December 17, 1996.

(8) Wet walls and dripping were observed in the air-filled part of this borehole above the Topopah Spring basal vitrophyre.

(9) Pulsed heat-flow meter logs indicate downward flow in the water-filled part of the borehole, suggesting leakage into the lower volcanic aquifer. It is important to point out that other observations employed to support alternative models neither support nor contradict the perched system concept. In particular, since the perched system is relatively shallow, it should not be expected to explain phenomena and/or geophysical anomalies that are associated with deeper parts of the Yucca Mountain geologic environment.

Because the Calico Hills aquitard appears to be either at or just below full saturation in the area of the LAHG, a minute addition of water to it would render this unit fully saturated. It is therefore very likely that conditions in the LAHG area vary temporally, and spatially, between perched and semiperched. If full saturation occurs only intermittently within this unit (as current data suggest), then one can expect flow within it to take place vertically downward under a near-unit hydraulic gradient and the hydraulic conductivity of the aquitard to be near its maximum saturated value. If, on the other hand, semiperched conditions were allowed to persist, flow within the aquitard would develop horizontal components, and the LAHG would dissipate to form a milder lateral hydraulic gradient. Because the observed lateral gradient is not mild but steep, the semiperched model does not offer a viable stand-alone interpretation for the LAHG.

None of the remaining conceptual models for the LAHG are consistent with key observations and data I used earlier to support the perched system concept. In particular, these models are inconsistent with the G-2 geophysical log, which suggests partial saturation within the Calico Hills Formation; with the strong correspondence between recorded water levels in G-2 and confirmed perched conditions along the contact between the Calico Hills Formation and the Topopah Spring basal vitrophyre in other wells; and with the striking correspondence between the geophysically indicated top of the saturated zone in G-2 and water table elevations recorded in other wells. The idea that topography controls the LAHG is additionally contradicted by the lack of any correlation between recorded water levels and topographic elevations of wells across the LAHG. Topographic control appears to be evident only on a much larger, regional scale and may help explain the general increase in water levels from their approximate values of 730 to 780 m in much of the Yucca Mountain area to about 1200 m in the upper Fortymile Wash and 1400 m at Pahute Mesa.

The drain model relies on a conjectured fault and graben for which there is no direct evidencial, although it is consistent with a measured gravity anomaly and the thickening of the Crater Flat Group between G-2 and G-1. It additionally postulates a complex and improbable flow system that requires that the drain (fault), and the entire volcanic system north of its inlet, be hydraulically isolated from the same system south of the inlet. What else would prevent water in the volcanic system from bypassing the inlet of the drain and causing the LAHG to dissipate? The model further attributes the low heat-flow "anomaly" in the unsaturated zone to cooling of the deep carbonate aquifer by water draining into it from above, which does not explain the observed strong negative correlation between heat flow in the unsaturated zone and the thickness of this zone (suggesting that the proposed mechanism may not be the cause of the anomaly). Finally, the model attributes relatively high water table temperatures along the Solitario Canyon, Bow Ridge, and Paintbrush faults to the upwelling of relatively warm water from the carbonate aquifer through these faults, which does not require postulating a drain.

The spillway model likewise relies on a conjectured fault and graben for which there is no direct evidence but which is consistent with a measured gravity anomaly and the thickening of the Crater Flat Group between G-2 and G-1. It further proposes an effective termination of the Crater Flat Group as an aquifer north of the LAHG without offering any direct evidence in support of such a termination. There also is no direct evidence for the conjectured reduction in permeability from south to north due to enhanced alteration and reduced fracturing, or for the proposed presence of the Eleana Formation north of Yucca Mountain. Although such presence is consistent with an aeromagnetic high attributed to magnetite-bearing argillites, it is consistent neither with the above-mentioned gravity anomaly nor with the stratigraphy observed in G-2; the Eleana Formation is not present in UE-25p1. The proposed neotectonic models require postulating complex and unproven tectonophysical effects on hydrogeologic conditions and flow.

"BACK-OF-THE-ENVELOPE" ASSESSMENT OF AVERAGE FLUXES AND VELOCITIES IN AREA OF SMALL HYDRAULIC GRADIENT

I mentioned earlier that the assessment of magnitudes and directions of ambient groundwater fluxes in the area of small hydraulic gradient is prone to large errors and uncertainties. I will, nevertheless, offer a crude, "back-of-the-envelope" assessment of average fluxes and velocities within five permeable units across this area as a means of establishing order-of-magnitude estimates for these quantities. These five units are the Topopah Spring, which constitutes the upper volcanic aquifer, and the Prow Pass, Upper and Lower Bullfrog, and Upper Tram, which together make up the lower volcanic aquifer. The six units are designated below respectively as TS, PP, UB, LB, and UT.

The average horizontal gradient of water level elevations across the area ranges roughly from 0.0001 to 0.0004 and suggests a southeasterly direction for mean groundwater flow. The most reliable estimates of permeability in the TS unit are (in my view) those derived from pneumatic injection tests in the unsaturated zone; these correspond closely to values obtained from the interpretation of pneumatic pressure monitoring data. Corresponding values of hydraulic conductivity, obtained from 153 injection tests in four boreholes, range approximately over three orders of magnitude from 2 x 10^{-5} cm/sec to 3 x 10^{-2}; I shall work with the geometric mean of these values, $K_{TS} = 10^{-3}$ cm/sec. The most reliable large-scale estimates of hydraulic conductivity in the lower volcanic aquifer are (in my view) those derived from C-well pumping tests; according to Table 8 of Geldon et al. (1997), K_{PP} = (1.4 - 3.5) x 10^{-3} cm/sec, K_{UB} = (1.1 - 3.5) x 10^{-3} cm/sec, K_{LB} = (2.5 - 7.4) x 10^{-2} cm/sec, and K_{UT} = (1.4 - 5.3) x 10^{-2} cm/sec. Considering the above ranges of hydraulic gradient, one calculates the following ranges for the average magnitude of horizontal flux (specific discharge), q in each unit, by means of Darcy's law:

Upper volcanic aquifer	Lower volcanic aquifer
q_{TS} $3.2 \times 10^{-2} - 1.3 \times 10^{-1}$ m/yr	q_{PP} $4.4 \times 10^{-2} - 4.4 \times 10^{-1}$ m/yr
	q_{UB} $3.5 \times 10^{-2} - 4.4 \times 10^{-1}$ m/yr
	q_{LB} $7.9 \times 10^{-1} - 9.3 \times 10^{0}$ m/yr
	q_{UT} $4.4 \times 10^{-1} - 6.7 \times 10^{0}$ m/yr.

A composite range of average fluxes for the PP, UB, LB, and UT components of the lower volcanic aquifer (LV) can be calculated by summing their average flow rates (flux times thickness) and dividing by their composite thickness. Upon averaging the thicknesses listed for each unit in Table 8 of Geldon et al. (1997) we find that in

Composite lower volcanic aquifer
q_{LV} $3.9 \times 10^{-1} - 5.0 \times 10^{0}$ m/yr.

To translate these into average velocities, one must know the corresponding kinematic (effective, advective) porosities. Tracer tests in the C-wells yield kinematic porosities for the lower volcanic aquifer that range from 0.4% to 12.5 %. Tracer tests conducted in tuffaceous rocks at Pahute Mesa yield values that range from 0.1% to 1.0 %. Let us for simplicity consider a range of kinematic porosities from 0.001 (0.1 %) to 0.1 (10.0 %). Using this range of porosities and the above range of specific discharge values, we obtain the following ranges of average magnitudes of velocity v for each unit:

Upper volcanic aquifer	Lower volcanic aquifer	Composite lower volcanic aquifer
v_{TS} $3.2 \times 10^{-1} - 1.3 \times 10^{2}$ m/yr	v_{PP} $4.4 \times 10^{-1} - 4.4 \times 10^{2}$ m/yr	v_{LV} $3.9 \times 10^{0} - 5.0 \times 10^{3}$ m/yr.
	v_{UB} $3.5 \times 10^{-1} - 4.4 \times 10^{2}$ m/yr	
	v_{LB} $7.9 \times 10^{0} - 9.3 \times 10^{3}$ m/yr	
	v_{UT} $4.4 \times 10^{0} - 6.7 \times 10^{3}$ m/yr	

Because fluxes are proportional to hydraulic conductivities, which in turn are often distributed lognormally, a similar distribution can be assumed for the above spatial flux averages. To define the corresponding distributional parameters, I propose to consider the lower and upper values listed above for each spatial flux average as the 10th and 90th percentiles, respectively, of a corresponding lognormal distribution; the 50th percentile will then be the geometric mean of these two end values. I likewise propose that kinematic porosities be assumed lognormally distributed with mean 1% and with 10th and 90th percentiles given, respectively, by 0.1% and 10%. The distribution of velocities can then be computed by a Monte Carlo method which, absent evidence to the contrary, considers fluxes and kinematic porosities to be mutually uncorrelated.

Local fluxes and velocities can be expected to deviate significantly from a southeasterly direction and to fluctuate over many more orders of magnitude than is implied above for their average counterparts. Because of an anticipated scale effect, the mean of large-scale spatial flux averages need not coincide with the mean of smaller-scale local flux values. Therefore, to define the distribution of local fluxes in the upper volcanic aquifer, I propose to first define the distribution of local-scale hydraulic conductivities by analyzing the statistics of corresponding air injection test data, then relate the local flux statistics to the latter on the basis of Darcy's law. In the lower volcanic aquifer, local-scale hydraulic conductivity data from single-well tests in the C-cluster lie systematically two to three orders of magnitude below larger-scale values obtained from pumping tests in the same wells. This may be due either to a scale effect or to a systematic bias in the determination of local values. I suspect the latter, and therefore recommend against using the available local-scale hydraulic conductivities to define local flux distributions in the lower volcanic aquifer. Instead, I propose to consider local fluxes in the lower volcanic aquifer to be lognormally distributed, with mean values identical to those of corresponding spatial flux averages, and values of 40th and 60th percentiles equal, respectively, to the 10th and 90th percentiles of these averages.

Because there is no information about hydraulic gradients in the carbonate aquifer, I find it impossible to calculate fluxes in this unit without the benefit of a properly calibrated groundwater flow model. Some single-well hydraulic test results were listed for this aquifer by Craig and Robinson (1984); these indicate a range of hydraulic conductivities between 2.5×10^{-5} and 2.1×10^{-3} cm/sec. A larger and less biased sample probably would yield a range several orders of magnitude wider. The elicitation panel has been presented with no field data concerning hydraulic gradients or parameters of valley fill alluvium except in the shallow discharge area of Alkali Flats. I therefore find it impossible to estimate fluxes in valley fill except to note that, depending on the relative percentages of fine and coarse materials in alluvial sediments, their local hydraulic conductivities can range over as many as ten orders of magnitude, from those of clays to those of coarse sands and gravel.

For aquitard units such as the Calico Hills Formation, vertical hydraulic conductivities probably are more relevant to flux calculations than are horizontal values. A few vertical and horizontal hydraulic conductivities have been determined from pumping tests in the C-well cluster; these are listed in Table 8 of Geldon et al. (1997).

The kinematic porosity of tuff has been discussed earlier. In the carbonate aquifer I expect this porosity to be normally distributed about a mean of 3%, with 10th and 90th percentiles equal, respectively, to 1% and 5%. In valley fill alluvium I likewise expect the kinematic porosity to be Gaussian, with a mean of about 12% and 10th and 90th percentiles, respectively, of 6% and 18%.

