MOL.19971009.0581

TRW

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WBS: 1.2.5.7
QA: N/A

Contract #: DE-AC01-91RW00134
LV.TE.JLY.05/97-071

May 30, 1997

Dr. Stephan J. Brocoum, Assistant Manager
Licensing
U.S. Department of Energy
Yucca Mountain Site Characterization Office
P.O. Box 30307
North Las Vegas, Nevada 89036-0307

Attention: Technical Publications Management Department

Dear Dr. Brocoum:

Subject: Transmittal of Deliverable, I.D. # SL5X4B1M, Unsaturated Zone Flow Model Expert Elicitation Project Report

This letter transmits Planning and Control System (PACS) Deliverable No. SL5X4B1M that was due for delivery to the U.S. Department on Energy on or before May 30, 1997. This report summarizes the results of the expert elicitation on the unsaturated zone flow model for the Yucca Mountain site. A major goal of the project was to document the uncertainties involved in assessing unsaturated zone flow processes, including uncertainty in both the models used to represent physical controls on unsaturated zone flow and the parameter values used in the models. The report has been reviewed and accepted by the Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O).

The report contains the selection criteria for the expert panel and a statement that potential conflict of interest was evaluated for each panelist. The conflict of interest forms will be maintained in the records package for this project. The report also contains workshop summaries; results of the individual elicitation; the technical basis for the expert's assessment; methodology used to aggregate results, where applicable; and the data, parameter values, and models considered in the expert assessments. Section 3 of the report provides probability distribution functions for net infiltration and percolation flux that will be used in the next iteration of total system performance assessment for the Viability Assessment. Appendix E summarizes the procedural controls used during this project.

The process used to conduct this expert elicitation is consistent with the overall guidance in NUREG-1563 on the use of expert judgment in the high-level waste management program. As requested by the acceptance criteria, we have evaluated this report against Site Characterization Analysis open items. The only related Site Characterization Analysis open item is comment 3. The NRC has already recommended proposed steps to close this open item based on DOE's substantial agreement with the process for expert elicitation defined in NUREG-1563. DOE is preparing a response that should lead to closure of this Site Characterization Analysis open item.

Finally, Section 3.4.6 of this deliverable provides recommendations for future site characterization work from the expert panel. Some of the recommended work, such as monitoring water inflow into the Exploratory Studies Facility, is already planned as part of the Site Characterization Program. Recommendations for new studies should be considered in the ongoing planning process.

If you have any questions regarding this deliverable, please call Martha W. Pendleton at 295-5550.

Sincerely,

for Jean L. Younker, Manager
Regulatory Operations
Management and Operating Contractor

Enclosures:
1. Unsaturated Zone Flow Model Expert Elicitation Project Report
2. Yucca Mountain Site Characterization Project Deliverable Acceptance Review
3. Participant Planning Sheets

cc w/encls:
R. L. Patterson, DOE/YMSCO, Las Vegas, Nevada
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K. K. Shrivastava, M&O/SAIC, Las Vegas, Nevada

WBS 1.2.5.7
SCPB: NA
QA: L

Civilian Radioactive Waste Management System
Management and Operating Contractor

Unsaturated Zone Flow Model Expert Elicitation Project

May 1997

Prepared for:

U.S. Department of Energy
Yucca Mountain Site Characterization Office
P.O. Box 30307
North Las Vegas, Nevada 89193-8608

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Under Contract Number
DE-AC01-91RW00134

Civilian Radioactive Waste Management System
Management & Operating Contractor

Unsaturated Zone Flow Model
Expert Elicitation Project

May 30, 1997

Prepared by:	Kevin J. Coppersmith, Geomatrix Consultants, Inc.	Date:	5/28/97
Prepared by:	Roseanne C. Perman Geomatrix Consultants, Inc.	Date:	5/28/97
Prepared by:	Robert R. Youngs Geomatrix Consultants, Inc.	Date:	5/29/97
Accepted by:	Martha Pendleton Lead Technical Evaluation	Date:	5/30/97
Approved by:	for Jean L. Younker Manager	Date:	5/30/97

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1.0 INTRODUCTION

1.1 OBJECTIVES

This report presents results of the Unsaturated Zone Flow Model Expert Elicitation (UZFMEE) project at 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 objective of this project was to identify and assess the uncertainties associated with certain key components of the unsaturated zone flow system at Yucca Mountain. This assessment reviewed the data inputs, modeling approaches, and results of the unsaturated zone flow model (termed the "UZ site-scale model") being developed by Lawrence Berkeley National Laboratory (LBNL) and the United States Geological Survey (USGS). In addition to data input and modeling issues, the assessment focused on percolation flux (volumetric flow rate per unit cross-sectional area) at the potential repository horizon. An understanding of unsaturated 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 unsaturated flow processes, including uncertainty in both the *models* used to represent physical controls on unsaturated zone flow and the *parameter values* used in the models. To ensure 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 unsaturated zone at the Yucca Mountain site.

1.2 RELATIONSHIP OF UZFMEE PROJECT TO STUDIES OF THE UNSATURATED ZONE AT YUCCA MOUNTAIN

The UZFMEE 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 the assumptions, models, inputs, and outputs of the UZ site-scale model. 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 as part of 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 unsaturated zone—including the expressions of uncertainty—will be directly applicable to the TSPA-VA.

The DOE is characterizing a site at Yucca Mountain, Nevada, as part of the Yucca Mountain Site Characterization Project (referred to as the YMP). 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. If the 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 (See Figure 1-1) 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), 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.

LBNL, in collaboration with the USGS, developed a three-dimensional model of the unsaturated zone (UZ site-scale model) of Yucca Mountain (LBNL, 1996). The model incorporates known geologic and hydrologic complexities, building on the work of many investigators. The primary objectives of the LBNL/USGS effort are:

1. to develop a numerical flow model and underlying conceptual model that incorporates all of the major flow processes, including moisture, gas, and heat, and includes the features and events that are or will be occurring in the unsaturated zone under ambient and thermally perturbed conditions for the next 100,000 years;

2. to evaluate current and future spatial-temporal variations in percolation flux at the potential repository horizon and other elevations, and the components of fracture/fault flow versus matrix flow;

3. to evaluate effects of important hydrologic features such as major faults, perched water, lateral flow barriers, and moisture, gas, or heat flow conduits;

4. to use available field observations to evaluate various conceptual and numerical scenarios for consistency;

5. to evaluate the effects of repository thermal loading on ambient conditions within the mountain, including in-place fracture and matrix thermal effects, perched water, gas moisture, and heat flow within and around faults, and thermohydrologic impacts on mineral assemblages; and

6. to evaluate the effects of climatic change on all ambient and thermally induced conditions in the potential repository area.

The UZFMEE study is intended to complement the UZ site-scale model while contributing to the performance assessment. The UZFMEE experts were given detailed summaries of the progress being made in various components of the UZ site-scale model, as well as calibration issues, available data, and models. The focus of the UZFMEE project was on evaluating the uncertainties associated with the various models, parameters, and components of the UZ site-scale model, as well as providing an independent perspective on the approaches taken in the model. As such, the UZFMEE project is a logical step in the unsaturated 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 unsaturated zone flow processes. Further, the TSPA, as a probabilistic analysis, will include an appropriate expression 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 UZFMEE project is to increase the credibility of the TSPA-VA by providing an expression of uncertainties regarding key issues for the unsaturated zone. This expression has been developed by experts from both within and outside the YMP. As such, results of the UZFMEE study are realistic and defensible assessments at this point in the characterization program for Yucca Mountain.

1.3 ORGANIZATION

The UZFMEE project was organized into four primary groups: the UZFMEE 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.

UZFMEE Contractor: Under contract with TRW, the UZFMEE contractor, Geomatrix, was responsible for conducting all aspects of the project and for delivering this report describing the methodology and the results. The UZFMEE 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. The participation role included developing a project plan, facilitating workshops, eliciting members of the expert panel, performing calculations and related analyses, and documenting 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 UZFMEE project are summarized in Table 1-1.

Expert Panel: The seven widely recognized earth scientists on the expert panel were responsible for providing and documenting their judgments regarding models, parameters, and uncertainties about unsaturated zone flow processes at Yucca Mountain. These subject-matter experts were responsible for developing the interpretations that form the technical substance of the UZFMEE 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. Members of both the MDT and the expert panel also acted as technical specialists.

1.4 PRODUCTS OF STUDY AND STRUCTURE OF REPORT

The UZFMEE study was conducted in approximately eight 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 seven 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 each member of the expert panel and the sensitivity analyses provided by LBNL, the experts finalized their assessments. The MDT performed the final calculations to show the individual and aggregated distributions on percolation flux at the proposed repository horizon at Yucca Mountain.

This report contains the products of the activities of the UZFMEE 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 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 seven individual experts and the aggregated results are provided. The conclusions of the study are summarized in Section 4. 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 deliberations 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; expert elicitation; documentation
Roseanne C. Perman	Geomatrix Consultants, Inc.	Project planning and methodology development; organizing workshops and field trip; elicitation documentation
Robert R. Youngs	Geomatrix Consultants, Inc.	Project planning and methodology development; eliciting and formulating alternative models; documentation of results/sensitivity
Peter A. Morris	Applied Decision Analysis, Inc.	Project planning and methodology development; peer review of project direction; expert elicitation methodologies
Robert W. Andrews	M&O/INTERA	Project planning and methodology development; expert selection
Gudmundur (Bo) S. Bodvarsson	Lawrence Berkeley National Laboratory	Project planning and methodology development; expert selection; sensitivity and feedback
Thomas Bjerstedt	U.S. Department of Energy	Project planning and oversight; expert selection; review of project direction
Dwight T. Hoxie	U. S. Geological Survey	Project planning and methodology development; expert selection process; expert elicitation
Edward M. Kwicklis	U. S. Geological Survey	Project planning and methodology development; expert elicitation; technical review of expert interpretations
Russ Patterson	U.S. Department of Energy	Project planning and oversight; review of project direction
Martha Pendleton	M&O/Woodward-Clyde Federal Services	Project planning and oversight; expert selection process; review of project direction

TABLE 1-2

EXPERT PANEL MEMBERS

EXPERT	AFFILIATION
Gaylon S. Campbell	Washington State University
Glendon W. Gee	Battelle, Pacific Northwest National Laboratory
James W. Mercer	GeoTrans, Inc.
Shlomo P. Neuman	University of Arizona
Karsten Pruess	Lawrence Berkeley National Laboratory
Daniel B. Stephens	Daniel B. Stephens & Associates
Edwin P. Weeks	U.S. Geological Survey

TABLE 1-3

TECHNICAL SPECIALISTS PARTICIPATING IN UZFMEE WORKSHOPS AND FIELD TRIP

WORKSHOP 1 - SIGNIFICANT ISSUES AND AVAILABLE DATA	
Robert Clayton	Woodward-Clyde Federal Services
Lorraine Flint	U.S. Geological Survey
Larry Anna	U. S. Geological Survey
Alan Flint	U. S. Geological Survey
Joseph Rosseau	U. S. Geological Survey
Gary LeCain	U. S. Geological Survey
Joe Wang	Lawrence Berkeley National Laboratory
Perry Montazer	Multimedia Environmental Technology
Gary Patterson	U. S. Geological Survey
June Fabryka-Martin	Los Alamos National Laboratory
Inche "Al" Yang	U. S. Geological Survey
Zell Peterman	U.S. Geological Survey

TABLE 1-3 (Cont'd.)

TECHNICAL SPECIALISTS PARTICIPATING IN THE UZFMEE WORKSHOPS AND FIELD TRIP

WORKSHOP 2 - ALTERNATIVE MODELS AND INTERPRETATIONS	
Mark Bandurraga	Lawrence Berkeley National Laboratory
Eric Sonnenthal	Lawrence Berkeley National Laboratory
Alan Flint	U.S. Geological Survey
Stuart Stothoff	Center for Nuclear Waste Regulatory Analyses
Stefan Finsterle	Lawrence Berkeley National Laboratory
Christine Doughty	Lawrence Berkeley National Laboratory
Sean McKenna	Sandia National Laboratories
Susan Altman	Sandia National Laboratories
Rick Ahlers	Lawrence Berekeley National Laboratory
Yu-Shu Wu	Lawrence Berkeley National Laboratory
Jerry Fairley	Lawrence Berkeley National Laboratory
Andrew Wolfsberg	Los Alamos National Laboratory
Srikanta Mishra	M&O/INTERA
Clifford Ho	Sandia National Laboratories
C. F. Tsang	Lawrence Berkeley National Laboratory
Jack Gauthier	SPECTRA Research
Linda Lehman	L. Lehman & Associates
Tetsu Tokunaga	Lawrence Berkeley National Laboratory
FIELD TRIP TO YUCCA MOUNTAIN	
Alan Flint	U.S. Geological Survey
Warren Day	U.S. Geological Survey
Steve Beason	U. S. Bureau of Reclamation