The C-well pumping tests have provided storativity and specific yield values for several components of the lower volcanic aquifer and for the Calico Hills Formation. Specific storage of the lower volcanic aquifer falls into a narrow range of (2 to 8) x 10^{-6} m^{-1}, which is typical of confined aquifers that consist of consolidated porous or porous-fractured rocks. Specific yields range from 1% to 20% but, for the most part, lie between 5% and 10%.

DILUTION AND DISPERSION OF SOLUTES IN THE SATURATED ZONE

In TSPA-1995 it was recognized that the saturated zone is not a significant geosphere barrier to radionuclide migration compared to the unsaturated zone as concerns time delay of breakthrough to the accessible environment. The greatest contribution of the saturated zone toward acceptable performance of a repository at Yucca Mountain was seen in its dilution effect. After exiting the base of the unsaturated zone, the radionuclides were assumed for TSPA purposes to be mixed (diluted) into a volume of groundwater equal to the width of the repository times an arbitrary mixing depth (of 50 m) times the mean aquifer flux. Further dilution was believed to occur by mixing of different groundwater sources either naturally along the flow path between the repository and the user of the tuff aquifer (or other groundwater sources supplied by this aquifer) or by the user tapping alternative sources (as in the slotting of a well over different units). Dilution was also expected to occur by the mixing of groundwaters from adjacent subbasins due to water withdrawal in the vicinity of their mutual boundary and to lateral as well as vertical dispersion.

In my view, the only mechanisms by which dilution can take place in the absence of groundwater withdrawal for sampling or use are molecular diffusion, advective dispersion caused by space-time meandering of pathlines and variations in velocity along as well as among stream tubes, and turbulent eddies that are unikely to occur in the vicinity of Yucca Mountain. Otherwise, dilution can occur when water is drawn into samplers or wells from multiple horizons and/or directions, and when waters in samplers or wells mix by diffusion and turbulence caused by shaking, stirring, or rapid flow. Density effects due to space-time variations in solution chemistry, temperature, and pressure may either enhance or prevent mixing (as in buoyant or gravity segregation of fluids having different densities). Another factor that may contribute to mixing is instability of fluid interfaces and resultant fingering; this does not appear to play a role in the saturated zone of Yucca Mountain.

In my view there is no scientific basis for the "stirred tank" model, according to which contaminated waters from the unsaturated zone mix rapidly with pristine waters in the saturated zone down to some specified "mixing depth." Quite the contrary, I expect buoyancy of warmer waters from the repository area, and small vertical dispersivity commonly observed in stratified materials, to keep the incoming plume of radionuclides at shallow depth except where it is intercepted by major vertical fractures or faults within which there is significant downward flow. I likewise question the scientific basis for the notion that waters from neighboring subbasins mix naturally along a flow path; only where flow paths from the two subbasins converge will their waters mix by dispersion under natural conditions.

Mixing by dispersion may occur, but it is important to recognize that dispersion cannot be interpreted as dilution except in special cases to be described later. On the laboratory scale, dispersion coefficients compensate for our inability to resolve the intricacies of advective transport and diffusion in the pore space, about which we have no direct information. On the field scale, dispersion coefficients compensate additionally for our inability to resolve the intricacies of advective transport and local-scale dispersion in a heterogeneous porous and/or fractured rock, about which we have only partial information. As space-time fluctuations in advective velocity are generally greater in the field than in the laboratory, the amount of information we lose through inadequate resolution of flow in the field is generally greater than that which we lose through inadequate resolution of flow in a laboratory sample of rock. It follows that the coefficient of dispersion, which compensates for this loss of information, is generally larger on the field scale than on the laboratory scale. In fact, longitudinal dispersivities appear to increase consistently with the scale of field observations, a phenomenon we attribute today to a corresponding increase in the scale of medium heterogeneity, which our groundwater flow and transport models fail to resolve (Neuman, 1990, 1995; Di Federico and Neuman, 1997a-c). Clearly, lack of resolution does not necessarily imply mixing and dilution; only if we sample on a scale comparable to that of unresolved heterogeneities should we expect dispersion to imply mixing and dilution. Hence confusing dispersion with mixing and dilution is inappropriate except in special circumstances.

Given that field-scale dispersion is associated with incomplete resolution of medium heterogeneities, one can reduce it by including in his/her groundwater flow and transport models a greater amount of detail about the spatial variability of medium properties. Since one never has exhaustive information about all small-scale details of medium heterogeneity, the only hope one has to resolve such details is by means of statistical and geostatistical methods. A geostatistical description of medium heterogeneity introduces uncertainty into groundwater flow and transport models which renders these models stochastic. Hence stochastic approaches provide an appropriate framework for the analysis of flow and transport in heterogeneous media (Dagan and Neuman, 1997).

Briefly, the stochastic view of field-scale dispersion is as follows. Given a sufficiently large sample of local-scale medium properties at a site, it is often possible to generate by conditional Monte Carlo simulation random but potentially realistic spatial distributions or images (called realizations) of these properties that are equally likely and honor the data. By local scale I mean any scale that (a) is much smaller than the rock volume under investigation, and (b) allows measuring many if not all requisite flow and transport parameters (permeability, porosity, and dispersivity) and state variables (heads, concentrations) by means of standard field techniques; the corresponding length scale is typically on the order of meters to tens of meters. Given adequate computer resources, it is then also possible to perform random but equally likely, and potentially realistic, high-resolution flow and transport simulations on a computational grid with local-scale cells, using local-scale medium properties such as permeability, porosity, and dispersivity. Since local-scale dispersivities are much smaller than their larger-scale counterparts, these simulations indicate much lesser (but more realistic) degrees of mixing and dilution than would simulations conducted on coarser grids with less spatial resolution. Hence for purposes of investigating mixing and dilution, I propose to follow the above approach of high-resolution, statistically based conditional flow and transport simulations. Even a small number of corresponding realizations may be more telling with regard to dilution and mixing than would deterministic or stochastic simulations that do not achieve a comparable degree of resolution.

In the same context, it is important to recognize that local-scale dispersivities increase with their scale of definition; a crude rule of thumb (which does not consider numerical dispersion) is to set the longitudinal dispersivity equal to one-tenth the length of a local-scale grid cell, and the transverse dispersivity a fraction thereof (one-tenth to one-third).

If a statistically significant number of conditional Monte Carlo flow and transport simulations are performed, their results can be averaged to yield conditional mean values of head, groundwater flux, groundwater velocity, solute concentration, and solute mass flux at each grid point at many discrete time steps. These conditional mean values are deterministic (sure, certain) and vary much more smoothly in space-time than do their random (uncertain) counterparts (as represented by individual realizations). Most importantly, they constitute optimum unbiased predictors of the actual but unknown local-scale values of head, flux, velocity, concentration, and mass flux at each point in space-time. The variance of the conditional Monte Carlo realizations provides a measure of the uncertainty associated with these predictions. Because uncertainty is of interest to TSPA and VA, I propose that it be quantified in the above manner. Even a small sample of realizations may yield meaningful, although probably not accurate, insight into the uncertainty associated with simulating flow and transport in the saturated zone under and around Yucca Mountain.

To my knowledge, there is only one proper way to avoid running many high-resolution conditional Monte Carlo simulations of flow and transport: Solve numerically, on a coarser computational grid than required for such simulations, a single set of deterministic flow and transport equations that control the space-time evolution of smooth conditional mean heads, fluxes, velocities, concentrations, and mass fluxes (it is the relative smoothness of these deterministic functions that allows, in principle, computing them deterministically on a relatively coarse grid). Unfortunately, the corresponding "conditional mean" flow and transport equations are not differential but integro-differential (Neuman and Orr, 1993; Neuman, 1993; Zhang and Neuman, 1996; Neuman et al., 1996; Tartakovsky and Neuman, 1997a, b). Fortunately, they can sometimes be approximated by differential equations that look like the familiar flow and transport equations (the same equations one would use, among others, for high-resolution conditional Monte Carlo simulations), but their coefficients and variables have different meanings and values. In particular, the conditional mean advection-dispersion equation now contains a conditional mean velocity vector that is much smoother, and a dispersion tensor that grows with time to become rapidly much larger, than their local counterparts.

The large dispersion compensates for resolution lost in smoothing the velocity and concentration fields (recall that solving the conditional mean equation is analogous to averaging the results of many conditional Monte Carlo simulations, each one of which is associated with nonsmooth velocity and concentration fields, which become smooth upon averaging). The more information about local-scale medium properties one builds into the model (i.e., the more strongly one conditions the model on local-scale data), the less smooth is the corresponding conditional mean velocity (as well as concentration) field and the smaller is the corresponding dispersion tensor. Clearly, building information into a model does not affect mixing and dilution; hence the dispersion tensor generally does not reflect these phenomena.

Because there is always uncertainty about local-scale medium heterogeneities, a deterministic analysis of transport is never warranted unless the advection-dispersion model is viewed and interpreted in the manner just described. This means that the computed concentration and mass flux are recognized to represent not actual but smooth predicted values with which there is associated a quantifiable error of prediction and smoothing, and that the computed concentrations are recognized to potentially spread, or disperse, to a much greater extent than do their real but unknown counterparts. (One can view this enhanced spread, or dispersion, not as that of real solute mass but that of information about the space-time distribution of this mass.)

Only in special, so-called quasi-ergodic situations can such enhanced dispersion be interpreted to imply mixing and dilution. These situations arise as the mean travel distance becomes large enough for a plume to encounter (sample) heterogeneities of all relevant scales in the longitudinal direction of flow, and when the source of contamination is wide enough so that the plume can sample all such heterogeneities in the transverse direction. An extreme example of nonergodic transport is that of an imaginary solute "particle" of infinitesimal volume that never diffuses, disperses, or dilutes. If the particle has unit mass normalized by porosity, then its concentration, predicted deterministically with a relatively large "field-scale" dispersion coefficient, merely represents the probability of finding this particle in the immediate vicinity of any given point in space-time.

Despite significant advances in stochastic flow and transport theories over the past two decades, stochastically derived field-scale dispersivities are known to overpredict the vertical spread of solutes in stratified media under seemingly quasi-ergodic conditions.

Model abstraction through reduction of dimensionality (as when three-dimensional transport is represented by a network of one-dimensional flow tubes) is associated with a loss of spatial resolution, which should be compensated for by a corresponding increase in dispersivities. Once again, such an increase must not be interpreted to imply enhanced dilution.

Bomb-pulse isotopes at depth within the unsaturated zone attest to the occurrence of intermittent fast flow through both welded and nonwelded volcanic units. Major springs associated with the Paleozoic carbonate aquifer constitute evidence for highly localized flow in parts of the Death Valley basin. It is safe to assume that focused flow is ubiquitous throughout both the unsaturated and saturated zones in the basin on many scales. I therefore propose that corresponding narrow channels of elevated permeability be included in high-resolution conditional simulations of flow and transport in and around the Yucca Mountain area. The low potential for dilution associated with such potentially fast-flow channels should (in my view) be weighted against the probability (which could be high for detectable features such as major faults) that they may be intercepted by water supply wells.