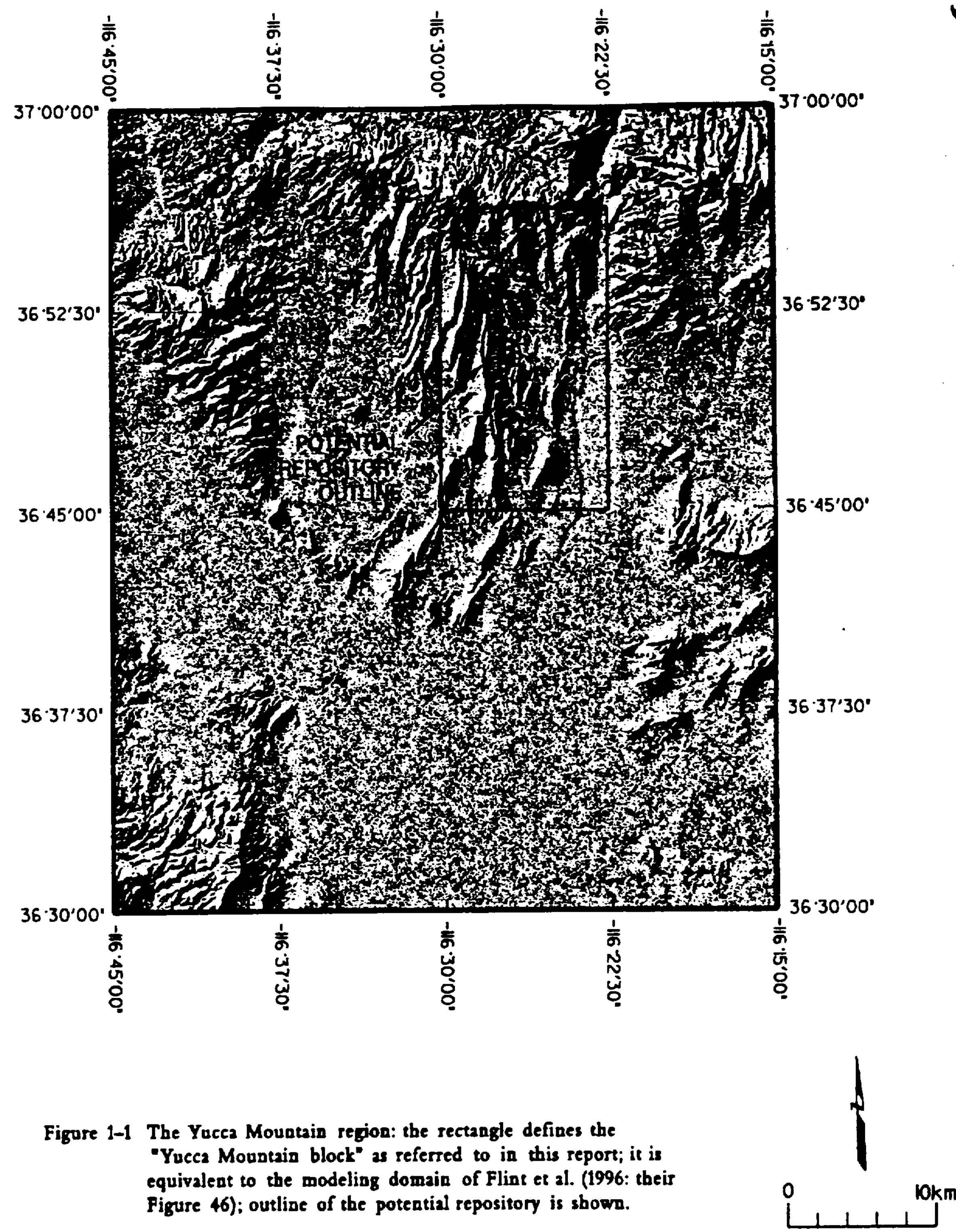

Figure 1-1 The Yucca Mountain region: the rectangle defines the "Yucca Mountain block" as referred to in this report; it is equivalent to the modeling domain of Flint et al. (1996: their Figure 46); outline of the potential repository is shown.

2.0 PROCESS FOR ELICITING EXPERT JUDGMENTS

2.1 INTRODUCTION

This section summarizes the methodology that was followed in carrying out the UZFMEE project. It is our belief that to be credible and useful, a technical analysis such as the UZFMEE must: (1) be based on sound technical information and interpretations, (2) follow a process that considers all available data, and (3) incorporate uncertainties into the assessments. A key mechanism for quantifying uncertainties in the UZFMEE is the use of multiple expert judgments. The *process* used to select the experts, facilitate their interaction and mutual education, and elicit their judgments is just as important as the technical content of their interpretations.

Because of the importance of the entire process, a methodology development team (MDT) was established at the outset. MDT members had experience in developing guidance for and implementing multi-expert studies, understanding technical aspects of unsaturated zone processes, and performing Total System Performance Assessments (TSPA). For example, Drs. Coppersmith and Morris were members of the Senior Seismic Hazard Analysis Committee (SSHAC, described below); and Drs. Coppersmith and Youngs participated on the Electric Power Research Institute (EPRI) methodology team for seismic hazards assessment in the eastern United States (EPRI, 1986) Several of the MDT (Drs. Coppersmith, Youngs, Perman, and Morris) also participated in the Probabilistic Volcanic Hazard Assessment for Yucca Mountain (U.S. DOE, 1996), which employed a multi-expert approach. Importantly, the MDT included representatives from performance assessment and site characterization for the Yucca Mountain project. The site characterization program has developed most of the data related to the unsaturated zone at Yucca Mountain, and the TSPA will be the primary user of the results of the UZFMEE project.

2.1.1 Pertinent Guidance Regarding Expert Judgment

In the study of any complex technical problem—such as unsaturated zone flow or percolation flux at Yucca Mountain—expert judgment is used. The data themselves do not provide an interpretation of the processes and outputs needed for subsequent analyses. For example, data regarding precipitation, matrix and fracture properties, fault and fracture characteristics, pneumatic data, measured saturations, moisture tensions, temperatures, or environmental isotopes provide no direct estimates of the nature and amount of percolation flux at depth within the hydrologic system. These data must be interpreted to assess fracture vs. matrix flow, moisture and gas flow pathways, lateral moisture flow, and fast-flow pathways. Various conceptual models of the unsaturated zone must be combined with observed data to interpret issues such as the interaction between fractures and matrix, the temporal behavior of flux through the system, amounts of percolation flux, and the spatial variability of that flux. Through the scientific process, experts integrate and evaluate data to arrive at conclusions that are meaningful to assessments of the unsaturated zone flow model, including quantitative and qualitative expressions of the uncertainties. This process is the same regardless of the abundance or scarcity of data. In this sense, expert judgment is not a substitute for data; it is the process by which data are evaluated and interpreted. If data are scarce and uncertainties high, the uncertainties expressed by each expert and the range of judgments across multiple experts should reflect this high degree of uncertainty.

The procedures and approaches for eliciting expert judgments, developed through conducting many studies, have been formalized in guidance documents followed in the UZFMEE project. DOE recently developed guidance for the formal use of expert judgment by the Yucca Mountain Project (DOE, 1995), and the Nuclear Regulatory Commission (NRC) staff has issued a Branch Technical Position (BTP) on use of expert elicitation in the high-level waste program (Kotra et al., 1996). Comprehensive guidance on eliciting expert judgment for seismic hazards recently was set forth in a study sponsored by DOE, the EPRI, and the NRC (SSHAC, 1995).

SSHAC (1995) defines the expert roles of *proponent, evaluator*, and *integrator*. A proponent advocates a particular technical view or interpretation; an evaluator weighs the relative merits of alternative views; and an integrator combines the alternative views into a composite distribution that includes uncertainties. The UZFMEE members were informed of their roles as evaluator experts and of the need to forsake the role of a proponent in making their assessments and evaluating uncertainties. Expert interactions are deemed very important in the SSHAC process and must be properly facilitated. Finally, the SSHAC process allows for aggregation of multiple expert views using a "weighing" approach rather than a weighting approach, when necessary. Individual *weights* can be applied to each expert's interpretation (as was done in the UZFMEE*)*, or an interactive process can be followed whereby the technical facilitator/integrator *weighs* the various interpretations and develops an assessment that he believes best captures the range of views and uncertainties.

The UZFMEE study closely follows the procedural guidance set forth in the SSHAC study, both in spirit (e.g., a belief in the importance of facilitated expert interactions) and, in many cases, in details of implementation (e.g., suggestions for conducting elicitation interviews). For example, the UZFMEE process was designed—in accordance with SSHAC guidance—to result in probability distributions that represent the "range of technical interpretations that the larger informed technical community would have if they were to conduct the study." However, inasmuch as SSHAC professes to be "non-prescriptive" in specifying a single way of implementing the process, it would be inappropriate to say that the UZFMEE conforms exactly to the SSHAC process. In some cases, the UZFMEE process followed approaches that were more appropriate for a relatively modest multi-expert study than a larger, resource-intensive study. For example, after the elicitation interviews, feedback to the experts was accomplished by providing each expert with a feedback package that summarized their assessments and the implications of those assessments to certain key issues. The experts then were given an opportunity to revise their assessments in light of the feedback, as suggested in the SSHAC guidance. A more resource-intensive approach might have been to conduct a feedback workshop. Either process enables the experts to review the assessments of others on the panel and to examine the calculated implications of their assessments.

The goal of all of the guidance documents is not to establish a rigid set of rules for eliciting expert judgment; rather, it is to draw from experience—both successes and failures—criteria for when expert judgment should be used and to outline approaches to motivating, eliciting, and documenting expert judgments. Other documents in the literature provide alternative approaches to the formal or informal use of expert judgment (e.g., Meyer and Booker, 1991).

2.2 UZFMEE METHODOLOGY

This section of the report summarizes the methodology implemented in the UZFMEE. It begins with an overview of the important steps in the process, followed by a more detailed discussion of those steps.

2.2.1 Steps in the Methodology

The principal steps followed in the UZFMEE project are described below.

(1) **Development of Project Plan.** The MDT first developed a project plan that outlined the goals and key elements of the project, timing of significant activities such as workshops, topics to be covered at workshops, and significant milestones. Throughout the project, the plan was updated to ensure that project goals were achieved.

(2) **Selection of the Expert Panel.** The MDT established criteria for participation on the expert panel. These criteria were intended to ensure that all expert panel members had significant professional stature and technical expertise. Highly regarded scientists and engineers were asked for their nominations to the panel, resulting in more than 75 nominations. From this list of candidates, seven experts were selected and participated on the panel.

(3) **Data Compilation and Dissemination.** The compilation and distribution of pertinent data, including published reference material, began early in the project and continued throughout. Before the first workshop, the experts were sent a number of data sets and publications. Panel members were provided access, if requested, to all Yucca Mountain data gathered as part of the project.

(4) **Meetings of the Expert Panel.** Structured, facilitated interaction among the members of the expert panel took place during three workshops and one field trip. The workshops were designed to identify the significant issues, available data, alternative models, and uncertainties related to the unsaturated zone flow system. Debate and technical challenge of alternative interpretations were encouraged to ensure that uncertainties were identified. At these meetings, researchers from a variety of organizations, including the U. S. Geological Survey (USGS), Lawrence Berkeley National Laboratory (LNBL), Center for Nuclear Waste Regulatory Analyses (CNWRA), and Los

Alamos National Laboratory (LANL) presented pertinent data sets and alternative models and methods.

(5) **Elicitation of Experts.** One-day individual elicitation interviews were held with each member of the expert panel. Through discussions facilitated by the elicitation team, each expert provided his preferred and alternative models for characterizing percolation flux at the potential repository horizon, expressed the uncertainties, and specified the technical basis for the assessment. The elicitation team documented the elicitation during the interview. The experts subsequently reviewed, revised, and supplemented the summary prepared by the elicitation team.

(6) **Feedback of Preliminary Results.** Based on the results of the elicitations, LBNL researchers conducted sensitivity analyses using the UZ site-scale model. These analyses were distributed to the members of the expert panel. In addition, the elicitation summaries of each expert, and a summary table of the key issues assessed, were provided.

(7) **Finalization of Expert Assessments.** After they received the feedback package, the experts reviewed the sensitivity analyses and the technical bases and conclusions of the other experts. They then developed a final draft of their elicitation summary. This draft was reviewed by the elicitation team for completeness and clarity, and finalized for this report (Appendix D).

(8) **Preparation of Project Report.** This report was developed to document the process followed, the expert elicitation summaries, and the results.

The rest of Section 2.2 describes in more detail the key activities involved in implementing the UZFMEE methodology.

2.2.2 Selection of the Expert Panel

The selection of members for the expert panel involved four steps: (1) developing selection criteria, (2) obtaining nominations from knowledgeable individuals, (3) selecting and inviting candidates to participate, and (4) having the candidates accept the invitation to participate.

Guidelines for selecting members of the expert panel were developed by the MDT. Candidates for the panel had to demonstrate the following characteristics.

(1) Status as an earth scientist or engineer of high professional standing and widely recognized competence based on academic training and relevant experience. Tangible evidence of expertise, such as documentation of research in refereed journals and reviewed reports, was required.

(2) Understanding of the general problem area through experience in one or more of the following areas: groundwater infiltration in arid environments; methods for characterizing unsaturated fractured rock, including matrix properties, fracture properties, and processes; analysis and numerical modeling of fluid flow in variably saturated fractured rock; or the quantification of uncertainties in data and modeling. Individuals who have or had a major role in the Yucca Mountain Site Characterization Project could be included on the expert panel; however, such experience was not a requirement for participation.

(3) Availability and willingness to participate as a named panel member, including a commitment to devoting the necessary time and effort to the project and a willingness to explain and defend technical positions.

(4) Personal attributes that included strong communication and interpersonal skills, flexibility and impartiality, and the ability to simplify. Individuals would be asked specifically not to act as representatives of technical positions taken by their organizations, but rather to provide their own technical interpretations and assessments of uncertainties.

(5) Ability to help create a panel that reflects diverse opinions, areas of technical expertise, and institutional/organizational backgrounds (e.g., from government agencies, academic institutions, and private industry).

The MDT conducted a broad search to obtain nominations for the expert panel. Letters requesting nominations were mailed to 29 earth scientists and engineers identified by the MDT. The letters requesting nominations contained a brief description of the project and included the above guidelines for selecting panel members. Nominations were received from 22 individuals; 75 candidates for the expert panel were nominated and considered in the selection process.

The MDT carefully evaluated each of the nominees to ascertain whether the selection guidelines had been applied properly, and to balance the panel with respect to knowledge and experience. The list of candidates was narrowed down to those individuals who met selection criteria 1 and 2, then the remaining criteria were applied. Areas of expertise that included net infiltration, rock properties, and modeling were discussed for each candidate, and lists of individuals having various types of experience were developed. The professional reputation and publications of each candidate were discussed, and the number of nominations each candidate had received was reviewed. A list of individuals to be invited to participate was developed during the evaluation process.