MATRIX DIFFUSION AND SORPTION

Matrix diffusion, when active, may enhance the retardation, mixing, and spread of contaminants in fractured porous rocks. Laboratory experiments by LANL have shown that matrix diffusion can take place even during relatively fast fracture flow in tuff, and even in the presence of fracture coatings. The only direct evidence for possible matrix diffusion on the field scale at Yucca Mountain is an apparent separation between PFBA and bromide tracer breakthrough curves in one tracer test conducted in the C-cluster of boreholes. Unfortunately, the interpretation of this tracer test is (in my view) somewhat ambiguous: Discrepancies between fitted models to the PFBA and bromide breakthrough data are of the same order as the offset between these data, attributed in the models to differences between the diffusions coefficients of PFBA and bromide in water; it is not clear whether the tracer data could be interpreted to imply diffusion not (just) into the rock matrix but (also) from fast to slower flow paths within fractures (this is supported by the observation that fractures in the tuffaceous aquifer do not carry any signature of calcite where the latter is known to occur in the matrix); and it is equally unclear whether the tracer data could be interpreted by allowing not only diffusion into, but also advection through, the matrix (and/or slow paths within fractures). The latter possibility is suggested by the observed dual porosity (or permeability) response of C-wells during pumping tests. I further anticipate advection through the matrix to take place where fractures are not in direct contact, as in the case of strata-bound vertical fractures that are not in direct contact across layer interfaces as well as horizontally within a layer.

Sorption is another transport phenomenon that may enhance the retardation, mixing, and spread of contaminants. Both kinetic phenomena and the spatial variability of sorption parameters may affect dispersion, but the manner in which this happens is not well understood, and corresponding field data are scarce. Whereas some field data suggest that linear sorption coefficients are negatively correlated with permeability, other data suggest that they are positively correlated or not at all. Hence theoretical predictions of dispersion based on this or another correllative relationship between sorption coefficients and permeability are, in my view, of limited applicability.

EFFECTS OF CLIMATE CHANGE

Significant variations in climate may affect large-scale, long-term features of basin-wide subsurface flow such as regional modes, areas and rates of recharge and discharge, regional groundwater elevations, overall directions and magnitudes of hydraulic gradients throughout the basin, and corresponding groundwater fluxes and velocities. Associated changes in weather patterns may alter smaller-scale, shorter-term space-time variations in subsurface flow. Such variations may also affect dispersion, which depends on space-time fluctuations in groundwater velocity. There appears to be convincing paleodepositional evidence that, in the past, the groundwater table beneath Yucca Mountain reached elevations that exceeded those of today by 80 to 120 m. A properly calibrated groundwater flow model, which represents the site and the basin at appropriate scales of resolution, may provide a useful tool for the analysis of possible future climatic effects on regional and site-scale flow regimes.

If variations in climate are slow in comparison to the rate at which groundwater flow in the basin adjusts itself to these variations, their effect on the subsurface flow regime may be evaluated by a sequence of steady-state simulations. Otherwise, the effect of climate change on subsurface flow must be analyzed by means of a transient groundwater flow model. To analyze the effect of climate change on groundwater chemistry almost certainly would require employing a transient model of chemically reactive solute transport for the basin.

A wetter climate than that of today may cause the Calico Hills aquitard on the north side of Yucca Mountain to saturate and thus allow the large apparent hydraulic gradient in this area to dissipate so as to form a milder gradient, as explained earlier.

WATER-TABLE CHANGES DUE TO DISRUPTIVE EVENTS

Observations of water level fluctuations in wells due to earthquakes indicate that they tend to be rapid, short-lived, and on the order of centimeters to meters. Hence future earthquakes of magnitudes similar to those recorded within the basin in recent history most probably will not cause major or long-lasting changes in the groundwater flow regime.

RECOMMENDATIONS FOR REDUCING UNCERTAINTY

The following (not listed in order of importance) are recommended to help reduce uncertainty about flow and transport in the saturated zone under and around Yucca Mountain.

1. Investigate the hydrogeology of the Timber Mountain area between Pahute Mesa and Yucca Mountain, which may hold the key to a reliable estimation of fluxes under and downstream of a repository at the site.

2. Conduct field tests to help determine the hydraulic properties of faults and fault zones in the Yucca Mountain area. Likewise, utilize available information about the pneumatic properties of faults in the unsaturated Topopah Spring unit when analyzing flow and transport in the saturated part of this unit.

3. Base calculations of groundwater flux in the Yucca Mountain area not only on site hydraulic data, but also on regional recharge and discharge data in a manner that renders all such calculations fully compatible and consistent with each other.

4. Where faults are not incorporated explicitly into flow models, account for them implicitly by rendering all hydrogeologic units anisotropic in horizontal and vertical directions parallel to dominant fault planes.

5. The C-well hydraulic tests have proven that it is possible to conduct, within reasonable time frames and budgets, pressure interference tests between boreholes at Yucca Mountain that span multiple spatial scales that are of importance and relevance to the characterization and analysis of groundwater flow at the site. Plan and conduct several additional tests of this kind, using existing boreholes, to better characterize the hydraulic properties of hydrogeologic units at the site; identify the hydraulic influence and properties of faults in the test area; and provide data against which it may be possible to calibrate a comprehensive, high-resolution groundwater flow model.

6. Develop a comprehensive, high-resolution groundwater flow model and render it compatible with all relevant site and basin-wide hydrologic and hydrogeologic data. Make the horizontal and vertical spatial resolutions of

this model much greater than those of present site and regional flow models, especially in and downstream of the Yucca Mountain area, and coordinate its development with that of a similar-scale model recently constructed for environmental management of the Nevada Test Site.

7. Quantify the uncertainty of all input data into the above model and include reliable prior information, especially that concerning hydraulic parameters from large-scale pumping tests, formally in its calibration. A model that encompasses the entire basin has better-defined boundary inflows and outflows than does a site model that has artificial boundaries, and is therefore better suited for calculation and calibration of water balance.

8. To further improve the prospects of constructing and calibrating a meaningful regional flow model, strengthen the isotope hydrology program of the Yucca Mountain project so as to obtain more extensive and reliable information about groundwater ages and directions of flow throughout the basin.

9. Drill an additional borehole strategically into the LAHG area, then log and sample it thoroughly enough to confirm or deny that the LAHG is an artifact of perched conditions, as some (including myself) propose.

10. To investigate mixing and dilution, conduct high-resolution, statistically based conditional flow and transport simulations in the manner described within the text. Even a small number of conditional Monte Carlo simulations, conducted in this manner, may be more telling with regard to dilution and mixing than would deterministic or stochastic simulations that do not achieve a comparable degree of resolution. They may also provide meaningful, if not fully accurate, insight into the uncertainty associated with such simulations.

11. Include narrow channels of elevated permeability in high-resolution conditional simulations to allow for focused flow and transport.

12. Conduct large-scale, long-term tracer experiments in and around the C-boreholes to obtain meaningful parameters (kinematic porosities, dispersivities, slow/fast path transfer coefficients, retardation factors) for transport simulations.

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ELICITATION SUMMARY
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OVERVIEW: CONCEPTUAL MODEL OF SATURATED ZONE FLOW

There are a number of key issues related to the saturated zone flow system and potential radionuclide transport in the Yucca Mountain region. Piezometric maps indicate that groundwater flow of radionuclide contaminants from the proposed repository likely would follow a pathway defined by a flow tube, southeast from Yucca Mountain to Fortymile Wash and then south to Amargosa Valley. Elevated heads in the underlying Paleozoic carbonate aquifer under Yucca Mountain probably preclude groundwater flow from the Tertiary volcanics into the carbonates. Scattered calcite is present in the volcanic rocks, particularly in fractures at depth. Caliche and other secondary or detrital calcite is present in the shallow alluvium, particularly as the groundwater flows farther south toward the Armagosa Desert. Calcite is important because of its ability to strongly adsorb Np(V), which is likely to be the most hazardous radionuclide released from a repository after 10,000 to 50,000 y.

The residence time of groundwater in the volcanic rock matrix is of vital importance to retarding the movement of radionuclides. Longer matrix residence times, away from oxygenated fracture flow, could permit the strong adsorption of Np(V) by Fe(II)-containing minerals. Robinson (LANL, SZEE Workshop 2) showed that fracture density and matrix porosity are inversely related. Therefore, there probably is sufficient opportunity for contact with rock surfaces, within either the matrix or fracture network. With this in mind, it is important to consider which hydrogeologic units are most likely to support fracture flow and which matrix flow.

Theoretically, accurate $\delta^{14}C$ age-dating of the groundwater could be used to estimate the time the water spends in matrix flow. B. Robinson (LANL, SZEE Workshop 2) suggested that if all of the flow occurred in fractures with no matrix diffusion, groundwater $\delta^{14}C$ ages would be only hundreds of years. Instead, these ages are thousands of years (E. Kwicklis, USGS, SZEE Workshop 1). Unfortunately, corrected $\delta^{14}C$ ages of groundwater beneath Yucca Mountain and Fortymile Wash are not simply interpretable, because the water in both cases is a mixture of waters of different ages. It seems likely, however, that the youngest groundwaters under Yucca Mountain (those derived from direct infiltration on the mountain?) are about 6000 y old. In Fortymile Wash, corrected C-14 ages decrease in the direction of groundwater flow from 7100 y in well WT-15 to 4200 y in well JF-3. This may reflect dilution of the groundwater with infiltration from recent snowmelt runoff in the wash..

Oxygen-deuterium isotopes and $\delta^{14}C$ data show that flow at the saturated zone beneath Yucca Mountain is combination of contributions from snowmelt recharge to the north at Pahute Mesa and Timber Mountain (-5° to 0°C), and local snowmelt recharge. Somewhat heavier (more positive) oxygen and deuterium isotope values in groundwater beneath Fortymile Wash indicate that these waters are also chiefly derived from snowmelt runoff, but at closer to 0°C (more recent?). The hydrochemical data support the conclusion suggested by piezometric and geophysical data, that the Solitario Canyon fault acts as a barrier to groundwater flow from Crater Flat, east toward Yucca Mountain. Isoconcentration contour maps suggest that west of the fault, groundwater flow in the Tertiary volcanics is toward the south.

A comparison of average $\delta^{18}O$, ΔD, Na, Ca, Cl and SO_4 concentrations in groundwaters under Yucca Mountain, with their concentrations in the presumed groundwater flow direction in wells J-13 and J-12 along Fortymile Wash, suggests that groundwater under Yucca Mountain contributes a negligible fraction of flow to the groundwaters in Fortymile Wash. The data also tentatively suggest that significant surface runoff (snowmelt runoff?) infiltrates to groundwater east of Yucca Mountain in Fortymile Wash. Although its amount currently cannot be estimated, such infiltration could significantly dilute radionuclide concentrations introduced from a Yucca Mountain repository. Groundwater from beneath Yucca Mountain can be thought of as being 'titrated' into the relatively large Fortymile Wash groundwater system. Given the large volume and rapid flow rate of groundwater in Fortymile Wash, one might expect a smearing out of peak radionuclide arrivals from releases at Yucca Mountain.

LARGE HYDRAULIC GRADIENT

I will defer to others the interpretation of causes of the large hydraulic gradient. The two alternative models discussed at the workshop (perched water and saturated zone) both seem reasonable.

INFLUENCE OF CLIMATE CHANGE

I have high confidence in the geochemical evidence for the position of past water-table levels related to past glacial episodes, including mineralization and zeolite zones. These indicators all seem consistent with the maximum water-tables elevation being 120 m above the present level. I believe that the positions of past waters tables provide reasonable constraints on future water-table elevations.

DISPERSION, DILUTION, AND SPATIAL DISTRIBUTION OF FLOW

Conceptual Model

Field pump tests provide a better description of large-scale hydraulic properties, but they are not particularly useful for assessing local properties—particularly matrix properties—at scales important to geochemical processes. The chemical data can confirm or refute hydrologic models. For example, the origin of recharge at Yucca Mountain (e.g., snowmelt) can be confirmed; confirmation of whether or not Fortymile Wash is more transmissive can be assessed; and whether or not groundwater has a volcanic source can be determined from chemistry data.