The candidates were contacted by telephone and invited to participate. They were informed that the estimated level of participation was 20 days (by the end of the project, many of the experts had spent significantly more time). Most accepted during the initial phone call; others requested time to consider potential conflicts of interest or schedule. A total of nine individuals were invited to join the expert panel; seven accepted, and two declined due to schedule conflicts.

The criteria for selecting the experts were reviewed with each expert before they made a commitment and throughout the project. Each expert had to commit a significant amount of time and would need to prepare for and attend all meetings. Information on potential sources of conflict of interest was provided by each expert and documented in the UZFMEE administrative files. The experts were informed of the role they would play in the UZFMEE assessment as an expert *evaluator* who considers a variety of viewpoints, challenges the interpretations of others, and arrives at a reasoned position that includes a representation of the uncertainties. The resulting panel consisted not only of experts of considerable stature and prominence in the hydrological community, but individuals with reputations as independent thinkers. The panel members clearly demonstrated that they were capable of evaluating all the data and hypotheses, and of providing the technical bases for their interpretations and uncertainties.

2.2.3 Review of Technical Issues/Expert Interaction

Technical issues related to the UZFMEE project were identified in the first workshop and reviewed throughout the project. The workshops and field trip provided an opportunity for technical discussion and interaction, with an objective of ensuring a common understanding of the issues to be assessed and the data available to provide the technical basis for assessment.

Literature and data sets pertaining to assessing unsaturated zone flow processes were sent to members of the expert panel throughout the project. A list of the references distributed is provided in Appendix B. In addition, some of the experts requested additional data or publications directly from the Yucca Mountain project researchers (cited as pers. comms. in Appendix D; e.g., Dr. Campbell requested weather data from Dr. A. Flint).

The following sections summarize the activities (workshops and field trip) conducted during the project. These are summarized under the topic of Review of Technical Issues/Expert Interaction because the workshops and field trip were the primary vehicle for accomplishing this interaction. Summaries of the workshops and field trip are included in Appendix C.

2.2.3.1 Workshop on Significant Issues and Available Data

The first of the three workshops conducted for the UZFMEE project was the Workshop on Significant Issues and Available Data. The goals of this workshop were to introduce the panel to the Yucca Mountain project, identify significant issues related to both the unsaturated zone site-scale modeling and the Total System Performance Assessment, and to present the various data sets related to the significant issues. Twelve technical specialists presented and discussed the data sets collected over the past several years to characterize unsaturated zone hydrology at Yucca Mountain.

2.2.3.2 Workshop on Alternative Models and Interpretations

This second workshop conducted for the UZFMEE project was designed to present and discuss alternative methods and conceptual models for evaluating UZ flow processes and assessing percolation flux. Key components of the UZ site-scale model were described. Eighteen technical specialists made presentations at the workshop. The specific subjects to be addressed in the expert elicitations were discussed, and elicitation training was provided.

2.2.3.3 Workshop on Preliminary Interpretations

The Workshop on Preliminary Interpretations, the third and final project workshop, was conducted prior to the elicitation interviews. This workshop provided an opportunity for the experts to present and discuss their preliminary interpretations and uncertainties regarding key issues in unsaturated zone flow processes. The experts presented their interpretations of each of five issues: net infiltration, rock properties, major pathways, calibration uncertainties, and alternative conceptual models.

2.2.3.4 Yucca Mountain Field Trip

The MDT organized a one-day field trip to Yucca Mountain at the request of the expert panel members, who wanted to observe first-hand the general setting of Yucca Mountain. The field trip was led by earth scientists from the USGS and the U. S. Bureau of Reclamation, who are conducting research for the Yucca Mountain project. Field trip stops were made to observe bedrock exposed in the Exploratory Studies Facility (ESF) and at the ground surface and to visit several data collection localities for the USGS infiltration studies. The field trip gave the experts an opportunity to observe field relationships and to discuss interpretations regarding issues important to unsaturated flow, such as surface water balance, infiltration monitoring, and the nature of bedrock structures.

2.2.4 Elicitation of Experts

Through the elicitation process the experts' interpretations of UZ flow processes at Yucca Mountain were obtained. The elicitations involved a series of activities, which can be grouped into three steps: (1) preparation for the elicitation, (2) the elicitation interview, and (3) documentation and review.

2.2.4.1 Preparation for the Elicitation

Peter A. Morris of the MDT provided elicitation training at the second workshop. The objectives of the training were to demonstrate how to quantify uncertainties using probabilities, to recognize common cognitive biases and compensate for them, and to present examples of the types of assessments that would be made at the elicitation (e.g., continuous variables, discrete hypotheses, and associated weights). The training was designed to allow the experts to be comfortable with the *process* of eliciting their judgments, so that the elicitation interview could be focused on the *technical issues* of importance to the UZFMEE.

A memorandum was provided to the expert panel members to assist them in preparing for the elicitation interview. This "Roadmap to the Elicitation" is shown in Table 2-1. The list of topics was intended to help the experts prepare for their interviews, to focus their data review on the issues of most significance, and to ensure that all important topics were addressed by all experts.

2.2.4.2 The Elicitation Interview

The elicitations of the expert panel members took place in individual one-day interviews in the San Francisco office of Geomatrix. The interviews were conducted by members of the MDT. The Geomatrix elicitation team was composed of K. Coppersmith, R. Youngs, and R. Perman. The technical specialists attending the elicitations were E. Kwicklis, D. Hoxie, and/or B. Bodvarsson. In addition, P. Morris, the normative expert for the project, attended the first elicitation interview and discussed the process of elicitations with the Geomatrix MDT members.

All data sets provided or made available to the experts during the project were present during the elicitations. The elicitation interview followed a logical sequence from general to more specific assessments. Alternative models, approaches, and hypotheses were discussed and probability distributions were developed. The Geomatrix team took written notes of all assessments during the interviews.

2.2.4.3 Documentation and Review

Documentation of the expert elicitations began with notes taken by the elicitation team during the interviews. Experience on several other expert assessment projects has shown this approach to be preferable to other documentation methods (e.g., written questionnaires, experts writing their interpretations following the interview). During the one-day interview, each UZFMEE expert was asked to make many assessments, to quantify his uncertainties, and, most importantly, to provide the technical basis for his interpretations. By having the elicitation team take notes, the expert was free to focus on thinking through his answers and thoroughly expressing his interpretations. The elicitation team was able to be flexible in the elicitation sequence (i.e., following the logic comfortable to the expert) while ensuring that all elements were covered.

Following the interviews, the elicitation team provided each expert with written documentation of the interview, organized by model component. The experts were instructed to review, revise, and expand their preliminary assessments in this "First Draft" documentation summary so that it fully reflected their interpretations. The summaries revised by each expert became the "Second Draft" document. The "Second Draft" summaries from each expert were then distributed to all members of the panel as part of the feedback package so that each expert could review the judgments of others and the technical basis for each judgment.

After reviewing the feedback package, the experts made additional revisions to their elicitation summaries to reflect any resulting changes in their judgments. These revised summaries became the "Third Draft" set. The "Third Draft" summaries were reviewed by MDT members as part of the report review process. The experts responded to any requests for clarifications, and the summaries were finalized. The final elicitation summaries are provided in Appendix D.

2.2.4.4 Feedback and Sensitivity

Feedback to the experts occurred throughout the UZFMEE project, primarily through interaction among experts. By presenting their ideas on models and interpretations at workshops and in general discussions, the experts both provided and received feedback from their peers on the panel.

More formally, feedback was provided to the experts in several other ways:

- At Workshop 2, the experts requested several data bases and analyses in order to develop their interpretations. Although not all of the requests could be honored due to time constraints, a number of data sets and previous analyses were compiled, and some new analyses were carried out. These are summarized in Table 2-2.
- At Workshop 3, the experts presented to the panel their interpretations of key issues. Discussions included the technical bases for the interpretations.
- A formal feedback package, including sensitivity analyses, was provided near the end of the elicitation process. Written elicitation summaries were provided to all panel members for their review, and various sensitivity analyses conducted using the UZ site-scale model were provided. The sensitivity analyses dealt with issues surrounding the modeling of net infiltration and the impact of various amounts of

percolation flux on the predicted results of the model. These analyses are also summarized in Table 2-2.

- The MDT reviewed the written elicitation summaries for adequacy and completeness of documentation of the technical basis for judgments.

The feedback-revision process required the experts to defend/revise their assessments and to provide appropriate documentation. In all cases, the experts on the panel responded positively to technical criticisms of their interpretations and to reviews of their documentation. The resulting assessments and finalized elicitation summaries reflect the significant effort expended by each member of the expert panel.

2.3.4.5 Aggregation of Expert Assessments

The approach taken to combine, or aggregate, the expert assessments is equal weighting. Importantly, this approach was not a "default" but a goal throughout the project. Accordingly, the proper conditions were created throughout the project to ensure that a deliberate, defensible decision could be made to use equal weights (after SSHAC, 1995). The actions that were taken to create these conditions included:

- carefully selecting highly qualified experts who represent diverse views and experience;
- establishing the commitment of each expert to provide required effort throughout the project;
- identifying a comprehensive data base and disseminating it to all experts;
- educating the experts in issues important to UZFMEE and training the experts in elicitation methodologies and the role of experts as evaluators;
- facilitating interaction of the experts in workshops and field trips to foster a free exchange of data and interpretations and scientific debate of all hypotheses;
- providing feedback and sensitivity analyses to the experts; and
- providing an opportunity for experts to revise their assessments in light of feedback.

It should be noted that, in accordance with the guidance provided by the SSHAC study (1995), conditions could have been such that differential weights would have been necessary. For example, if a member of the expert panel had been unwilling to forsake the role of a *proponent* who advocates a singular viewpoint, for that of an *evaluator* who is able to consider multiple viewpoints, that expert may have been given less weight or removed from the panel entirely. Or the interpretations of a member of the panel would be given less weight if the rest of the panel declared him to have extreme, outlier views relative to **both** the views of the rest of the panel and the larger technical community. In this case, a weight of 1/7 (1 view in 7 on the panel) would be excessive relative to the true weight of his views when compared to the larger community (if, for instance, 1 in 100 might share the view).

TABLE 2-1
ROADMAP TO THE ELICITATION
UZFMEE PROJECT

Objective:
The principal objective of the elicitation is to define the percolation flux at the potential repository horizon, its uncertainty, and its spatial variability. In addition, an assessment will be made of the partitioning of flux between the fractures and matrix, seepage into the drifts, and flow beneath the drifts. We are looking for your ideas and your perceptions of uncertainty pertaining to these topics.

Topics:
The following topics will be covered during the elicitation:

1. basic concepts of moisture flow through Yucca Mountain;
2. basic components and processes that affect flow through the mountain (e.g., fracture-matrix interaction, transient pulses, steady-state);
3. net infiltration;
4. approaches to estimating percolation flux at the potential repository horizon (see below);
5. seepage into the drifts; and
6. flow patterns below the potential repository horizon.

Percolation Flux:
The bulk of the elicitation will be devoted to assessing the methods for estimating percolation flux as well as quantifying the key uncertainties in models and parameters in the various methods. The following topics will be evaluated as approaches to estimating percolation flux or as calibration methods:

- Net infiltration
- Temperature gradients
- Saturations and water potentials
- Chloride mass balance
- Isotopic evidence
- Perched water/water balance
- Fracture coatings

Partitioning of the total percolation flux into components occurring in the matrix and in the fractures also will be assessed.

TABLE 2-2
FEEDBACK PROVIDED TO EXPERTS*

Feedback Provided Prior to Workshop 3

- Comparisons between TOUGH2 and WEEPS models to assess the need for a hybrid equivalent continuum and dual permeability model;
- Recent and ongoing measurements of hydraulic conductivity and other rock properties;
- Summary of geostatistical analyses and information;
- Monte Carlo analyses of percolation flux distributions for fracture and matrix components;
- Variation and uncertainty in thermal conductivity and temperature gradients.

Feedback Provided Prior to Finalizing Assessments

- Draft elicitation summaries for all the experts;
- Summary table indicating the experts' assessments of key issues;
- Development and testing of a coupled surface runoff module for TOUGH2 to evaluate the potential for lateral flow at the bedrock/alluvium contact;
- UZ site-scale model calculations using simulations of a high-infiltration scenario (up to 45 mm/yr) and comparisons with temperature, saturation data, and perching conditions;
- Uncertainty analysis in estimations of percolation flux using temperature data and assumed heat flux and property distributions;
- Estimates of percolation flux for borehole SD-12 using the entire temperature profile and a technique that alleviates the need for assuming a heat flux.

* Includes additional data sets and analyses requested by members of the expert panel.

3.0 ASSESSMENT OF KEY ISSUES

3.1 INTRODUCTION

The UZFMEE experts addressed a variety of technical issues for characterizing the unsaturated flow system at Yucca Mountain. These issues included characteristics that are important to modeling the flow system (e.g., spatial distribution of infiltration, temporal pulses of infiltration, lateral flow), as well as issues that are important to the Total System Performance Assessment (TSPA; e.g., percolation flux at the potential repository horizon, partition of flow between fractures and matrix, seepage into the drifts). In addition, the experts were asked to provide their perspectives on additional data or activities that could serve to reduce the uncertainties in the UZFMsite-scale model. The experts' assessments are given in their elicitation summaries (Appendix D) and summarized in this chapter.

It is important to remember the context of the experts' assessments. First, the goal of this expert elicitation was to quantify the *uncertainties* associated with various aspects of the UZFM site-scale model so that the TSPA-VA can incorporate a range of uncertainty when modeling this important process. As a result, the experts focused considerable attention on *what is not known*, and the reasons for that lack of knowledge. The reasons could include data gaps, poor data quality, non-pertinent data, multiple models consistent with the data, minimal model calibration, etc. 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. For example, percolation flux at the potential repository horizon is a key issue for the TSPA. Each expert worked through the approaches that have potential value in estimating percolation flux, gave their interpretation of the validity of the approaches in light of available data, and, ultimately, provided a quantitative assessment of the average percolation flux at the potential repository horizon. Each flux estimate incorporates the uncertainties in the various approaches to estimating flux, the alternative models that can be used to explain the available data, and the physical properties and parametric values used in the various models.

It is also important to note that the experts' assessments are, to a large extent, an expression of the professional judgment of each expert and are not based on extensive modeling or calculations. These judgments are derived not only from a consideration of Yucca Mountain data, but also data and observations made at analog sites. Members of the panel were given a limited time in which to review Yucca Mountain data sets 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 or conducted by the project in response to their requests for additional information. As a result, the experts devoted their effort to understanding what data exist and the modeling and calibration efforts that have been conducted, and to estimating uncertainties in the key parameters and inputs.

3.2 RELATIONSHIP OF UZFMEE TO UZ SITE-SCALE MODEL AND TSPA

LBNL and the USGS are developing a model of the unsaturated zone at Yucca Mountain (termed the UZ site-scale model). The model is intended to capture key aspects of the unsaturated flow system using all of the data developed for the project. The relationship between the UZ site-scale model and the UZFMEE project should be clear. The two studies are complementary: the UZFMEE is designed to address the key components of the UZ site-scale model, to evaluate the uncertainties in those components, and to an evaluate the suitability of embedding various aspects of the component-level modeling in the site-scale model. For example, the site-scale model as discussed in Bodvarsson and Bandurraga (1996), uses the net infiltration maps developed by the USGS (Flint et al., 1996) as input to the analysis. During the UZFMEE project, the experts were asked to consider the manner in which net infiltration has been modeled, the uncertainties in pertinent data sets, and the uncertainties in the temporal and spatial distribution of net infiltration. The experts identified several key issues related to net infiltration, such as the influence of lateral flow at the bedrock-alluvium interface, the episodic nature of infiltration events, and the contribution of storm runoff to infiltration. To respond to the experts' requests for constraints on these factors, the UZ model was updated to include a two-dimensional model of surface water and shallow infiltration (see Feedback Package on Table 2-2) that specifically incorporates the potential for lateral flow along the bedrock-alluvium contact.

This is a case in which the UZFMEE project had a direct influence on the scope and content of the UZ site-scale model. In other cases the assessments made by the expert panel provided interpretations of key issues that serve as a "check" or independent perspective for the UZ modelers to consider. For example, the temporal behavior of the UZ flow system was evaluated relative to recent data that indicate bomb-pulse isotopes (associated with nuclear bomb testing) at the depth of the potential repository . The experts considered the isotopic data and the potential for "fast-flow" paths within the UZ system that would explain the presence of the isotopes at depth as well as their spatial distribution. Likewise, the experts considered the degree to which a temporal pulse induced by episodic infiltration (from major storm events) might be dampened as it passes through the stratigraphic section. The expert assessments provide a basis for the UZ modelers either to include a temporal pulse or to consider a steady-state model beneath certain attenuating hydrostratigraphic layers.

Finally, in a few cases, the experts provided quantitative input to the UZ model, particularly in terms of the assessment of uncertainty. For example, several experts provided their assessment of the spatially and temporally averaged net infiltration across the Yucca Mountain block. They expressed this average as a probability distribution function that—across many experts—gives a reasonable expression of uncertainty. In addition, several experts expressed their ideas about the spatial distribution of net infiltration across the Yucca Mountain block. The expert assessments can be compared with those previously developed for the UZ site-scale model and, if appropriate, to provide inputs to the model.

Certain assessments made by the experts provide information that can be input to the TSPA. For example, the percolation flux at the potential repository horizon (middle non-lithophysal portion of the Topopah Spring tuff [TSw]) is vital to the performance of the potential repository. The percolation flux is spatially and perhaps temporally variable and subject to considerable uncertainty. The UZFMEE members provided a spatially and temporally averaged estimate of percolation flux and the uncertainty associated with that estimate. Percolation flux is not measured directly. Each of several indirect methods for estimating flux has its own set of uncertainties. Methods considered by the experts included surface-water balance, saturations and water potentials, temperature gradients, and environmental isotopes. To variable degrees, data are available to exercise these methods. In general, the experts expressed a range of uncertainty in their percolation flux estimates due to uncertainties in the applicability and conceptual basis for all methods, limited data to exercise the methods, limited calibration, and fundamental uncertainties in the nature of fluid flow in unsaturated, fractured rock. The TSPA, as a probabilistic analysis, is capable of incorporating the experts' quantitative expressions of uncertainty in percolation flux.

Another assessment that should prove of value to the TSPA is the experts' evaluation of the partitioning of the flux into fracture and matrix components within the TSw, and between the fast- and slow-flow components. The performance assessment includes models of the unsaturated zone that consider the two components because they are important to issues of seepage into the drifts under ambient conditions and under conditions of high thermal load. (Note that thermohydrology—which considers the potential for seepage into the drifts during the immediate post-emplacement period characterized by elevated thermal loads—is an issue not considered here). These performance assessment models rely on estimates of the relative components of flux in the matrix and in the fractures within the TSw, for which the experts provided interpretations. They discussed both the "fast" component of flow, which would explain the bomb-pulse isotopes at depth, and the relative contributions of the fast and slow components to total flux.

3.3 COMPONENTS OF THE UNSATURATED ZONE MODEL

Figure 3-1 illustrates the key UZ site-scale model components, all of which the experts addressed. The panel was provided with information and interpretations developed by Yucca Mountain specialists on all aspects of the UZ system, including the input data, calibrations, alternative conceptual models, and UZ model outputs. Through several presentations and interactive discussions with the data collectors, analyzers, and modelers, the experts developed their perspectives on the interpretations being made and the associated uncertainties.

Clearly, the unsaturated zone flow system at Yucca Mountain is complex. There are spatial variabilities and significant uncertainties in our present understanding of key aspects of the system. Appendix D contains the summaries of the expert elicitations regarding these issues. To compare the interpretations across the panel, Table 3-1 summarizes the assessments for several key issues. In turn, these interpretations are summarized in more detail below.

3.4 SUMMARY OF EXPERT INTERPRETATIONS

In this section we summarize the range of interpretations made by members of the expert panel regarding certain key issues related to the unsaturated zone. The intent is to provide the reader with a perspective on 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.

Before reviewing the expert interpretations, the "boundary conditions" for the assessment must be discussed. First, this assessment considers the characteristics of the unsaturated zone under *ambient* conditions. Such conditions likely are most representative of the period following the thermal pulse (first thousand years or so) associated with the emplacement of waste packages. "Ambient" conditions means a climatic regime comparable to that which now exists (the same average precipitation, seasonal distribution of precipitation, solar radiation, and vegetation). Ambient conditions, of course, allow for rare or extreme storm events, but do not consider significant changes to *average* conditions. In addition, it is assumed that there are no perturbations in the unsaturated zone due to the emplacement drifts or other engineered systems. The only exception to this is that the experts were asked about seepage into the drifts. In this case, the experts were to consider open drifts having no backfill or ventilation.

We recognize that the assumption of ambient conditions precludes an evaluation of potentially important processes, such as the influence on the unsaturated zone of entering into a wetter climatic regime or the impact of the thermal pulse on the potential for seepage into the drifts. That these considerations were omitted from this study should not be construed as downgrading their importance. Rather, these issues will be addressed as part of other studies conducted for the TSPA.

Each of the key issues shown in Table 3-1 is discussed below.

3.4.1 Net Infiltration

Net infiltration is defined as water that penetrates to sufficient depth so that it is not removed from the system by evapotranspiration. A distinction is made between "net infiltration" defined from a surface-water balance and associated near-surface processes, and "percolation flux" defined at the potential repository horizon. In most cases, the experts concluded that net infiltration is equivalent to percolation flux at the potential repository horizon, although there may be perceived differences in their spatial distribution, and some experts used different methods to estimate the two quantities. All of the experts concluded that net infiltration is the fundamental control on the overall water balance for the UZ system under ambient conditions. Likewise, they concluded that, over Yucca Mountain and throughout time periods of hundreds to thousands of years, net infiltration varies spatially. Despite this general agreement, the experts differed on the degree to which net infiltration can be estimated reliably and used to provide a strong constraint on percolation flux at the level of the potential repository.

Throughout the UZFMEE project, the experts were exposed to the detailed studies of net infiltration being performed by the USGS under the direction of Dr. Alan Flint. At the first two workshops, Dr. Flint made presentations on his data collection efforts during the past several years and the conceptual models that he has employed to estimate the amount and spatial distribution of net infiltration. He also led a field trip to the Yucca Mountain area, providing an opportunity for the expert panel to observe first-hand some of his field instrumentation sites and laboratory testing facilities. Finally, at the third workshop, which centered on the experts' preliminary assessments, Dr. Flint was available to answer questions regarding his modeling efforts and the uncertainties associated with his analyses.

The focus of the expert panel differed from that of the investigators conducting UZ data collection and modeling efforts. Up to now, the Yucca Mountain project has developed "best estimates" of the amount and spatial distribution of net infiltration (represented by various maps published by Dr. Flint and his colleagues), without explicit quantitative expressions of the uncertainties in these estimates. The focus of the expert panel, in contrast, was on providing a quantitative expression of the uncertainties in the estimates of net infiltration. Their judgments regarding uncertainties had to include not only data uncertainties, but also uncertainties in the fundamental conceptual models, including: the temporal distribution of storm events; the timing and nature of precipitation; the influence of topography, slope, and slope aspect; the influence of soil thickness and rooting depth; bedrock permeabilities and the role of faults and fractures; and the importance of lateral flow within the soils and at the bedrock-soil contact. As a result, in questioning Dr. Flint about his data collection methods (e.g., spatial distribution of precipitation stations and neutron boreholes, field measurements during storm events) and modeling efforts (e.g., one-dimensional modeling of flow, lateral flow processes, runoff component), the experts were probing for information that would assist them in defining the uncertainties in the assessment.

The experts' assessments of net infiltration were based heavily on the data collected by the YMP and the modeling conducted to estimate the amount and spatial distribution of infiltration, as well as experience gained by the experts at other locations. For example, the precipitation record developed by Dr. Flint for his modeling comes from site-specific rainfall measurements (during ~15 yrs) coupled with longer-term regional observations that have produced a simulated longer-term record (~100 yrs). The spatial distribution of net infiltration is assessed by Dr. Flint to be controlled largely by the spatial distribution of precipitation, as well as soil thickness and soil water-holding capacity. The panel generally accepted as reasonable these basic interpretations of the spatial distribution of net infiltration, as represented in the latest version of Dr. Flint's map (Flint et al., 1996). However, as discussed below, some of the experts suggested that the upper reaches of washes having shallow alluvium perhaps should be considered locations of higher infiltration than depicted on the maps. This conclusion was based to a large extent on experience elsewhere showing that lateral flow along the bedrock-alluvium interface and accumulation in washes can add significantly to infiltration.

Net Infiltration: Temporal Issues

The experts' general conclusion was that net infiltration is an episodic process linked to the occurrence of major storm events or sequences. This was based partly on the precipitation record developed for the Yucca Mountain project, which shows the episodic nature of precipitation and the possible influence of El Nino events, and partly on experience at other locations within the southwest desert. These storm events or sequences last from a few days to a few weeks and may be related to snowmelt events. The panel judged the average frequency of these episodic storm events to range from annual to approximately once every 20 years. Two experts (Dr. Neuman and Mr. Weeks) concluded that the severity of infiltration events would increase for recurrence intervals of more extreme storm events (e.g., a 500-year storm event would lead to more infiltration than a 50-year storm event).

The experts generally concluded that between these episodic infiltration events, there is little to no net infiltration. During these intervening periods, evapotranspiration would preclude significant infiltration. Because of the episodic nature of infiltration events and their relative infrequency (years to a few tens of years), most experts suggested that a long precipitation record (e.g., ~100 years, as developed by Dr. Flint) is needed to properly simulate the episodic and transient nature of these events. Likewise, because of the short duration of the events, precipitation measurements must be made with short time-steps (probably on the order of one hour rather than one day).

Net Infiltration: Spatial Issues

Most of the UZFMEE experts agreed that the spatial distribution of net infiltration in the Yucca Mountain region varies greatly. Also, the spatial variability is generally in accord with that given on Dr. Flint's most recent map (Flint et al., 1996). For example, all agreed that the areas underlain by thick alluvial deposits likely experience the least infiltration because of the high storage capacity of the alluvium and the consequent opportunity for losses due to evapotranspiration. However, several experts concluded that the newest Flint maps may not account for the potential for significantly higher infiltration beneath washes having relatively thin alluvial cover (less than 1-2 m). The process for this infiltration is postulated to be runoff from the ridge-tops and steep side-slopes toward and into the upper washes, lateral flow within the alluvium and along the bedrock-alluvium contact, and infiltration along faults and fractures in the bedrock. Several experts concluded that these processes would modify the Flint map to show less infiltration along the ridge-tops and more infiltration within the washes. This model implies the presence of faults and fractures having sufficiently high permeabilities to accommodate concentrated flowbeneath the washes. Some of the experts cited evidence based on field mapping for the downward coalescence or "horsetailing" of faults, which could concentrate flow. Although the experts concluded that the total surface area of the bedrock containing these faults and fractures likely is small, they are judged to be prime candidates for concentrated infiltration. Although it was noted in the field that many of the shallow fractures within the Tiva Canyon Tuff (TCw) appear to be filled with secondary mineralization, most of the experts did not consider this an impediment to infiltration. Dr. Neuman also concluded that, because of the relatively high matrix permeability of the Paintbrush nonwelded unit (PTn), high-permeability paths may develop even without faults or fractures.