There are three general groundwater types in the Yucca Mountain area with distinguishable chemistries: alluvial groundwater, volcanic rock groundwater, and groundwater in the deep regional carbonate aquifer. The general occurrence of volcanic rock groundwater is consistent with the proposed groundwater flow system in the volcanic rocks under Yucca Mountain. Maps of δD, $\delta^{18}O$, and $\delta^{13}C$ suggest sources of groundwater and recharge to the volcanic aquifer.

A key issue for radionuclide transport is whether or not—and to what degree—flowpaths from the repository enter the carbonate aquifer at distances of 5 to 30 km. The regional hydrologic model suggests that groundwater flow paths enter the carbonate aquifer about 10 km south of the site and, farther south, come back up into the alluvial aquifer. If flow in the carbonates occurs, important Np(V) adsorption by calcite could be expected.

Dilution Factor

A number of processes can lead to dilution of contaminants within a groundwater system. Most important is turbulence, which might result from very high velocities. Turbulent flow is not expected within the volcanic aquifer. Temperature effects and density differences can contribute to dilution, such as from warmer water rising along faults. Dispersion can occur if flow along fractures enters porous media, such as flow within strata-bound faults and fractures. Other types of differences in permeability along flow paths can lead to dispersion. Transients in the flow system can cause changes in velocities and flow directions, which can lead to mixing and dilution. Climate changes may cause head changes, which also may lead to dilution.

Dilution factors, which are the ratio of peak concentrations, can be expressed as a function of source size and distance (EPRI, 1996). I would estimate that the dilution factor of a peak radionuclide release from Yucca Mountain might range from 10 to 50 at Armagosa Farms.

HYDROCHEMISTRY, TRANSPORT PARAMETERS

General Comments

My overall conclusion is that the DOE approach to defining amounts of radionuclides that could be released from the buried waste and transported to the accessible environment through the unsaturated and saturated zones is in general highly conservative. The possible benefits of sorption, solubility, and redox reactions on reducing the maximum possible concentrations of radionuclides in groundwater have not been sufficiently emphasized. An analysis of transport processes and parameters that considers only sorption reactions as the geochemical control on maximum radionuclide concentrations is inadequate. Sorption only delays the peak release of long-lived radionuclides such as ^{237}Np to the environment. Solubility, if applicable, can greatly reduce or eliminate releases.

The following are some of the assumptions in TSPA-95 that may be unnecessarily conservative (Langmuir, 1997).

1. The assumed solubility of U (VI) in Yucca Mountain groundwater probably is $\sim 10^2$ too high.

2. The assumed solubility of Np (V) in Yucca Mountain groundwater probably is at least $\sim 10^1$ too high.

3. Reduction of Np (V) to Np (IV) by Fe (II)-containing minerals in the matrix of the volcanic rocks seems likely during groundwater flow. Reduction could lower the solubility of Np by $\sim 10^3$ times.

4. Adsorption of Np (V) by trace or minor minerals in the tuff, which are relatively ubiquitous and include Mn oxides, Fe(II)-containing silicates, and calcite, could reduce Np concentrations in the rock matrix by orders of magnitude.

It is difficult to incorporate these concepts quantitatively into my assessment. However, in providing my assessments of sorption coefficients (K_d) for the various hydrogeologic units, I will consider the potential for the above conditions (e.g., presence of minerals) in providing my probability distributions. I will also provide my assessment of the redox state of the rock matrix.

Sorption Coefficients, K_d

There are problems with using a "minimum K_d" approach (i.e., a conservative "minimum" K_d value is defined for a given radionuclide). This minimum value is always subject to potential surprises by additional studies and experiments. It makes more sense to define a probability distribution for "effective K_d" values for a given radionuclide and hydrogeologic unit that reflects the uncertainty in laboratory-derived values and the potential for various conditions along the flow paths within the unit.

The laboratory-derived K_d values (Table 26 in Triay et al., 1997) provide information on the volcanic aquifers (devitrified) and volcanic aquitards (vitrified and zeolitic). The K_d values must also be assessed for the valley-fill alluvium and the carbonate aquifer. The important radionuclides of concern are Pu, Np, I, Tc, and U. Plutonium is controlled by solubility (~10^{-7}), so I will not consider it further except in the context of colloids; Tc and I are essentially non-sorbing (K_d ~0).

In general, I would expect the field or "effective" K_d values to be higher than the laboratory-determined values. All of the reactions require water contact with the rock. Adsorption reactions are fairly fast, but mineral (redox) water reactions take longer. In the field there will be longer periods to allow for redox reactions. Along a particular flow path there may be K_d values that are lower than typical laboratory values for that species, but I would not expect such values to remain low along entire flow paths.

The apparent K_d values for Np(V) may increase by three orders of magnitude as the redox potential or Eh decreases; the threshold Eh for the increase in K_d is about 200 to 300 mV. Based on my experience with Eh measurement and theory, I can estimate the range of Eh values that I would expect to find in the matrix of the volcanic units. The following CDF expresses my uncertainty in the Eh.

Eh (mV)	Percentile of CDF
800	100%
300	50%
250	40%
100	10%
-400	0%

The low Eh part of the distribution reflects the conditions expected in dead-end pores in the matrix in the presence of Fe(II)-bearing minerals; high Eh conditions would reflect oxygenated, convective groundwater flow. To use this distribution, one must assess the potential for fracture versus matrix flow, or the relative components of fracture and matrix flow. Note that "matrix" flow does not necessarily involve only the matrix, but could include slow flow through a fracture network. The important thing is for sufficient contact area and time for reactions to occur. I believe that there is a 60% likelihood that there is significant matrix flow in the volcanics versus 40% that there is not at some point along a flow tube in the volcanic rocks, but I would like the hydrologists on the project to help in this assessment. Until that is done, my assessment of Eh conditions is only qualitative. I will incorporate this idea into my assessment of effective K_d values.

Considering first Np, effective K_d values are estimated for the volcanics, alluvium, and carbonates. For the volcanics, I will assume that the laboratory values (from Table 26 of Triay et al., 1997) are appropriate for the fractures and that the K_d values for the matrix will be a factor of 10 to 100 times higher, due to the conditions discussed above (e.g., more time and presence of reactive minerals). The laboratory K_d values for Np and devitrified tuffs (i.e., volcanic aquifer) range from 0 to 10, with an expected value of 3 and a covariance of 0.3 (beta distribution).

For alluvium, my assessment comes from considering the constituents of the alluvial deposits. The alluvium likely will contain weathered volcanic rocks, clays, and iron oxides. The conditions will be oxidizing in an unconfined system, and iron and manganese oxides might represent a few percent of the total constituents. South of Amargosa Farms, calcium carbonate may be present as caliche. Incorporating the uncertainties in the mineralogy, my assessment of the Np K_d value for the alluvium is expressed by the following cumulative distribution function (CDF):

K_d [Np](ml/g)	Percentile of CDF
1000	100%
100	95%
40	50%
10	10%
1	0%

In arriving at an effective K_d for the carbonates, I must consider the sorption characteristics of calcite, and the potential for rapid flow through fractures in the unit. Laboratory studies of ^{237}Np sorption in calcite in J-13 water indicate K_d's of 50 in short-term batch tests, increasing to nearly 1000 after a 30-day sorption period (Triay et al., 1997). Studies by Triay et al. (1997, p. 208) conclude, "Our results indicate that diffusion from the fracture into the matrix can take place even at relatively fast flow rates. Neptunium can be significantly retarded, even during a fracture flow scenario. Neptunium retardation in fractures could be due both to diffusion into the matrix and sorption onto the minerals lining the fracture walls." Bearing in mind these conclusions, as well as the laboratory studies of calcite and the potential field conditions within the carbonate, I would estimate the K_d for the carbonates as two alternative values of 100 (having a weight of 0.2) and 1000 (having a weight of 0.8).

Considering uranium, the solubility that has been assumed for U(VI) has been 3 x 10^{-5} mol/L but, assuming that the solid at saturation in high-Eh waters will be uranophane $Ca(H_3O)_2(UO_2)_2(SiO_4)_2 \bullet 3H_2O(c)$, the solubility should be about 5 x 10^{-7} mol/L. As a result of this low solubility, the initial concentration of U will be low. If there are low-Eh pathways, the K_d values for U(IV) will be much higher. I would suggest that the laboratory-derived K_d values be used.

OTHER ISSUES

Thermohydrology

I think that the potential effect of the thermal pulse on the saturated zone beneath the site will be a function of whether the flow occurs in the fractures or in the matrix (which includes tight fractures). If there is fracture flow only, then effects will occur at greater distances from the repository. If there is significant matrix flow, I would expect the increased temperatures to cause silica in the volcanic rocks to dissolve, to move to cooler locations, and then to precipitate and possibly clog the system. If calcite is saturated in the water, because of its retrograde solubility, it will precipitate and may clog the matrix and fine fractures adjacent to the hot waste. The clogging may lead to additional residence time for radionuclides in the matrix. Refluxing of condensed water may cause similar effects to occur at the water table beneath the site.

Colloids

There are three kinds of colloids:

1. Degradation colloids from the waste (e.g., Pu oxides, Fe(III) oxides from canister corrosion).

2. Precipitation colloids, which are precipitated from solutions at or near the waste supersaturated with respect to actinide solid phases (also called radiocolloids).

3. Geocolloids or pseudocolloids, which are generated by the attachment of radionuclides (in soluble or colloidal form) to other colloids, such as colloidal-sized mineral and rock particles that are naturally present in the groundwater.

The conditions required for transport of colloids are fast pathways through the engineered barrier system, the unsaturated zone, and the saturated zone. This implies no or ineffective backfill around the waste packages and the existence of interconnected fracture flow through the unsaturated zone and groundwater system, and probably travel times of a few years or less.

I believe that the likely fate of colloids will be the following. Many will be filtered out by crushed tuff backfill or tuff invert under unsaturated conditions. Degradation colloids (such as Pu oxides) and radiocolloids will be undersaturated with respect to the groundwater as soon as they move away from the waste. They will therefore tend to dissolve in the groundwater and, once in solution, tend to be adsorbed by rock surfaces in fractures and especially in the matrix. Actinides on the surfaces of geocolloids will tend to desorb with groundwater flow. They will be readsorbed by surrounding rock surfaces that have the same surface bond strengths toward the actinides but have unoccupied surface sites and orders of magnitude more reactive surface area.

The colloidal microspheres tracer test in the C-wells showed that the peak arrival preceded the conservative tracers (20 hrs versus 30 hrs). About 85 percent of the microspheres were lost. This suggest that colloids can move in the saturated zone, but radionuclides/colloidal particles must travel first through the unsaturated zone, and losses are expected in the saturated zone.

The key radionuclide of concern in colloidal transport is plutonium There are a couple of references in the recent relevant literature related to Pu colloidal transport. Marty et al. (1997), discuss Pu transport in a shallow aquifer in Mortland Canyon, Los Alamos National Laboratory. Pu movement was at the surface in alluvial sediments. The Pu subsequently was washed downward on sediments to the shallow groundwater table. This scenario is not analogous to possible Pu migration in the saturated zone beneath Yucca Mountain. In a second study, Pu from underground nuclear tests at the Nevada Test Site moved in the groundwater several kilometers from an underground test (J.L. Thompson, verbal, and 1996). The Pu was probably within melted tuff particles that were transported by explosive injection. This is obviously not an analogue for Yucca Mountain. One final caution: bomb pulse ^{36}Cl-aged water found deep in the unsaturated zone under Yucca Mountain indicates the existence of fast paths that may extend to the saturated zone. It is possible that colloidal radionuclides could take the same pathways.