Despite the high degree of agreement among the experts regarding the potential importance of lateral flow and concentration beneath washes, it was recognized that this process is difficult to observe directly. Some experts concluded that Dr. Flint's measurements of moisture content during and following storm events may, in fact, be related to lateral rather than vertical flow. Drs. Stephens and Gee made suggestions (discussed later) for field measurements and experiments specifically to address this issue.

Net Infiltration: Temporal and Spatial Average

To provide a measure of the uncertainties associated with estimates of net infiltration, the experts were asked to provide their judgments regarding the amount of net infiltration occurring at Yucca Mountain. The estimates are temporal averages (over periods long enough to include several episodic infiltration events—generally longer than 50 to 100 years) and spatial averages (over the Yucca Mountain block defined in Dr. Flint's map, as shown in Figure 1-1). Dr. Flint's temporal and spatial average for equivalent time periods and locations is about 4.5 mm/yr, as presented to the expert panel in the second and third workshops. Dr. Flint did not provide his assessment of the uncertainty in this estimate.

The probability distribution functions (expressed by percentiles and mean values) for this spatial and temporal average are given in Table 3-1 for the five experts who offered an interpretation. Dr. Neuman and Mr. Weeks declined to give an assessment of net infiltration based on surface and near-surface data. Dr. Neuman noted inherent difficulties in attempting to model the area's highly complex and spatially variable surface and near-surface hydrologic system, as well as the paucity of data necessary to provide reliable estimates of episodic infiltration events. Mr. Weeks noted significant uncertainties and variabilities in developing a surface-water balance. Both experts used other means (discussed below) to estimate percolation flux at depth.

In general, the PDFs for net infiltration are quite broad for each expert and for the panel as a whole, reflecting the perceived high degree of uncertainty regarding infiltration processes, pertinent data, and models. Note that values in Table 3-1 shown to tenths of millimeters per year are calculated based on elicited values for the PDF; they should *not* be interpreted as indicating accuracy to this level of precision. For the five experts who provided an assessment of net infiltration, average values ranged from 3.9 to 11.3 mm/yr, with an aggregate mean across the five experts of 8.7 mm/yr. Fifth to 95th percentiles ranged from tenths of millimeters per year to several tens of millimeters per year. (Estimates of percolation flux at the potential repository horizon are given later in this section.)

In general, net infiltration was estimated based on a review and evaluation of the studies being performed for the Yucca Mountain project. Some experts noted that with incorporation of additional data and refinement of models, the Yucca Mountain project through time, has increased its "best estimates" of net infiltration. Some of the experts concluded that additional consideration of the potential for focused infiltration in washes and more explicit inclusion of surface runoff may lead to net infiltration estimates greater than those presented by Dr. Flint. That potential increase is reflected in mean values that are somewhat higher than Dr. Flint's mean value of 4.5 mm/yr. The large range in the estimates reflects the potential for significantly different estimates than have been proposed. The low values would imply that, averaged over long periods, higher storage potential and more efficient evapotranspiration processes will minimize infiltration. The high values generally are based on rough estimates that, in general, net infiltration is a certain percentage (5% to 30% is cited by the experts based on experience elsewhere) of the average precipitation within arid desert environments.

Net Infiltration: Modeling Issues

Some of the experts provided their perspectives on the approaches being taken to model net infiltration. Arguments are made by Drs. Neuman and Gee that one-dimensional flow modeling is incapable of accounting for lateral flow at the bedrock-alluvium contact and for runoff. While acknowledging that these processes are clearly three-dimensional, Dr. Campbell noted that the grid blocks used in the TOUGH2 model are too large to provide the spatial detail needed to take advantage of the additional information provided by a two- or three-dimensional model. Dr. Stephens placed low confidence in the Bucket model used by Dr. Flint, concluding that it is inadequate for the level of detail considered in this analysis. Likewise he concluded that, at the local scale, simply to vary infiltration as a function of topography following the Maxey-Eakin model is unsatisfactory unless it can be shown that there is an orographic effect or some basis for precipitation to vary with local elevation.

Net Infiltration: Additional Data Collection

Because of the importance of net infiltration to understanding the unsaturated flow system, some of the experts suggested continued or additional data collection. Acknowledging the difficulties in developing reliable mechanistic models of net infiltration, Dr. Pruess suggested that monitoring and data collection related to net infiltration should continue in order to develop a more defensible appraisal of long-term system behavior. Dr. Gee concluded that a mass-balance model with field-measured values is needed to lower uncertainties in net infiltration. He suggested that a test could be conducted at the ground surface above the ESF with a very long (>1 km) line source and a constant drip. Dr. Stephens noted that unsaturated zone flow at local scales is needed for the analysis of Yucca Mountain. He suggested that a local watershed, ideally overlying the ESF, should be studied thoroughly to develop a local water balance for a few years to assess the local amounts and spatial distribution of infiltration. This local watershed could be thoroughly instrumented and studied, including use of rain gauges, detailed mapping of fractures (including beneath the alluvium at some locations), nests of piezometers in the alluvium and bedrock, and detailed mapping of the depth to bedrock. Surface flow during storm events and subsurface flow along the bedrock-alluvium contact could be measured using trenches, buried pan lysimeters, and TDR probes. The local study could be used to calibrate models for other parts of the mountain.

3.4.2 Lateral Diversion

Given specified amounts of net infiltration and its spatial variability, the experts were asked to address the degree to which flow through the hydrostratigraphic units down to the potential repository horizon within the TSw might include a significant lateral component. In particular, it has been suggested (Moyer and Geslin, 1995) that a capillary barrier may exist between the welded TCw unit and the underlying PTn that could divert moisture laterally downdip along the contact between the two units. If a significant amount of the moisture that infiltrates above the repository is diverted downdip (east), the amounts and spatial distribution of percolation flux at the potential repository horizon could be quite different—perhaps quite less—than the net infiltration.

In general, all the experts concluded that a contrast in hydraulic properties across lithologic interfaces likely would lead to lateral flow, particularly across the TCw-PTn contact.

Dr. Campbell also suggested that the PTn-TSw contact would be conducive to some lateral flow; and Dr. Gee hypothesized that textural differences within the PTn itself could create lateral flow. However, the panel generally agreed that the nature of the TCw-PTn interface, which appears to be extensively faulted along a series of small faults, would cause moisture flowing laterally along the interface to be captured and to flow vertically down the faults. Thus, lateral diversion is suggested to occur over a few meters to tens of meters, but not regionally along any of the interfaces.

The experts' conclusions regarding lateral flow were based on observations made in the ESF showing the nature and lateral continuity of the TCw-PTn interface and on interpretations of the hydraulic properties of the two units. For example, Mr. Weeks noted that localized perching is possible within depressions on the irregular TCw-PTn interface, but the numerous faults and significant matrix permeability of the PTn would limit the extent of lateral flow. The lack of borehole evidence for perched water at the PTn contact and the lack of evidence of paleospring deposits at the upper PTn contact exposed in outcrop were cited by some experts as arguments against significant lateral diversion of water at the TSw-PTn contact.

Some of the experts noted that infiltration and lateral flow into the various stratigraphic units within Solitario Canyon to the west of Yucca Mountain may affect the study area. For example, Dr. Stephens suggested that lateral flow could be an important contributor to the perched water bodies identified beneath the potential repository.

3.4.3 Temporal Behavior of UZ Flow System

The experts agreed that the temporal behavior of net infiltration was characterized by episodic events associated with major storm events or sequences. A potentially important issue is the degree to which the temporal "pulse" of infiltration is attenuated as moisture flows through the unsaturated zone system. A knowledge of this temporal behavior would assist in modeling the flow system as steady-state or transient.

Most of the experts concluded that the available data and modeling suggest that the transient pulse from infiltration is significantly dampened as water travels through the UZ system. To most of the experts, the presence of bomb-pulse environmental tracers is best explained by a "fast-flow" component of flux. Further, they believe that the fast-flow component is associated with transient pulses of moisture created from episodic infiltration events. To reach depth in such short periods, the fast-flow component is postulated to travel through the UZ system quickly, likely within faults, fractures, or other preferential flow paths, and with little matrix interaction. For example, Mr. Weeks postulated that the fast component of flow bypasses most of the volume of water in the PTn and TSw, and that the flow probably results from temporary perching at or near the top of the PTn, which allows for transient flow through the PTn. Dr. Stephens agreed with recent site-scale modeling that suggests that the travel-time curve for flow velocity is bimodal: the bulk of the fast-flow component has a travel time of thousands of years, but the slow-flow component has times of hundreds of thousands of years. A part (probably a relatively small volume) of the fast-flow component has extremely short travel times, as represented by the isotopic evidence. (Interpretations of the relative *volumes* of the fast and slow components of flow are discussed further below.)

Most of the experts concluded that, although the fast-flow component maintains transient temporal properties to depth, the infiltration pulse is dampened as moisture moves through the PTn and other layers having different hydraulic properties. For example, Dr. Neuman noted that he would expect only small temporal fluctuations in mean annual percolation flux across the potential repository horizon because of the buffering effect of the PTn. Most of the experts concluded that, below the PTn, the temporal behavior of flow can be modeled as steady-state as long as the fast-flow component is considered separately. However, Dr. Pruess cautioned that this assessment is quite uncertain, and Mr. Weeks noted that, although there probably is some damping within the TSw, fracture flow would be expected to be somewhat episodic and not steady-state.

3.4.4 Percolation Flux at the Potential Repository Horizon

Although not directly measurable, the amplitude and spatial variability of percolation flux at the potential repository horizon of the TSw is a critical assessment and input to the Total System Performance Assessment. Inasmuch as moisture percolating into the waste emplacement drifts could lead to degradation and corrosion of the waste packages and transport of radionuclides out of the drifts and down to the water table, details of percolation flux are important. These details include: the bulk or spatially averaged rate at which certain volumes of water reach the level of the potential repository from the surface, the spatial variability of that flux, the components of the flux that are carried in the rock matrix and in fractures, and the potential for seepage into the drifts given ambient thermal conditions. (The potential for seepage given elevated thermal conditions is not considered here.) Each of these aspects of percolation flux were considered by the experts to gain their perspectives on the associated uncertainties.

Methods Used to Estimate Percolation Flux

A variety of methods exist for estimating the amount and spatial variability of percolation flux. To facilitate the elicitation process, the experts were asked to estimate the temporally and spatially *averaged* percolation flux; that is, averaged temporally over sufficiently long periods to include multiple episodic flux events, if any (in the same manner as net infiltration), and averaged spatially over the Yucca Mountain block (See Figure 1-1). They then considered temporal and spatial variabilities in flux at the potential repository horizon. In general, the experts concluded that methods for estimating average percolation flux differ considerably in their ability to indicate the spatial and temporal variability of that average. For example, despite the uncertainties, most experts concluded that the use of the spatial variability of net infiltration provided—at least potentially—the best resolution regarding the spatial variability of percolation flux. Other methods that rely on bulk characteristics of the UZ system, such as temperature gradients, have less resolving power relative to spatial variabilties at the scale of the potential repository block.

The various methods for estimating percolation flux considered by the experts are summarized below, as is the degree of reliance the experts placed on each method.

Net Infiltration. This method assumes that the amount of moisture that infiltrates below a level where it is affected by evapotranspiration is available to percolate to depth. Uncertainties associated with net infiltration were discussed previously. The use of net infiltration to characterize percolation flux requires an interpretation of the degree to which infiltrating moisture might be diverted laterally, in a regional sense, so that it would not percolate to the potential repository. Its use to characterize the spatial variability of flux requires a consideration of the diffusion, dispersion, and/or concentration that might occur as moisture travels through the section down to the potential repository horizon. The temporal variability of flux is estimated by assessing the relationship between the temporal nature of infiltration events—generally judged to be episodic—and the degree to which the UZ system dampens that temporal signature.

Most of the experts used net infiltration to estimate percolation flux at the potential repository horizon. For example, Dr. Stephens acknowledged that uncertainties in net infiltration are significant, but stated that it may provide the best vehicle for estimating average percolation flux at the potential repository horizon. Other experts also concluded that net infiltration provides a fundamental constraint on the flux at depth in the TSw. Dr. Campbell placed highest weight on net infiltration as an estimator of percolation flux and stated that none of the other methods is suited to an analysis of spatial and temporal variation (discussed in more detail below). In contrast, Dr. Neuman placed little reliance on estimates of net infiltration at Yucca Mountain to estimate percolation flux at depth. He stated that the near-surface processes that generate net infiltration are complex and difficult to quantify. He identified several sources of error and uncertainty that make unreliable the estimates of net infiltration rates at Yucca Mountain. Similarly, Mr. Weeks noted that so many variables and uncertainties are involved in the water balance analysis that the usefulness of net infiltration to estimate percolation flux is doubtful.

Temperature Gradients. Convective heat flux is heat that is advected through rock with percolating water as a result of temperature gradients. If the heat flux, the temperature gradient, and the rock thermal conductivity are known, the convective heat flux, and therefore the percolation flux, can be computed. Uncertainties in estimates of percolation flux result from uncertainties in total heat flux, temperature gradient, and estimates of rock thermal conductivity.

In general, the experts did not embrace the use of temperature gradients and heat flux to estimate percolation flux at Yucca Mountain. Mr. Weeks and Dr. Pruess endorsed the method, indicating that it is useful in providing a volumetric average flux in addition to a velocity, and concluded that it is robust. They noted, however, that its application to Yucca Mountain is limited because of data limitations, particularly the large spacing of temperature measurements in the unsaturated zone and uncertainty in estimates of heat flux in the saturated zone.
Dr. Neuman also cited a lack of reliable data about heat fluxes within the unsaturated zone and

about rock thermal conductivities at ambient water saturations. Several experts expressed a similar concern that the significant uncertainties in heat flux preclude definitive use of this method at present.