Water-Table Changes from Disruptive Events

There is a very low probability of a significant water-table change associated with earthquakes or another disruptive event.

RECOMMENDATIONS FOR REDUCING UNCERTAINTY

Several activities come to mind that might reduce uncertainties associated with predicting possible radionuclide transport in the saturated zone. These include the following.

1. The C-well tests should be run for longer times to evaluate the relative importance of matrix versus fracture flow in the Tertiary volcanic rocks.

2. The available groundwater chemistry and isotopic data for the whole Yucca Mountain/Fortymile Wash flow system to its discharge area in the Armagosa Desert should be mapped in detail. The southern end of this system was last examined by Claassen (1983). Such an effort might lead to conclusions regarding amounts of possible mixing of volcanic, carbonate, and alluvial groundwaters in southern Fortymile Wash.

3. The literature contains a large amount of old $\delta^{14}C$ groundwater data. These data should be corrected using the same NETPATH approach presented to us by Kwicklis (1997, USGS, SZEE Workshop 1). This would provide an internally consistent $\delta^{14}C$ data set for the general area, including the complete Yucca Mountain groundwater flow system. Such data might be useful for computing groundwater travel times and matrix versus fracture flow.

4. More emphasis should be placed on interpreting and modeling the groundwater geochemical data in the vicinity of Yucca Mountain in the context of the geology and groundwater hydrology. The groundwater chemistry should be related to depths of sampling, water levels and transmissivity, fracture zones, specific formations and their mineralogy, and rock matrix versus fracture flow properties. Such an analysis could help explain much of the water chemistry information, which in turn should help us resolve ambiguous interpretations of the groundwater hydrology.

5. Geochemical and hydrologic data and models should be used, to evaluate the relative contributions of infiltrating surface runoff and groundwater from under Yucca Mountain to the volume of groundwater flow in Fortymile Wash east and

southeast of Yucca Mountain. Runoff infiltration in Fortymile Wash may be the chief diluent for radionuclides released from the proposed repository.

6. Pump tests of shallow wells in the Tertiary volcanics under Yucca Mountain probably will sample fracture flow which is likely to be oxidizing with an Eh above 300 mv. The only way to determine if matrix flow will lead to Eh values low enough to cause reduction of Np(V) to insoluble Np(IV) is theoretically, or preferably experimentally, in the laboratory. My predictions of percentile of CDF values for Np(V) adsorption were based on theory. Laboratory experiments could be performed in closed vessels using rock fragments or an ultracentrifuge and rock cores to speed up flow, with measurements being made of dissolved oxygen levels and Eh as a function of time.

7. The prediction that maximum uranium concentrations in Yucca Mountain groundwater are limited by the solubility of uranophane is based on computer modeling. Experiments should be performed on the solubility of uranophane in simulated groundwater in the presence of volcanic tuff materials to confirm my model calculations.

APPENDIX: DETAILED INTERPRETATION OF YUCCA MOUNTAIN HYDROLOGY USING CHEMICAL AND ISOTOPIC DATA FOR THE GROUNDWATER

Groundwater Geochemical Data Base

The accumulated database of chemical analyses for major dissolved species in regional groundwaters has been critically reviewed and culled by Perfect (1994) and Perfect et al. (1995). (See also Luckey et al., 1996). Oliver and Root (1997) made a similar effort to assemble the most reliable groundwater data for stable isotopes. Past attempts to age-date the groundwater using C-14 data (cf. Claassen, 1983; Benson and McKinley, 1985; White and Chuma, 1987; Luckey et al., 1996) led to excessively old ages, because incorrect or inadequate methods and assumptions were used to adjust apparent C-14 ages to true ages.. Ed Kwicklis, working with Don Thorstenson of the USGS, has attempted to apply more rigorous corrections to the raw $\delta^{14}C$ data based on application of the geochemical computer code NETPATH. Resultant corrected ages for groundwater in the Tertiary volcanics under Yucca Mountain generally range from about 6000 to 12,000 y (Kwicklis, 1997).

Because of DOE's lack of funding or emphasis on saturated zone work until recently, little effort has been devoted to understanding groundwater geochemistry in the vicinity of Yucca Mountain in order to extend or correct the conclusions drawn in papers written ten years ago (cf. Winograd and Thordarson, 1975a; Claassen, 1983; and White and Chuma, 1987). Stable isotopes and C-14 data for wells north of Armagosa Valley under Yucca Mountain and Fortymile Wash were discussed by Peterman (1997) and Kwicklis (1997), respectively. Until recently, little emphasis has been placed on analyzing and interpreting the significance of the full data set for the saturated zone, including well and spring data for the groundwater flow system for 20 km farther south to wells and springs in the discharge area on the California-Nevada state line (Claassen, 1983). The most recent publication that attempts to integrate the groundwater hydrology and geochemistry (Luckey et al., 1996) cites the older work with regard to C-14 age-dating, and does not attempt to interpret groundwater chemistry in any detail.

Preliminary Conclusions Related to Groundwater Hydrology Based on Chemical and Isotopic Data

1. The general hydrochemical facies of groundwaters in the vicinity of Yucca Mountain have been recognized since even before the report by Winograd and Thordarson (1975). Groundwaters that have flowed exclusively in the Tertiary volcanic rock are chiefly of the Na + K: HCO_3 type. Waters flowing only in the Paleozoic carbonates are chiefly Ca + Mg: HCO_3 type. Alluvial waters, which receive input from both the volcanics and carbonates, may be Na + K or Ca + Mg: HCO_3 waters, and in some Cl is the dominant anion (Perfect, 1994).

2. The piezometric map suggests that groundwater flow in the Tertiary volcanics moves from Crater Flat toward the east and under Yucca Mountain. However, water levels in wells just west of the Solitario Canyon fault (e.g., H-6 & WT-7 at 776 m) are about 45 m higher than water levels east of the fault (731 to 728 m), indicating that the fault acts as a barrier to east-west groundwater flow (cf. Luckey et al., 1996). This conclusion is also supported by the water chemistry. For example, maps of $\delta^{18}O$, ΛD, and Cl (Oliver and Root, 1997; Peterman, 1997) suggest that west of Solitario Canyon fault, groundwater moves toward the south-southwest.

3. $\delta^{18}O$ and δD analyses indicate that groundwater throughout the area, whether in the Paleozoic carbonates, Tertiary volcanic rocks, or valley alluvium, originated chiefly as snowmelt or snowmelt runoff at $^-5°$ to 0°C (cf. Claassen, 1983; Benson and Klieforth, 1989). In other words, very little of the groundwater derived from infiltration of rainfall or summer storm runoff in the washes. That Yucca Mountain obtains its groundwater recharge from snowmelt is evident from the relatively low (for the region) groundwater chloride concentrations of 6 to 8 mg/L, and the depleted oxygen and deuterium isotope values in groundwater of -13.4 to -14.0 per mil and -100 to -105 per mil, respectively, under the mountain.

4. Corrected $\delta^{14}C$ ages of groundwaters under Yucca Mountain range from about 6000 y (well G-4 in the volcanics) to 27,000 y (well p#1 in the Paleozoic Carbonate Aquifer) (Kwicklis, 1997)[1]. The oldest waters in the Tertiary volcanics

[1] According to Kwicklis (verbal communication), the uncertainty in these corrected ages is at least ± 1000 y].

east of Solitario Canyon fault are about 11,000 to 12,000 y old. It seems likely that these older volcanic waters were derived chiefly from snowmelt at higher elevations to the north, as on Pahute Mesa[1], which is about 2200 ft higher than Yucca Mountain, and that waters of intermediate age have followed shorter flow lines from recharge sources to the north. Consistent with this argument is the fact that, with few exceptions, the oldest groundwaters also have the lightest (most negative) values of $\delta^{18}O$ and δD (Figures 1 and 2) and visa versa, and that groundwaters in the volcanics under Yucca Mountain generally increase in age and decrease in their δD and $\delta^{18}O$ values from north to south (Figure 3).

5. Most groundwater in Fortymile Wash is derived from snowmelt and snowmelt runoff in upper Fortymile Wash and Yucca Wash drainages (Benson and Klieforth, 1989). Corrected C-14 ages of such water ranges from 0 yrs (modern) from UE 29a#2 in upper Fortymile Wash, to 7100 y from WT-15 just north of Yucca Wash (Kwicklis, 1997). Farther south along Fortymile Wash at J-13, the apparent C-14 groundwater age is 5100 y, decreasing to 4600 y at J-12 and 4200 y at JF-3. Given that groundwater flow moves from WT-15 to JF-3, the only explanation for these decreasing ages with flow is that groundwater under the wash is diluted locally by infiltrating modern runoff.

6. Because C-14 ages of groundwater in wells J-13, J-12, and JF-3 have been diluted by mixing with younger infiltrating waters, they cannot be used to estimate groundwater flow rates along Fortymile Wash south of Yucca Mountain. However, assuming such mixing has not occurred in upper reaches of the wash between Wells UE 29a2 and WT-15, a distance of about 9.6 km, we can estimate a maximum groundwater flow rate of 1.4 m/y between these wells.

7. Radionuclides such as Np-237 that have long half-lives (2.1×10^{6} y) and may be unreactive in the groundwater are the most likely to constitute a health hazard in the accessible environment. For such species, dilution during groundwater flow, if it occurs, is the only process that can reduce their concentrations.

   Hydrologists generally believe that groundwater from beneath the proposed Yucca Mountain repository would move in a flow tube to the southeast into Fortymile Wash, and thence south parallel to the wash toward the assessable environment at Armogosa Farms and farther south in the Armagosa Desert. The direction of this hypothesized flow tube is consistent with the general appearance of the regional piezometric map.

[1] Average $\Lambda^{18}O$ and ΛD values of three well waters from Pahute Mesa are -14.4 and -112.3 per mil, respectively (White and Chuma, 1987).

Values of $\delta^{18}O$ and ΔD indicate that most of the groundwater under Fortymile Wash has derived from the infiltration of snowmelt runoff in Yucca Wash and Fortymile Wash (see above). The piezometric map suggests that a large fraction of the groundwater flowing from under Yucca Mountain would enter Fortymile Wash between wells J-13 and J-12. Presumably, chemical changes in the groundwater between wells J-13 and J-12 should reflect such an input if it were significant. The composition of average groundwater under Yucca Mountain (sampled from 9 to 17 wells) is compared to the composition of waters from wells J-13 and J-12 in the table below.

TABLE DL-1
AVERAGE CONCENTRATIONS IN GROUNDWATER IN THE TERTIARY VOLCANIC ROCKS UNDER YUCCA MOUNTAIN EAST OF SOLITARIO CANYON FAULT COMPARED TO CONCENTRATIONS IN GROUNDWATER FROM WELLS J-13 AND J-12.

Isotope/Species (units)	Average Concentration Under Yucca Mtn	Concentration in J-13 (Fortymile Wash)	Concentration in J-12 (Fortymile Wash)
$\delta^{18}O$ (per mil)	-13.7	-13.0	-12.8
δD (per mil)	-102	-97.5	-97.5
Na (mg/L)	66	42	38
Ca (mg/L)	10	12	14
Cl (mg/L)	6.5	7.1	7.3
SO_4 (mg/L)	22	17	22

Comparison of these results shows that there is no way to create the groundwater in well J-12 by mixing groundwater from under Yucca Mountain with the groundwater from well J-13. This suggests that the relative volumetric importance of groundwater flowing from beneath Yucca Mountain into Fortymile Wash is negligible compared to the volume of infiltrating snowmelt and other runoff recharging groundwater in the washes. The volumetric lack of importance of Yucca Mountain groundwater (average $\delta D = -102$ per mil) is particularly obvious from the fact that $\delta D = -97.5$ per mil in all five wells along Fortymile Wash from north of the mountain to south of it (wells WT-15, WT-14, J-13, J-12, and JF-3).