Saturations and Water Potentials. This method relies on estimates of saturations and water potentials taken from rock samples, which, in turn, provide information primarily on the matrix properties of the rock. Because the PTn is highly porous and highly permeable, most of the moisture flow through this layer is presumed to be in the matrix. Therefore, this method focuses on the flux through the PTn (as opposed to the TCw or TSw). The approach assumes a unit hydraulic gradient within the depth interval of interest, in which case the percolation flux is equal to the unsaturated hydraulic conductivity. The latter is estimated from the saturated hydraulic conductivity and parameters determined from fits of closed-form functions to the moisture-retention data for the media (e.g., Brooks-Corey unsaturated hydraulic conductivity function).

Drs. Neuman and Campbell used this method to estimate percolation flux and associated uncertainties. Both experts noted that the paucity of data on measured unsaturated hydraulic conductivities leads to considerable uncertainties in its application. Dr. Stephens noted that measurements of unsaturated hydraulic conductivities would greatly reduce uncertainties associated with using saturated hydraulic conductivities and various estimation models (e.g., van Genuchten properties) to predict the saturation profiles. He concluded that the models that estimate hydraulic conductivity may be inappropriate for the processes that operate here, where matric potentials are <1-2 bars. As a result, he did not rely on this approach to estimate percolation flux. Dr. Campbell was skeptical of the water potentials obtained from the borehole samples and from boreholes using psychrometers. He relied instead on measurements made with matric potential sensors, such as heat-dissipation probes and tensiometers. Dr. Neuman used available matrix properties and state variables for units within the PTn to obtain average porosities, saturations, and saturated hydraulic conductivities. Based on data recently obtained using a centrifuge on two samples (L. Flint, pers. comm. to S. Neuman), a relationship between hydraulic conductivity and saturation was developed. Dr. Neuman derived a geometric mean for relative hydraulic conductivity at certain saturations to arrive at an unsaturated hydraulic conductivity. Dr. Neuman considered the uncertainties in developing these values using limited data, as well as uncertainties represented by other constraints, to estimate a range of percolation fluxes.

Chloride Mass Balance. In this method, the chloride concentrations in precipitation and surface water are compared with those at depth (in perched water and the saturated zone). From these concentrations, and assuming a mixing of waters along the path, the percolation flux is estimated. Because of the assumed mixing, the method averages over a relatively large area and likely would include both the matrix and fracture components of flux.

The experts, in general, viewed the chloride mass balance method as supportive of other methods of estimating percolation but insufficient for obtaining independent estimates of percolation flux. For example, Drs. Gee and Neuman noted that, despite uncertainties related to assumptions about the initial concentrations of chloride entering the system at the ground surface, the flux values obtained using this method generally agree with other estimates. Dr. Pruess was skeptical of the assumption of mixing because the flow field is likely non-uniform and subject to variable amounts of mixing. Mr. Weeks noted that comparison of chloride concentrations in surface water with those in perched water suggests that water moves through the section without picking up much chloride, despite high chloride content in the PTn. This suggested to him that the system is recharged primarily by fracture flow. He concluded that the chloride mass balance observations do not provide a constraint on percolation flux.

Isotopic Evidence. Elevated concentrations of ^{36}Cl (expressed as $^{36}Cl/Cl$ ratios) and tritium, interpreted to be bomb-pulse isotopes related to nuclear testing in the 1950s and 1960s, have been identified in the Exploratory Studies Facility (ESF). The presence of these isotopes at potential repository depths may provide evidence for flow paths, velocities, and flux. To estimate percolation flux, flow and transport modeling has been conducted using a dual permeability model (A. Wolfsberg et al., presentation at UZFMEE Workshop 1), which suggests that fast flow through faults can account for the ^{36}Cl signature at average flux rates of about 5 mm/yr.

All of the experts concluded that the ^{36}Cl data from the ESF provide strong evidence of fast transport paths for water and solutes from the surface to the potential repository horizon and perhaps below. The data also suggest to several experts pathways for the fast transport and the maximum *velocities* of that transport. However, primarily because the data do not indicate the *volumes* of water, most of the experts were skeptical that the observations provide a basis for confidently estimating percolation flux. For example, Drs. Neuman and Gee used the observations to calculate the maximum flow velocities of the fast paths through the PTn and TSw. Several experts noted that the correlation between ^{36}Cl samples taken within and immediately adjacent to mapped faults (called "feature-based" samples) supports the notion that fast flow occurs within fault zones and associated fractures. Dr. Campbell interpreted the variations in ^{36}Cl concentrations as indicative of transit times. Many of the samples (feature-based and other) are at modern (<10,000 years old) water concentrations, indicating that the transit time is less than 10,000 years for much of the water in both the fractures and the matrix. The fact that many samples had less than bomb-pulse concentrations, but greater than modern concentrations, indicates to him that much of the water is older than 10,000 years. He noted that some of the water having concentrations greater than those of modern water could represent the mixing of bomb-pulse water with modern water, but it seemed to him unlikely that all of them could be the result of that mixing. Mr. Weeks also noted that the measured ^{36}Cl concentrations that are greater than previous background levels may represent a small amount of bomb-pulse water diluted by a much larger volume of older water. This dilution would account for the fact that high ^{36}Cl concentrations sometimes are found without correspondingly high tritium concentrations.

Two experts used the observations of ^{36}Cl to estimate percolation flux. Dr. Campbell endorsed the modeling by Wolfsberg et al. and estimated the associated uncertainty. Dr. Gee used the isotopic evidence as a secondary check on flux values assessed from other approaches. He noted the approximate spacing of ^{36}Cl spikes, related the spikes to faults, assumed a funneling or concentration within the faults, and calculated the concentrated flux within the faults. This net influx of water was then averaged over the area of the potential repository to arrive at an average flux of about 10 mm/yr.

Some of the experts concluded that the isotopic evidence indicates how the flux is divided between the fractures and the matrix, and their degree of interaction. This will be discussed further in Section 3.4.5, Partitioning of Flux Between Fractures and Matrix and Between the "Fast" and "Slow" Components.

RadiocarbonActivities. Mr. Weeks presented an approach (Workshop #3) for estimating percolation flux using radiocarbon activities of dissolved inorganic carbon. Radiocarbon is mobile in both the liquid and gas phases. Gaseous diffusion should tend to smooth and integrate the radiocarbon signal, averaging the radiocarbon activities of matrix and, presumably, both fast and slow components of fracture flow (assuming local equilibrium). Mr. Weeks concluded that gas samples from the TSw show decreasing radiocarbon activity with depth, which is matched by a percolation of a few millimeters per year. His estimates ranged from 1 to 10 mm/yr.

Perched Water/Water Balance. The experts regarded perched water as providing a constraint on percolation flux in two possible ways. As discussed by E. Kwicklis (in Rousseau et al., 1996), radiocarbon activities measured in water samples collected from some of the perched water bodies is used to estimate mean residence times. Assuming a mixing model, these residence times provide a constraint on percolation flux. The perched water bodies could also be used to develop a water balance between percolation flux, the volume of the perched water bodies, and the rate of drainage of the bodies.

Because of the paucity of data and inconsistencies in the data that exist, none of the experts placed a strong reliance on using perched water to estimate flux. Mr. Weeks said that the mean residence times of 4000-11,000 years developed by Kwicklis would result in fluxes of 0.01-0.02 mm/yr. (Mr. Weeks indicated that the low end of his PDF for percolation flux is supported by these results.) He noted, however, that the radiocarbon ages of water squeezed from cores beneath the perched water bodies are much younger (500-1000 yrs). As noted by other experts as well, these younger ages could be due to lateral flow from infiltration in Solitario Canyon. To Mr. Weeks this raises doubts about the validity of using flux estimates from the mixing model.

Although several experts noted the potential benefit of developing a perched water balance, they concluded that there presently are few data on which to base this work. For example, Drs. Stephens, Campbell, and Mercer indicated their belief that a perched water balance is important and potentially could be embedded in the site-scale model. As such, for certain percolation fluxes, the model would have to be consistent with data on rock properties as well the location and volume of known perched water. (Note that, as part of the feedback to the experts, sensitivity studies were conducted using the UZ site-scale model to examine the nature of perching as a function of a range of percolation fluxes.) Dr. Stephens further recommended that a regional groundwater water balance be developed to assist in estimating percolation fluxes.

Fracture Coatings. This method for estimating percolation flux is based on the rate of calcite deposition in lithophysal cavities and fractures as a result of percolating water. Mr. Weeks performed a calculation based on outgassing of CO_2 in response to increasing temperature with depth, assuming that the water is saturated with calcite. Assuming a temperature gradient of 0.025 degrees C/m and a recharge period of 10 Ma, he obtained a percolation flux of 2 mm/yr. He noted that it seems unlikely that calcite would precipitate from rapid pulsed recharge to the extent needed to get ^{36}Cl to the potential repository horizon. Because this method likely would not record the flux related to the fast-flow component, Mr. Weeks and Dr. Pruess noted that it probably provides a lower bound to flux estimates.

Percolation Flux Estimates: Temporal and Spatial Averages

Each expert provided an assessment of percolation flux at the potential repository horizon, averaged temporally over sufficiently long periods to incorporate major percolation events (if any) and averaged spatially over the Yucca Mountain block (Table 3-1). Four experts specified that their assessed average net infiltration rate should also be considered their percolation flux rate. They predicted a low potential for significant amounts of lateral flow, which would divert water laterally above the repository (thus lowering the flux at the repository), or lateral flow from Solitario Canyon (thus increasing flux at the repository). The remaining three experts provided a PDF that defined their assessment of percolation flux and associated uncertainties.

Dr. Campbell provided separate estimates of flux for three approaches (net infiltration, ^{36}Cl, and flux through the PTn). He also provided relative weights that express his degree of confidence in the approaches to estimating percolation flux at Yucca Mountain, given the strengths and weaknesses of the methods as well as the data available to exercise the methods. His low-weighted methods were used as support for, or a check on, the estimates based on his three approaches. His three PDFs are combined into a single PDF using the relative weights provided by Dr. Campbell.

Dr. Neuman and Mr. Weeks developed their estimates of percolation flux using a variety of methods to constrain—to various degrees—different parts of their probability distributions. For example, the lower flux values in Mr. Weeks' distribution are based on radiocarbon activities and mixing in the perched water; the central values are based on radiocarbon activities with depth; and the high values are based on analysis of the temperature data. Dr. Neuman's estimate of the maximum percolation flux rate (as high as 50 mm/yr) is based on measured moisture fluxes into the ESF during periods when it was not ventilated. This large estimate has a considerable effect on Dr. Neuman's mean estimate (means are particularly sensitive to outliers). His mean estimate of 21.1 mm/yr is considerably higher than the mean values of others on the panel. Dr. Neuman notes that his best (maximum likelihood) estimate of 17 mm/yr is a more meaningful estimate than the mean value.

Figure 3-2a summarizes the experts' estimates of percolation flux; the means and percentiles of the probability distributions are given in Table 3-2. It should be noted that, in most cases, the experts developed probability density functions based on assessing percentiles of the distribution (e.g., the 5th, 10th, 50th, 90th, and 95th percentiles). Dr. Neuman specified that the PDF be lognormally distributed, and he provided percentiles of the distribution. Dr. Pruess specified particular intervals over which a uniform distribution was assumed. For the other experts, smooth spline fits were made to their assessed percentiles. In all cases, the mean values were calculated from the distribution rather than being elicited directly from the experts.

Figure 3-2b shows the combined percolation flux estimates of all seven experts. The seven individual assessments were combined using equal weights. As discussed in Section 2, an equal-weights aggregation is justified by the methodology followed in the study. Shown on

Figure 3-2b are the probability distribution and cumulative probability distribution for the combined assessments, along with the individual mean and median estimates. Shown in the bottom panel of the figure are the mean values, 5th, and 95th percentiles for each expert.

Across the panel of experts, the combined estimate of average percolation flux at the potential repository horizon has a mean value of 10.3 mm/yr, a median (50th percentile) of 7.2 mm/yr, and a 5th- to 95th-range of 1.1 to 30 mm/yr. We believe that this probability distribution represents a reasonable estimate of percolation flux—and perceived uncertainties—at for the potential repository horizon, given our present level of knowledge. This spatial and temporal average has potential applicability to both the TSPA and the UZ site-scale modeling. The TSPA uses estimates of percolation flux—along with estimates of seepage into the drifts—to evaluate the flux entering the drifts and potentially contributing to degradation of the waste packages. The probability distributions developed by the UZFMEE panel provides a quantitative estimate of uncertainty that can be incorporated into the TSPA. The percolation flux estimates can also be used in the UZ site-scale model. Because all of the experts concluded that average percolation flux is essentially equivalent to net infiltration at shallow depths (and the flow is essentially vertical), the assessed fluxes can be used as input to the UZ site-scale model to evaluate the impact of fluxes on the unsaturated flow system. By having a quantitative estimate of the uncertainties in flux, the modeling results can provide realistic representations of the impacts of various amounts of net infiltration.

Percolation Flux: Spatial Issues

The percolation flux estimates discussed above are temporal and spatial averages. The temporal behavior of the unsaturated zone system has been discussed previously. Each expert also assessed the manner in which the percolation flux at the potential repository horizon would be distributed spatially. Because there are no direct measurements of flux at this level, their judgments derive from a consideration of the degree to which the various approaches to calculating percolation flux provide information on spatial variability. Either because of the inherent nature of the method, which may rely on a spatially averaged mechanism such as temperature techniques or radiocarbon gas, or because of inadequate data density, net infiltration was cited most commonly as a possible vehicle for assessing the spatial distribution of percolation flux at depth.

In general, most experts believed that the spatial pattern of flux at the potential repository horizon will resemble the spatial pattern of net infiltration (either that developed by A. Flint or a revised version that accommodates lateral flow into washes). However, several experts concluded that diffusion processes, local lateral diversion, and medium heterogeneities will lead to a more subdued or smoother pattern than net infiltration. An example of such a pattern cited by the experts is the flux cross-section across Yucca Mountain that S. Finsterle presented at UZFMEE Workshop #2. This cross-section compared the variation in net infiltration from Dr. Flint's map with the percolation flux based on temperature profile modeling derived from UZ site-scale efforts. In this case, the locations of high infiltration (marked by high-frequency spikes) generally are underlain by locations of high percolation flux, but without the high-frequency variations.

Drs. Pruess and Neuman were not convinced that distribution of the percolation flux will resemble the net infiltration map, believing that there are mechanisms that could increase as well as decrease spatial variability of percolation at depth. Dr. Neuman did not expect the percolation flux at depth to reflect Dr. Flint's map, because he considered the Flint map to be unreliable and because of lateral redistribution. He believed that the vertical and lateral distribution of percolation flux could be better defined based on a much more detailed set of data describing saturations, pressure heads, hydraulic conductivities at ambient saturations, and PTn thicknesses. Dr. Pruess noted that washes may localize infiltration, and locally high darcy velocities may persist to depth; in other cases they may be redistributed at depth. He stated that it is also possible that heterogeneous structures may funnel spatially distributed infiltration into localized, preferential fast-flow paths, leading to locally high percolation fluxes.

3.4.5 Partitioning of Flux between Fractures and Matrix and between "Fast" and "Slow" Components

Percolation flux is expressed as the volumetric rate of flow per unit area. It is important to the performance assessment to understand how much of that volume is carried in the rock matrix and how much in the fractures of the TSw. Further, it is important to have an understanding of the relative contribution to the total flux made by a fast- and a slow-flow component. We distinguish here between estimates of flow *velocity* and volumetric *flux* rates; we are interested in the latter.

The experts first divided the total percolation flux into matrix and fracture components, and then considered the issue of fast or slow paths. There was general agreement across the panel that most of the total flux in the TSw occurs within the fractures. In most cases, the experts limited the matrix flow within the TSw based on the matrix hydraulic properties that have been measured. The relatively low matrix permeabilties led most experts to conclude that the matrix fluxes are approximately 0.3 to 3 mm/yr (the range across the panel; the average value was about 1.5 mm/yr). The remainder of the flux was judged to occur within the fractures of the TSw. Given the flux estimates developed by the experts, the relative contribution to the percolation flux from the fractures and the matrix is approximately 90% and 10%, respectively. Dr. Stephens noted that this partitioning is quite uncertain and, as shown by the UZ site-scale modeling, the relative components of the flux are a function of the total percolation flux.

Next to be considered were identifying the components of the flux that occur as fast flow, as represented by the environmental isotopic evidence, and as slow flow. As the names imply, "fast" and "slow" refer to the relative flow velocities, but say nothing about flux volumes. Generally, the fast-flow component was postulated to be a component of the flow occurring within the fractures (which includes faults), because of the evidence for low matrix permeabilities within the TSw. The experts generally agreed that the fast-flow component likely represents a relatively small part of the total flux carried by the fractures. For example, Dr. Campbell postulated that although the fractures probably carry 90% of the total flux, less than 1% of the total flux occurs as fast flow, based on simulations conducted by LBNL and LANL. Dr. Stephens also concluded that the fast-flow component likely is a minor component of the total flux. Dr. Neuman arrived at a similar conclusion. Mr. Weeks was unsure of the volumes that occur as the fast-flow component.

The experts also considered the area over which the fast-flow component occurs. Mr. Weeks believed that the ^{36}Cl data suggest that fracture flow within the TSw is ubiquitous. He noted that the presence of many fractures accommodating the flux, as opposed to a few carrying large volumes, is consistent with the lack of observed seepage into the ESF. However, he also postulated that relatively few fractures are accommodating the flux, perhaps 1% to 10%; the fast-flow component is a subset of this fracture component; and, therefore, the fast-flow component would occupy less than 1% to 10% of the area. Dr. Neuman arrived at a similar conclusion, estimating the cumulative area of pores and fracture voids associated with fast paths as between 0.03% and 2% of the total area of the ESF in plan view.. Using a different approach, Dr. Gee noted that fault mapping at the surface shows that roughly 5% of the area contains flow-contributing fractures, some of which will have locally high fluxes (calculated in the range of 150-200 mm/yr based on ^{36}Cl). Assuming 5% of the area and assuming that the rest of the flux is in the matrix at about 2-3 mm/yr, flux averages about 10 mm/yr across the area. This suggests to Dr. Gee that only a small percentage of the total area (5% or less) contains the fast-flow paths.

3.4.6 Seepage into Drifts

Also included in the assessment is the potential for moisture to seep as advective flow into the drifts, assuming drift geometries similar to those of the ESF and assuming ambient conditions. There was general agreement that a capillary barrier will exist around the drifts that most likely will divert moisture traveling in the matrix around the openings. Judgments about the potential for seepage occurring within the fractures varied somewhat across the panel. Drs. Mercer and Pruess said that moisture in fractures could overcome the negative matric potential, but were uncertain about the number or extent of these seeps. Based on moisture tensions measured and/or interpreted in the ESF, Dr. Gee speculated that seepage in an unventilated drift is unlikely, although testing of a sealed drift would be required to resolve the issue. Dr. Stephens and Mr. Weeks concluded that only a small percentage (<1% to 10%) of the total area and total number of fractures would carry sufficient flux to cause seeps. Likewise, Dr. Neuman concluded that 0.03% to 2% of the total area of the ESF carries the fast flow, and, because full saturation is needed for seepage, only some of these fast paths will produce seepage into the drifts. Several experts noted that a modest amount of ventilation of the drifts would be sufficient to preclude significant seepage.

It generally was concluded that, because of the ventilation system operating within the ESF, the observations of dry conditions along the walls of the ESF provide only limited information about the moisture conditions that will prevail without ventilation. The dry conditions were believed generally to support the absence of large, concentrated volumes of flux. However, as noted by Mr. Weeks, if localized large-volume flow occurs as a transient phenomena, our period of observation of the ESF may be too short to have observed a pulse of moisture capable of causing seepage into the ESF. The experts were unable to provide criteria that could be used to identify the future locations of seeps. Mr. Weeks and Dr. Neuman suggested that the locations should be modeled as random.

3.4.7 Modeling Issues and Recommendations for Future Work to Reduce Uncertainties

As part of the elicitation, the experts were asked for their judgments about the applicability of various conceptual models for characterizing the unsaturated flow system (e.g., equivalent continuum versus dual permeability models, transient pulses versus steady-state, 1-d versus 3-d models of net infiltration). The purpose was to obtain perspectives that the UZ site-scale modelers could consider in their continuing efforts. Likewise, the experts provided their perspectives on high-priority future data collection or modeling efforts that could reduce significantly the uncertainties related to the UZ flow system. These perspectives are summarized in Table 3-1 and are provided in the elicitation summaries for each expert (Appendix D).

UNSATURATED FLOW ZONE MODEL (UZFM) EXPERT ELICITATION PROJECT
SUMMARY OF KEY ISSUES

	GAYLON CAMPBELL	GLENDON GEE	JAMES MERCER	SHLOMO NEUMAN	KARSTEN PRUESS	DANIEL STEPHENS	EDWIN WEEKS
Net Infiltration: Temporal Issues	•Major storm events with intervals of ~10 yrs •Essentially no infiltration between these events	•Major storm events with intervals of about one year. •Essentially no infiltration between these events	•Episodic storm events with average intervals of about 5 years give rise to most (~80% of infiltration)	•Major storm events lead to infiltration; recurrence interval tied to precipitation record	•Infiltration occurs from few isolated storm events, 1-2 per year •Infiltration near zero or negative between these events	•Infiltration occurs during short bursts of severe storm events that have recurrence intervals of 20 yrs •Between these events, infiltration occurs, but in low amounts	•Storm event or sequence every few years leads to infiltration event; intervening time essentially no net infiltration •More severe events with longer recurrence intervals
Net Infiltration: Spatial Issues	•Agree with basic Flint map and relative importance of various factors •Horse-tailing faults important	•Flint map generally OK, but expect more infiltration at upper reaches of washes •Funneling of water into faults and fractures (<5% of surface area) is important process	•At lower net infiltration values, Flint map is OK •At higher values, would expect higher values in washes and lower values on ridge-tops •Lateral flow within alluvium into fractures is important	•Expected to be heterogeneous, but Flint map is counter-intuitive; highs expected in washes, lows on ridge tops •Lateral flow at bedrock-alluvium contact into fractures/faults/high-permeability paths	•May be nonlinear relationship between amount of infiltration and spatial distribution	•Flint infiltration map is generally OK, but would expect moderate infiltration amounts on ridgetops and high rates in washes •Underflow at alluvium-bedrock surface is important process	•Net infiltration map would be smoother than Flint's, with lower highs on the ridges and higher rates in the washes •Flow at alluvium-bedrock contact into open fractures is important
Net Infiltration: Temporal and Spatial Average *(Note: mean values are calculated)*	Mean: 7.4 mm/yr Median: 7 mm/yr 5th: 1 mm/yr 95th: 15 mm/yr Averaged over 50-1000 yr	Mean: 12.7 mm/yr Median: 12.7 mm/yr 5th: 7 mm/yr 95th: 18 mm/yr Averaged over 100 yr	Mean: 8.4 mm/yr Median: 7.5 mm/yr 5th: 2 mm/yr 95th: 20 mm/yr Averaged over ~100 yr	Assessed percolation flux, and thus net infiltration, on the basis of deeper subsurface data	Mean: 11.3 mm/yr Median: 7 mm/yr 5th: 0.5 mm/yr 95th: 40 mm/yr Averaged over several major storm events	Mean: 3.9 mm/y Median: 3.1 mm/y 5th: 0.7 mm/y 95th: 10 mm/y Averaged over 100 yr	Assessed percolation flux, and thus net infiltration, on the basis of deeper subsurface data
Lateral Diversion at Top of PTn or Other Interfaces?	•Yes, but no more than few tens of meters at bottom of PTn and top of TSw	•Likely, but not on a regional-scale	•Yes, but not much lateral diversion because of faults and irregularities	•Expect some degree of lateral flow and redistribution at top of PTn and top of TSw; not major •No evidence for or against lateral flow, so assume vertical	• Yes, but will occur over limited scales	•Yes, some degree of diversion is likely, although faults and fractures will preclude regional-scale diversion •Lateral flow from Solitario Canyon may be important contribution to perched water bodies	•Yes, but significant diversion is unlikely

UNSATURATED FLOW ZONE MODEL (UZFM) EXPERT ELICITATION PROJECT
SUMMARY OF KEY ISSUES

	GAYLON CAMPBELL	GLENDON GEE	JAMES MERCER	SHLOMO NEUMAN	KARSTEN PRUESS	DANIEL STEPHENS	EDWIN WEEKS
Temporal Behavior of UZ Flow System	•Episodic infiltration events; dampening of pulsed flow at PTn; essentially steady-state below PTn (except fast-flow component, which is transient)	•Episodic infiltration events lead to pulse of water that can reach depth quickly, as evidenced by ^{36}Cl	•Transient pulse related to infiltration is significantly dampened as it moves through system; fast-flow component remains transient	•Transient pulse related to episodic infiltration events dampened in PTn •Fast flow component is transient and slightly dampened	•Episodic pulses can flow through system •Pulses dampened as they pass through PTn and other layers with different hydraulic properties •System may not be steady state	•Fast-flow component is yrs to tens of yrs; fracture component travel times are – thousands of yrs; matrix component – hundreds of thousands of yrs	•Transient pulse related to infiltration eventsmoves through system with little matrix interaction •At high percolation fluxes, a significant fraction may occur in fractures as pulses following extreme precipitation events
Method(s) Used to Estimate Percolation Flux at Repository Horizon	Relative weights: Net Infiltration/surface water balance (0.3) ^{36}Cl (0.3) Flux through PTn (0.2) Convection heat flux (0.05) Radiocarbon decay (0.05) Mineral coatings (0.05) Perched water (0.05)	•Net infiltration, checked with water potentials and isotopic evidence	•Net infiltration, checked with chloride mass balance, temperature gradients, and perched water	•Saturations and water potentials within PTn, supplemented by isotopic evidence and ESF moisture balance	•Net infiltration	•Net infiltration	•Temperature gradients •Radiocarbon gas •Perched water
Percolation Flux Estimate: Temporal and Spatial Average *(Note: mean values are calculated)*	Mean: 5.3 mm/yr Median: 4 mm/yr 5th: 1 mm/yr 95th: 14 mm/yr Based on net infiltration, ^{36}Cl, and flux through PTn	•Same spatial and temporal average as net infiltration	•Same spatial and temporal average as net infiltration	Mean: 21.1 mm/y Median: 17 mm/y 5th: 6 mm/y 95th: 50 mm/y	•Same spatial and temporal average as net infiltration	•Same spatial and temporal average as net infiltration •Lateral input from Solitario Canyon to TSw is probably minor	Mean: 7.4 mm/yr Median: 6 mm/yr 5th: 1 mm/yr 95th: 22 mm/yr
Percolation Flux: Spatial Issues	•Generally same as net infiltration map, but smoother •As predicted by LBNL model results	•Generally same as net infiltration map	•More uniform distribution than infiltration, because of diffusion into TSw fracture network (which contains ubiquitous fractures)	•Should generally correlate with infiltration map, but local lateral flow, medium heterogeneities and fast-flow channels will modify	•Not known; may be similar to net infiltration map; or heterogeneities may develop new variability	•Generally same as infiltration map (highs and lows generally the same locations) •Superimposed are local highs at faults and fractures	•Map expected to be subdued replica of net infiltration map
Components of Flux in TSw: Fractures versus Matrix	Fractures (95% of flux) Matrix (5%)	•90% of flux in faults/fractures •2-3 mm/yr occurs in matrix	•Most (~90%) of flux is in fracture network of TSw	•Maximum flux in matrix is 1.5 mm/yr; therefore, at 17 mm/yr total flux, ratio of matrix to fracture flux is 10% to 90%.	•Matrix conductivity is about 0.3 mm/yr; rest is in in fractures •Slow component in both fractures and matrix	•Partitioning is uncertain (10% to 70% in fractures based on UZ model, depending on total flux); possibly most of total flux is in matrix	•Matrix can carry 1 mm/yr, rest is in fractures •Small percentage (1% - 10%) of total fractures are accommodating flux