Infiltrating runoff could represent an important potential diluent for radionuclide-carrying groundwater that might enter the Fortymile Wash groundwater system. Unfortunately, the lack of wells south of well JF-3 makes it difficult to assess the importance of such dilution.

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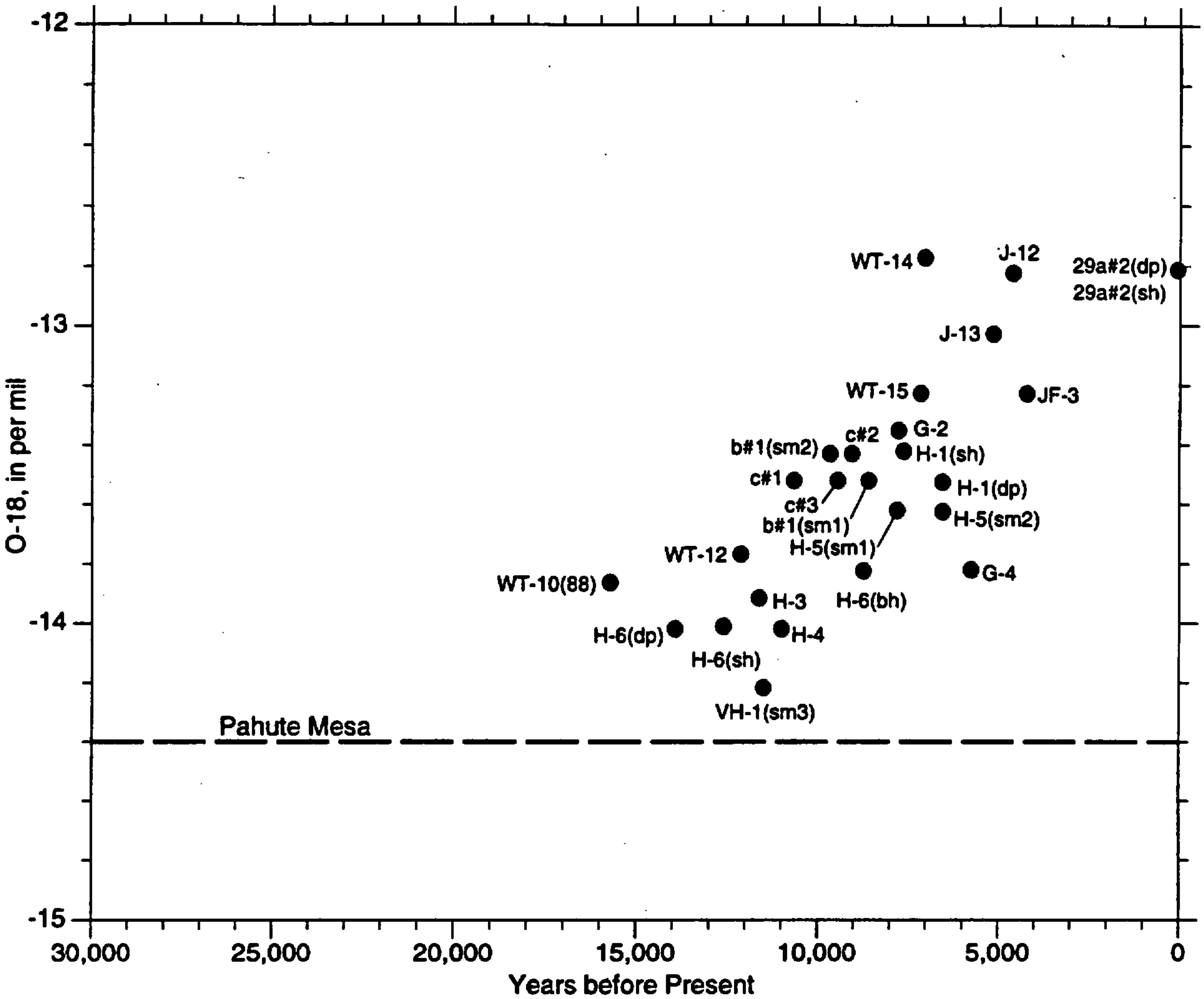

Figure DL-1 $\delta^{18}O$ values in groundwaters with the Tertiary volcanics under Yucca Mountain and the alluvium of Fortymile Wash, plotted against their corrected $\delta^{14}C$ ages (Kwicklis, 1997). Also shown is the average $\delta^{18}O$ value of three well waters on Pahute Mesa, the possible recharge source for Yucca Mountain groundwater (Benson and Kieforth, 1989).

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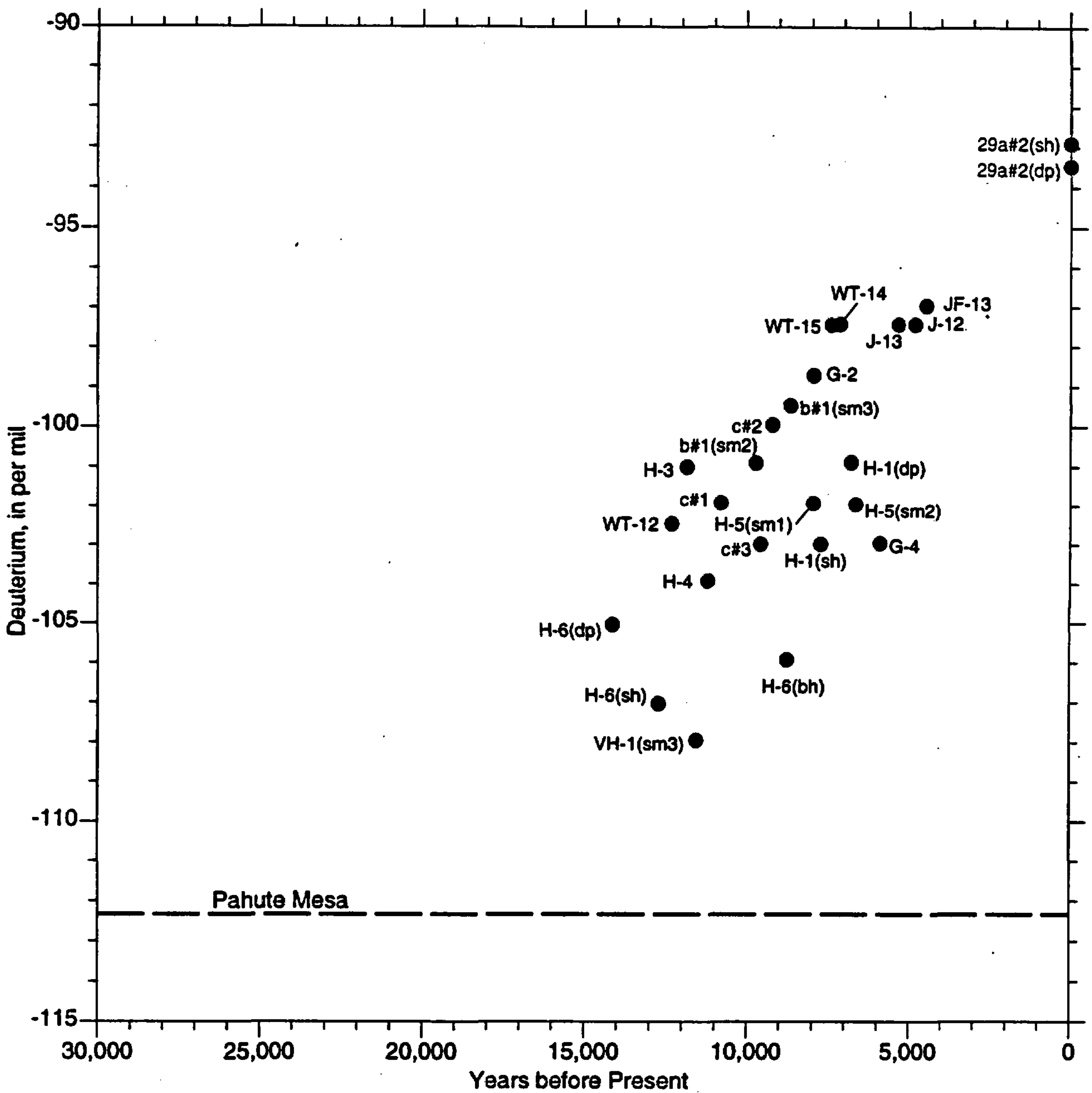

Figure DL-2 δD values in groundwaters with the Tertiary volcanics under Yucca Mountain and the alluvium of Fortymile Wash, plotted against their corrected $\delta^{14}C$ ages (Kwicklis, 1997). Also shown is the average δD value of three well waters on Pahute Mesa, the possible recharge source for Yucca Mountain groundwater (Benson and Kieforth, 1989).

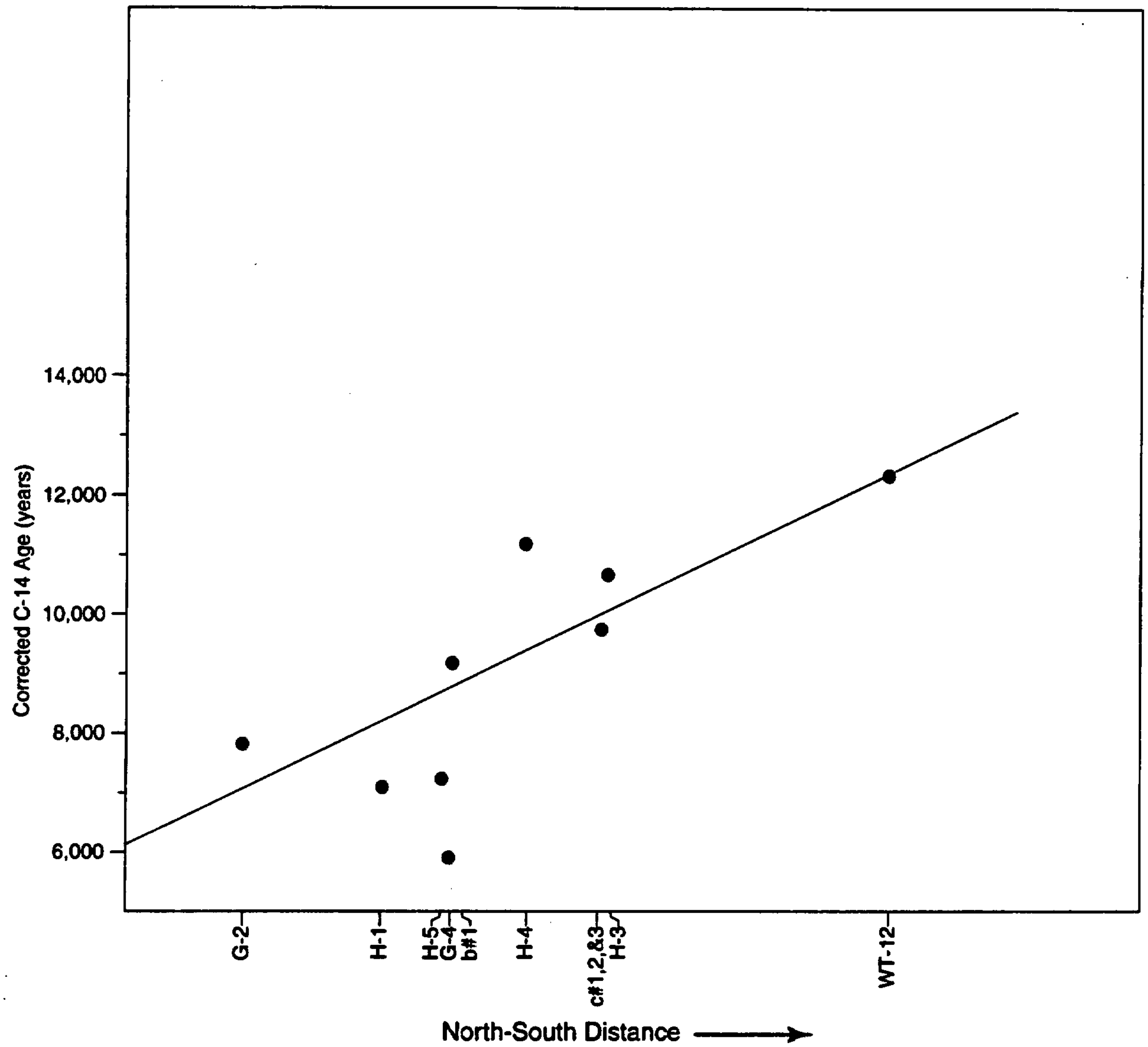

Figure DL-3 Average corrected $\delta^{14}C$ ages of groundwaters in the Tertiary volcanics under Yucca Mountain east of Solitario Canyon fault, plotted against the north to south distances of the wells. The line drawn has no statistical significance.

ELICITATION SUMMARY
CHIN-FU TSANG

OVERVIEW: CONCEPTUAL MODEL OF SATURATED ZONE FLOW

A possible conceptual model is that flow travels vertically downward (with tortuosity) under gravity in the unsaturated zone from the repository level to the water table. Once it reaches the water table, it is assumed to travel approximately horizontally along hydrogeologic units in the saturated zone. The flow in the saturated zone occurs primarily in the Bullfrog Formation, which is the most permeable volcanic unit, its permeability being one or two orders of magnitude greater than that of the other layers because of fractures. There is new evidence that upward flow also occurs from the carbonate aquifer into the volcanic aquifer. However, the primary hydrogeologic unit that carries flow from beneath Yucca Mountain to distances of 5 to 30 km is expected to be the subhorizontal volcanic aquifer. Along the way, flow will encounter various faults at which the volcanic unit may be offset partly or completely, and these faults may be low-permeability barriers or higher-permeability zones. At these points, flow may digress to a different depth and may even bifurcate into more than one flow plume.

Flows in both the unsaturated and saturated zones are expected to be channelized; i.e., to follow preferred flow paths much like particular stream lines in potential theory. Flow in the saturated zone was discussed by Moreno and Tsang (1994), and in the unsaturated zone, by Birkholzer and Tsang (1997).

In general, flow channelization is due to two principal features of geologic systems: (1) major geologic structures, including major faults and fractures and the more permeable porous units (the so-called high-K channels); and (2) smaller-scale heterogeneities that vary greatly in permeability. Geologic structures are important in directing flow, as emphasized by L. Lehman and others (SZEE Workshop 2). Unfortunately, because it is much easier to study vertical formation variations within one well than horizontal variations between wells (which requires many wells), we tend to know more about the flow characteristics of horizontal layering than we do about faults and fractures. However, with sufficient geologic surveys and hydrologic testing, we have the potential of assessing the major structures and putting them in our hydrologic models (see below).

For the Yucca Mountain conceptual model, one can incorporate the first type of feature, major geologic structures, by deterministically including faults in the flow model and assigning hydraulic conductivity values to them. Long-term, multi-well interference tests, such as the C-well tests, should be performed to provide information on appropriate hydraulic conductivity values for these faults.

The analyses of C-well interference test data by Geldon et al. (1997) and by Reimus and Turin (1997) are interesting. I am not convinced that the interpreted areal elliptical shape of the drawdown from the C-wells is realistic. I would expect more of a "starfish" shape that reflects faults and high-permeability pathways. A more complete, long-term interference test with pumping in a C-well (or another well) and observation in as many wells as possible would be most valuable. Based on current information, we expect some wells as far as 2 km away to respond. Then a more serious inverse modeling could be done to fit the data by adjusting the permeabilities not only of the various units involved but also of major faults. The hydraulic property of a fault can be reasonably well determined if it is near one of the observation wells. I believe that this is one of the most critical experiments that needs to be done to obtain the parameters necessary for calculating flow and transport in the Yucca Mountain saturated zone.

The second type of feature that causes flow channeling, the smaller-scale heterogeneities, must be more roughly estimated, perhaps using geostatistics. The key parameters are average permeability, its variance, and correlation lengths. These parameters can be assessed from the breakthrough curves or multiple measurements in packed wells. Thus smaller-scale heterogeneities are more difficult to evaluate; nevertheless, they can be important because the "fast paths" or channels that result can have velocities that are ten times faster than average and may allow very little dispersion (Birkholzer and Tsang, 1997; Moreno and Tsang, 1994). Consequently, these features can be important to transport issues. Because of these heterogeneities, tracer-test breakthrough curves often show an early peak in concentration that arrives before the average tracer arrival, with a long tail after. Tracer tests, such as those done at the C-wells, should be done for long periods to allow a proper definition of the tail region. It is possible to analyze the tracer breakthrough curves to obtain information and parameters associated with the small-scale heterogeneities that control flow channeling. A more direct way is to obtain permeability values from packed-off intervals in the many boreholes at the site. This can also be done by flow-meter testing without packers. In this case, a conventional spinner flow meter may not be accurate enough. One may need to use a heat-pulse flow meter (Paillet et al., 1987) or the fluid logging method (Tsang et al., 1990). C-hole data already indicate that strong variations in permeability occur at Yucca Mountain (Reimus and Turin, Milestone SP23APMD, July 1997; Geldon et al., Draft Report, April 1997). Flows into C#1, C#2, and C#3 are dominated by three, three, and four specific vertical intervals, respectively, with one interval in each case carrying more than 50 percent of the flow into the well. This is consistent with the current knowledge that roughly 10 to 20 percent of the fractures contribute to flow, with only 1 to 10 percent contributing significantly.

Note that permeability heterogeneity related to flow channeling cannot be evaluated with tests that are inherently averaging, such as temperature surveys and pressure data in observation or production wells that are open over a wide vertical interval.

Keeping in mind the above discussions, let us turn to the conceptual model of flow and transport in the saturated zone at Yucca Mountain. To start, we need to know the source term at the unsaturated-saturated zone interface, where channelized flow from the unsaturated region enters the saturated region, and where flow is expected to be channeled. The source term must be studied carefully and its characteristics evaluated. Two potentially important issues need to be considered. First, under steady flow conditions in the unsaturated zone, flow is expected to be channeled along relatively small pores (corresponding perhaps to smaller local permeabilities), because the large pores will be occupied by air, while the main flow in the saturated zone will be channeled along higher-permeability regions. The switch-over from lower-permeability areas to higher-permeability areas of the heterogeneous field needs to be evaluated in terms of possible dilution process. Second, the water table cuts through a number of hydrogeologic units, such as the Bullfrog, Prow Pass, and Calico Hills units, whose permeabilities differ by several orders of magnitude. The particular units in which leakage from the potential repository reaches the saturated zone may each provide different source term characteristics. These two issues are in addition to the usual concern of solute transport through the capillary fringe and effects of changes in the water table.

Beyond the source region at the water table, flow will follow hydrogeologic units, probably primarily the Bullfrog unit. Here, flow will be according to stream lines, and dilution will be minor. As it encounters offsets due to faults cutting through the hydrogeologic unit, it will digress, bifurcate, or spread out depending on the fault permeability and local conditions. It is not clear whether there will be significant dilution at such locations, but careful analysis can, and should, be made to answer this question. Solutes along the stream lines are subjected to local dispersion or molecular diffusion and can spread to neighboring stream lines. The dilution resulting from this process would be much smaller than that commonly assumed for dispersion (note that the so-called dispersion also reflects the lack of information that has nothing to do with dilution; see Neuman's discussion in SZEE Workshop 3).

After a tortuous journey, flow arrives at the users' area and is collected from a so-called capture zone. If a fault or special feature occurs near this area, for instance, Fortymile Wash or the Amargosa Valley, it should be evaluated. It may provide a focusing effect near the location where the regulatory criteria are to be applied. Such features must be included in the model.

The evidence for upward flow from the carbonate aquifer is convincing, although I cannot be certain from the information provided what the magnitude of the flux is. A careful study of all thermal logs of the different wells, with the help of subsite- or site-scale modeling, may allow a good estimate of the magnitude of the upward flow.

LARGE HYDRAULIC GRADIENT

Bill Dudley's summary of the hypotheses related to the large hydraulic gradient (LHG) north of the site was very comprehensive (SZEE Workshop 2). Al Freeze and Shlomo Neuman (SZEE Workshop 3) presented their analyses of these hypotheses; I have nothing new to add. I believe that both of their models are viable. I tend to favor slightly the model of a perched unit that was connected at one time (weight of 0.6) over the saturated zone model (weight of 0.4). Both models are consistent with the similarities in geochemistry. The perched model is consistent with evidence that the G-2 water level is dropping slowly. The LHG is not a unique feature in the region, so the regional model developed by the USGS can be used to evaluate the significance of the two alternative explanations for the feature. Because of the existence of other LHG features, I believe that there is a very low probability of any sudden or transient changes to the LHG. One test of the two LHG models would be to re-drill G-2 and pack off intervals to evaluate the presence of an unsaturated zone beneath the apparent water-table level by studying pressure changes in the packed-off intervals. This is a cost-effective way to study this problem.

HYDRAULIC CONDUCTIVITY AND FLUX BENEATH YUCCA MOUNTAIN

First of all, much of the available data are based on single-hole tests, which may underestimate the units' mean hydraulic conductivities by as much as a factor of ten, because of the strong effect of local permeability values near the well. One problem is that single-well tests are based on a convergent or divergent flow field, but the results are applied to calculations of transport over a large area, probably under a flow field that more closely resembles a parallel pattern. I would place much more confidence in the results of interference tests and long-term tests.
Concerning estimated values of hydraulic conductivity, it depends what purpose they will serve. On principle, with today's computer and simulation technology, it is possible to

calculate steady-state flow through a relatively complex structure of hydrogeologic units and faults. However, if I were asked to do a "back-of envelope" estimate of flow velocity under the repository, I would consider primarily the high-permeability Bullfrog unit of the volcanic aquifer, and would use the following cumulative distribution function (CDF) to characterize the probability of its hydraulic conductivity:

Hydraulic Conductivity (cm/s)	Percentile of CDF
10^{-1}	99%
10^{-2}	50%
10^{-3}	20%
10^{-6}	1%

This assessment is weighted toward the results of the long-term interference tests, as presented in Geldon et al. (1997) and as obtained from calibration studies of the LBNL subsite-scale model. The above distribution of hydraulic conductivity includes the effects of small-scale fractures, but not major faults. Basically the table says that the hydraulic conductivity of the Bullfrog unit is centered around 10^{-2} cm/s, with 80% probability that it is between 10^{-3} and 10^{-1} cm/s. If the hydraulic gradient is assumed to be 0.0003, then the flux is 3×10^{-6} cm/s, which is 0.95 m/yr or 1 m/yr, with a range between 0.1 and 10 m/yr corresponding to the hydraulic conductivity values of 10^{-3} and 10^{-1} cm/s, respectively.

If we consider the volcanic aquifer as a whole, and ask for the probability of finding different hydraulic conductivity values spatially, I would guess that the CDF would be:

Hydraulic Conductivity (cm/s)	Percentile of CDF
10^{-1}	99%
10^{-2}	85%
10^{-3}	65%
10^{-6}	1%

Again it is dominated by the high-permeability Bullfrog unit at least on the site scale. Such a distribution should be used for stochastic analysis, but it would require other considerations and inputs.

The hydraulic conductivity of the volcanic aquitards or confining units would be a factor of 10 to 1000 times (uniform distribution) less than the above values for the volcanic aquifer. This is consistent with the C-well data. A large factor of ten allows for the possible presence of fractures within the aquitards.

I estimate that the ratio of horizontal to vertical permeability ranges from 1:1 to 10:1. Some of the anisotropy effects have been accounted for by modeling the horizontal layers explicitly. In the horizontal plane, there is much less information for anisotropy. I attach little significance to the interpreted ellipse from the C-well drawdown. The data are too uncertain and sparse to draw any conclusion. More important are the various faults and major fractures that could strongly affect the horizontal flow.

INFLUENCE OF CLIMATE CHANGE

This subject is outside my area of expertise: I consider the interpretations of past water-table rises associated with glacial periods to be reasonable. I have no reason not to expect future water-table fluctuations to be similar to those interpreted for past glacial cycles. Outside the scope of the present discussion is the issue of the unsaturated zone, which may become saturated if infiltration is substantial. That key issue, which would change the whole character of Yucca Mountain, was addressed by the UZEE panel members.

The regional model, with more properly defined hydraulic boundaries, can be used to assess the effects of variations in recharge and discharge due to climate changes. This has not been, but certainly should be, coupled with the site-scale model in a consistent and definite way. One way is to ensure that the regional model provides the total flow across each side of the site model boundaries, so that flow is conserved as one goes from the regional to site-scale model or vice versa. This would provide constraints to model calibration and provide that the flow and transport at the site scale conform with the regional picture.

DISPERSION, DILUTION, AND SPATIAL DISTRIBUTION OF FLOW

The "mixing depth" concept is not realistic. Rather, we need to consider the three stages of tracer transport to address this issue. First, one must consider the source term to the saturated zone. This is briefly discussed in the earlier section on Conceptual Model. It is likely that there will be channeled flow in the unsaturated zone (Birkholzer and Tsang, 1997), and that these channeled flow paths will then enter the saturated zone. Thus the source term is not a smeared-out plume, but a number of localized, higher-concentration "point sources." Second, once the solutes enter the saturated zone, they will again follow certain stream tubes, or flow channels, with only minor dispersion within each stream tube (Moreno and Tsang, 1994). The degree of such channelization depends on the degree of heterogeneity (standard deviation of the hydraulic conductivity values), and the spacing of these channels depends on the spatial correlation structure of heterogeneities in permeability. Then, thirdly, the different flow paths will come to the observational "fence" area and to an extraction well, where they will be captured and pumped for various uses. At this point, a dosage limit is to be imposed.

Dilution Factor

One can see from the above discussion that we cannot expect large dilution of the solute concentration between the source zone at the unsaturated-saturated zone interface and the capture zone of the users' wells. Molecular diffusion will occur within the flow channels, but there will likely be only a small longitudinal dispersion. Over even kilometers of distance, unless convinced by the type of calculations proposed below, I would expect dilution to be only about a factor of 2 to 10. This is because longitudinal dispersion occurs from Taylor dispersion, which has a characteristic length that is on the order of the width of the channel.

There are two places where significant dilution may occur. The first is at the interface between the unsaturated and the saturated zones, especially if the interface (i.e., the water table) fluctuates. If flow channels go from a low-permeability area in the unsaturated zone to a high-permeability area in the saturated zone, spreading may also occur. Unfortunately, this has not been carefully studied. Research is underway: we hope to have some results and know their implications in the near future. The other dilution step is at the production well. The production well creates what is called a capture zone (e.g., see Javandel and Tsang, 1985), inside of which all the stream lines are captured and mixed in the production wells.

A "dilution factor" can be assessed by using a "bundle-of-particle-lines" model (cf. e.g., Tsang et al., 1996; Cliffe et al., 1991). Consider the source term at the saturated-unsaturated zone interface to be represented by a number of localized "point sources" that correspond to channeled flow in the unsaturated zone. Then, from each point source, particles are traced along stream lines through the hydrogeologic units, allowing for flow around fault-related offsets and across or around faults. Along the way one can account for molecular diffusion and local dispersion by allowing particles to jump to neighboring stream lines. These particle lines are traced to the capture zone of the users' wells, where these lines and flow lines without contamination are collected. Thus dilution can be calculated. As mentioned earlier, with today's computational capability, such calculations are entirely feasible, even for a series of parameter sets.

Now we would like to estimate the spacing of those flow lines that contain a high concentration of contaminant from the unsaturated zone (the "point sources" mentioned above). One indication of this can perhaps be found from the spacing between Cl-36 spikes at the Yucca Mountain Exploratory Studies Facility (ESF), which is on the order of 1000 m. Assuming that these ESF surveys may have missed some Cl-36 spikes, either due to the sparseness of surveying points or due to uncertainties related to measurement and analysis, the spacing may be smaller. For a rough estimate, we may say that the spacing is between 300 and 1000 m.

Now let us assume that the width of the contaminant channel in both the unsaturated and saturated zones is 10 m, a number that depends on the structure of heterogeneities. A rough estimate of the dilution factor can be made, if the vertical flux in the unsaturated zone coming to the water table is taken to be 10 mm/yr, and the horizontal flux in the saturated zone is 1 m/yr. If flow transition from the unsaturated to saturated zone is steady state and follows stream lines, there will be no dilution. However, if we assume that within the width of a saturated zone flow channel, there is mixing, then the dilution factor from each unsaturated zone channel concentration to each flow line in the saturated zone is 1 m/10 mm, which is 100. Here the dilution factor is defined as the ratio of concentration within an unsaturated zone channel to the concentration of a volume of water passing across a point in the flow channel of the saturated zone. The same flow line, which travels for 3 km under the leakage shadow of the repository, may receive contaminant from 3 km/300 m ~ 10 channels, assuming channel spacing to be 300 m. Then the dilution factor reduces to 10. Now assume that the dilution along the particle flow lines from the source region to the capture zone of users' wells to be insignificant. Then in the capture zone, the 10-m-wide contaminated flow line is mixed with uncontaminated flow lines to the well, which may introduce an additional dilution factor of perhaps 10. Thus the total dilution factor would be on the order of 100. Note, however, that the high concentration in the unsaturated-zone channel may not be the usual starting concentration at the source of the saturated zone, which is commonly taken as the much lower mean concentration of leakage from the repository, calculated by averaging the contamination channels in the unsaturated zone and the uncontaminated spaces in between.

The above approach is not intended to provide a conclusive value, but to indicate an approach for estimating a more realistic dilution factor than the unrealistic mixing-depth model. It should be checked by at least one set of calculations using the detailed "bundle-of-particle-lines" numerical model described above.

Effective Fracture Density

I would estimate the range of distances between significant fractures to be between 10 and 100 m. Sonnenthal et al. (1997) presented a detailed analysis of fracture lengths and spacing based on data from a detailed line survey along the ESF made by the USGS/Bureau of Reclamation. They noted that the mean spacing between fractures having lengths greater than 1 m was 0.53 m. But for fracture lengths greater than 10 m, the mean spacing was estimated to be 20.9 m. It is useful to remember here that only a small proportion of these fractures contribute to fracture flow. Further, the spacing between groups of Cl-36 spikes is on the order of 1000 m, and each group usually is associated with a fracture zone or other feature. Within each group, the spacing between Cl-36 spikes can be as small as 10 m. As remarked earlier, there is a good possibility of other Cl-36 spikes not been detected in the survey, so that actual spacing may be closer.

HYDROCHEMISTRY, TRANSPORT PARAMETERS

Sorption

If the data are carefully considered, it should be possible to use the laboratory sorption parameters (Kd) derived for Yucca Mountain rocks. Hadermann and Heer (1996) reported a migration experiment done at the Grimsel site in Switzerland. They found good agreement between laboratory and field measurements of Kd. They also demonstrated that matrix diffusion exists in the field by examining the tails of the breakthrough curves. They emphasized that to obtain consistency, the flow model must be conceptualized correctly based on a careful analysis of field hydraulic data. Under such a "strong" prerequisite, results from column experiments probably are consistent and useful for estimating field data. It is somewhat troubling that there is a ten-fold discrepancy between the C-well data and laboratory data. It is likely that the flow field was not properly modeled.

Because flow is channeled, lateral diffusion over long periods will allow diffusion into the intervening areas of slow flow, thus enhancing sorption. Therefore, the diffusion into "dead-end" pores can be viewed as travel through very slow stream tubes, a process that can be taken into account in modeling. However, the effect may not be significant.

The use of Kd is open to some questions. It would be useful to consider real chemistry and perform chemical modeling, accounting for detailed chemical reactions to assess the range and limit of this approach.

OTHER ISSUES

Thermohydrology

The thermal effects on the saturated zone from repository heating are straightforward. The uncertainty concerns primarily the source term from the unsaturated zone (the heat power variations, effect of phase change, and input of condensed water). If a simple heating load of reasonable quantity is imposed on the saturated zone, no convection is expected to occur in the saturated zone, because the hot portion is on top. A conduction-only model and an increase in temperature to 60°C seem reasonable. The temperature change will change the viscosity and may lead to precipitation and dissolution of minerals, but the impact of this latter effect will not be great because of the small temperature rise involved, based on experiences from studies of geothermal reservoirs. Also, it is likely that by the time the contaminants arrive at the water table, the heat pulse will have passed.

Water-Table Changes from Disruptive Events

I am not an expert in this area, but my feeling is that such changes will be transitory in the time frame of the repository and will not have sustained impact.

RECOMMENDATIONS FOR REDUCING UNCERTAINTY

1. Perform long-term interference tests with pumping in a C-well (or another well) and monitoring as many observation wells as possible over a wide area. These tests will help determine the horizontal distribution of hydraulic conductivity and the hydraulic parameters associated with major faults. Analysis using a multi-

parameter fit of a numerical model will be needed. Associated with this effort, a long-term tracer test should also be performed. Careful design studies with numerical model are needed.

2. Re-drill borehole G-2 and emplace packers to study relative changes in packed intervals to reduce the uncertainty concerning the causes for the large hydraulic gradient.

3. Use the temperature log data in a calibration of a 3D site- or subsite-scale model, especially to address the question of upward flow into the volcanic aquifer.

4. Recalibrate the site-scale model, allowing for a more careful and definite coupling with the regional model. For example, the fluxes into and out of the site-scale area in the regional model must be consistent with the imposed boundary conditions on the site-scale model, so that total fluxes at the boundaries are conserved. This eventually would yield more convincing results from the site model.

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APPENDIX E
QUALITY ASSURANCE

QUALITY ASSURANCE

The Saturated Zone Expert Elicitation Project was completed under the Quality Assurance Program for the Civilian Radioactive Waste Management and Operating Contractor (CRWMS M&O). The process and procedures for M&O staff conducting the activity were defined in the Project Plan for this expert elicitation project. Section 2.0 of this report summarizes the process for eliciting expert judgments. As discussed in Section 2.0, formal guidance for the process of expert elicitation has been established and successfully applied in other comparable assessments.