UNSATURATED FLOW ZONE MODEL (UZFM) EXPERT ELICITATION PROJECT
SUMMARY OF KEY ISSUES

	GAYLON CAMPBELL	GLENDON GEE	JAMES MERCER	SHLOMO NEUMAN	KARSTEN PRUESS	DANIEL STEPHENS	EDWIN WEEKS
Components of Flux in TSw: Fast Flow versus Total Flux	Fast flow component is <1% of total flux	~5% of area is faults and fractures +Some fractures accommodate fast flow (~150-200 mm/yr)	+Not sure of volume that fast-flow component represents; would trust results of LBNL model	+Fast flow component is small part of total flux +Area of ESF with fast paths is 0.03-2% of total area (19-1200 m^2 out of 64,000 m^2 of tunnel)	+^{36}Cl is localized, thus only a small number of fractures could be carrying fast-flow component	+Fast-flow component is small % of total flux	+Fractures and ^{36}Cl are ubiquitous, suggesting fast-flow occurs over many fractures +Not sure of flux represented by fast flow component
Seepage into the Drifts	+Not sure under ambient conditions +Avoid by providing a small amount of ventilation	+Seepage is very unlikely based on available data, consistent with absence of seeps in ESF, even in faults	+Expect seepage into drifts due to film flow along wall of drift; water-filled fractures are believed to be ubiquitous, as evidenced by ^{36}Cl found everywhere	+Full saturation needed for seeps, therefore percent of area with seeps will likely be less than area with fast paths (0.03% - 2%, see above) +Location unpredictable	+Slight negative matric potential should stop matrix component; fracture component will enter drift	+Will occur only at fractures, not matrix +A very small part of total area (<1%) will occupy seeps +Location may be predictable	+Matrix component will go around drifts +Most of fracture component can enter drift +Small percentage of fractures (1%-10%)carry flux; area of drifts seeing seeps will be less than 1% - 10% +location unpredictable
Modeling Issues	+1-d finite difference model for net infiltration is OK +Dual-K needed through PTn; ECM probably OK below PTn +Fast paths need to be represented +Add faults and test sensitivity +Upscaling should reasonably match measured matrix properties	1-d infiltration modeling doesn't adequately address runoff +Need mass balance model for infiltration +Neutron probe data do not capture episodic nature of storm events	+Transient component of flow should be included +Dual-K above PTn, ECM probably OK below, as long as fast-flow component included +Fast-flow component in PTn probably requires faults modeled in this unit +Expect little fracture-matrix interaction in TSw	+1-d modeling is not capable of incorporating lateral flow at bedrock-alluvium contact +Uncertainty and error analyses of heat flux estimates and measured temperature profiles should be conducted	+A WEEPS-type model embedded in a more complex model may be way to portray fast-flow component +Continuum description of flow assumes volume-averaging and may miss much of localized flow volume +Role of faults is not understood; may not be needed in PTn +Spatial stability of flow paths through time is uncertain	+No confidence in Bucket model for infiltration; Maxey-Eakin not satisfactory for points within a watershed +Perched water balance and overall water balance including water table fluctuations should be modeled +TOUGH2 modeling should predict key observations such as the wet spot in ESF at station 75+00	+Transient pulse through PTn and deeper in section with little matrix interaction +Episodic pulse, not steady state +Predictability of which fractures in TSw will carry flow should be modeled as random

UNSATURATED FLOW ZONE MODEL (UZFM) EXPERT ELICITATION PROJECT
SUMMARY OF KEY ISSUES

	GAYLON CAMPBELL	GLENDON GEE	JAMES MERCER	SHLOMO NEUMAN	KARSTEN PRUESS	DANIEL STEPHENS	EDWIN WEEKS
Additional Data Collection/Future Work to Reduce Uncertainties	•Water potential, water content, hydraulic properties measurements in situ in ESF •Unsaturated conductivity measurements should be high priority •Surface water balance info: plant uptake, rock cover on slopes, snow, washes, rock-alluvium contact	•Mass balance using drip line source above ESF and pan •Inject water above sealed-off room of ESF to test for seepage •Perform non-linear fit to temperature data to see if profiles show curvature	•Run UZ model to examine the effect of higher infiltrations •Evaluate effect of more infiltration in washes	•Extract from pumping test data in perched water bodies, information about the drainable porosity of the fracture system •Develop a detailed database of saturations, pressure, hydraulic conductivities at ambient saturations, and PTn thicknesses to obtain vertical and lateral resolution of percolation flux in PTn	•Monitoring and data collection related to net infiltration should continue	•Thoroughly study and instrument small drainage basin above repository, including rain gauges, mapping of fractures, nests of piezometers, observation of bedrock-alluvium contact, buried pan lysimeters, and TDR probes •More unsaturated hydraulic conductivity measurements •More accurate measurements of water potentials in PTn using tensiometers and heat-dissipation probes •Infiltration study of Solitario Canyon and development of hydrographs of perched water	•Large-scale experiments in the ESF: install plastic sheets on roof and walls and monitor water inflow •Obtain temperature logs with measurements at close intervals

TABLE 3-2

SUMMARY OF ESTIMATES OF PERCOLATION FLUX

	PERCOLATION FLUX (MM/YR)*					
EXPERT	MEAN	5TH	15TH	50TH	85TH	95TH
G. Campbell	5.3	1.1	2.0	3.8	9.4	13.6
G. Gee	13.2	3.0	5.5	**12**	21.7	27.5
J. Mercer	8.4	**2**	4.4	7.5	10.8	**20**
S. Neuman	21.1	**6**	9.0	17.3	34.2	**50**
K. Pruess	11.3	0.5	1.8	7.0	25.0	40.0
D. Stephens	3.9	0.7	1.3	3.1	6.3	**10**
E. Weeks	7.4	1.0	2.3	6.1	11.7	21.7
Aggregate	10.3	1.0	2.3	7.2	19.3	30.0

* Numbers in bold were assessed directly by the experts. The other numbers were interpolated from their assessed distributions.

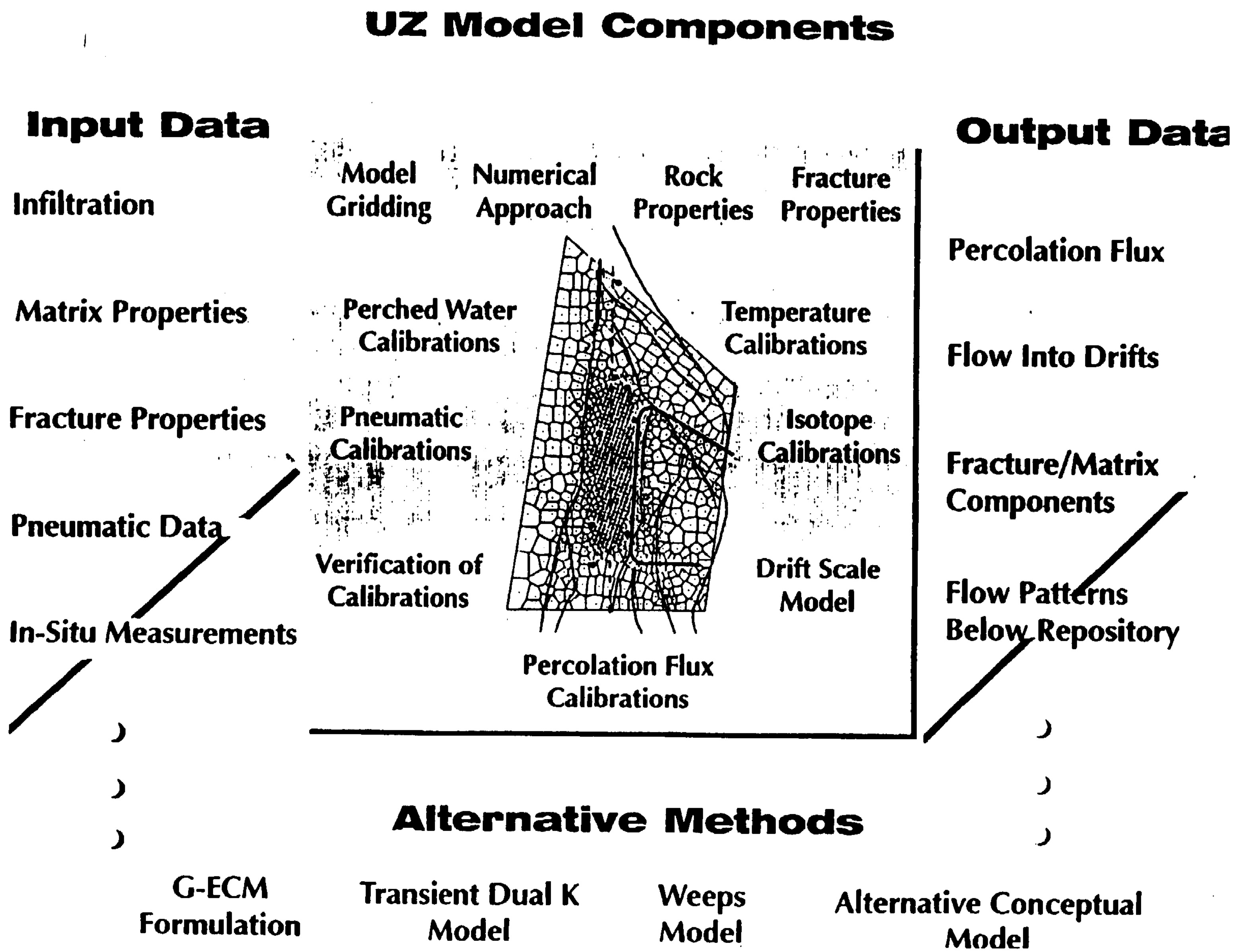

Figure 3-1 Components `the UZ Site-Scale Model

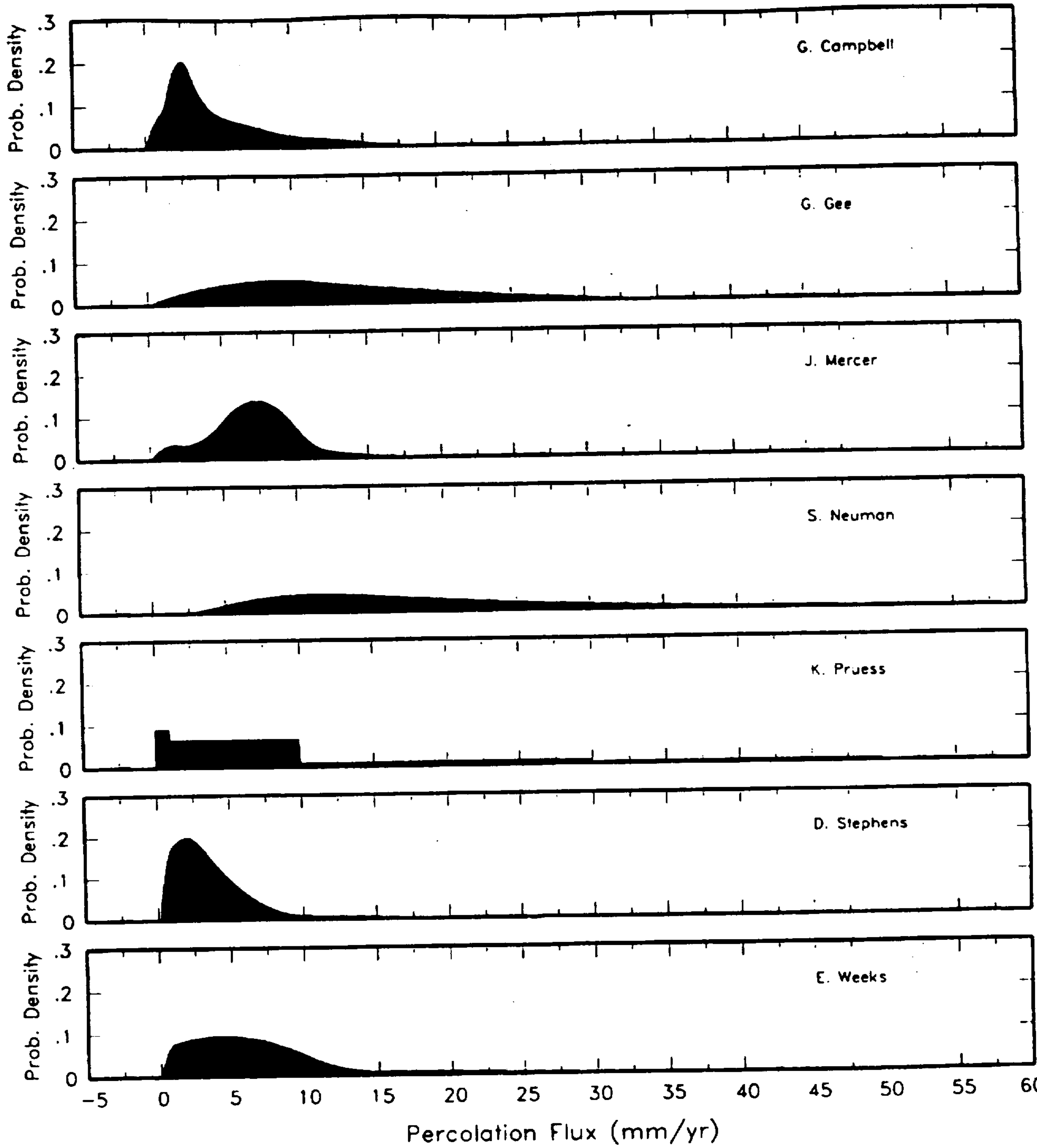

Figure 3-2a Probability density distributions for percolation flux at the repository level defined by the seven experts.

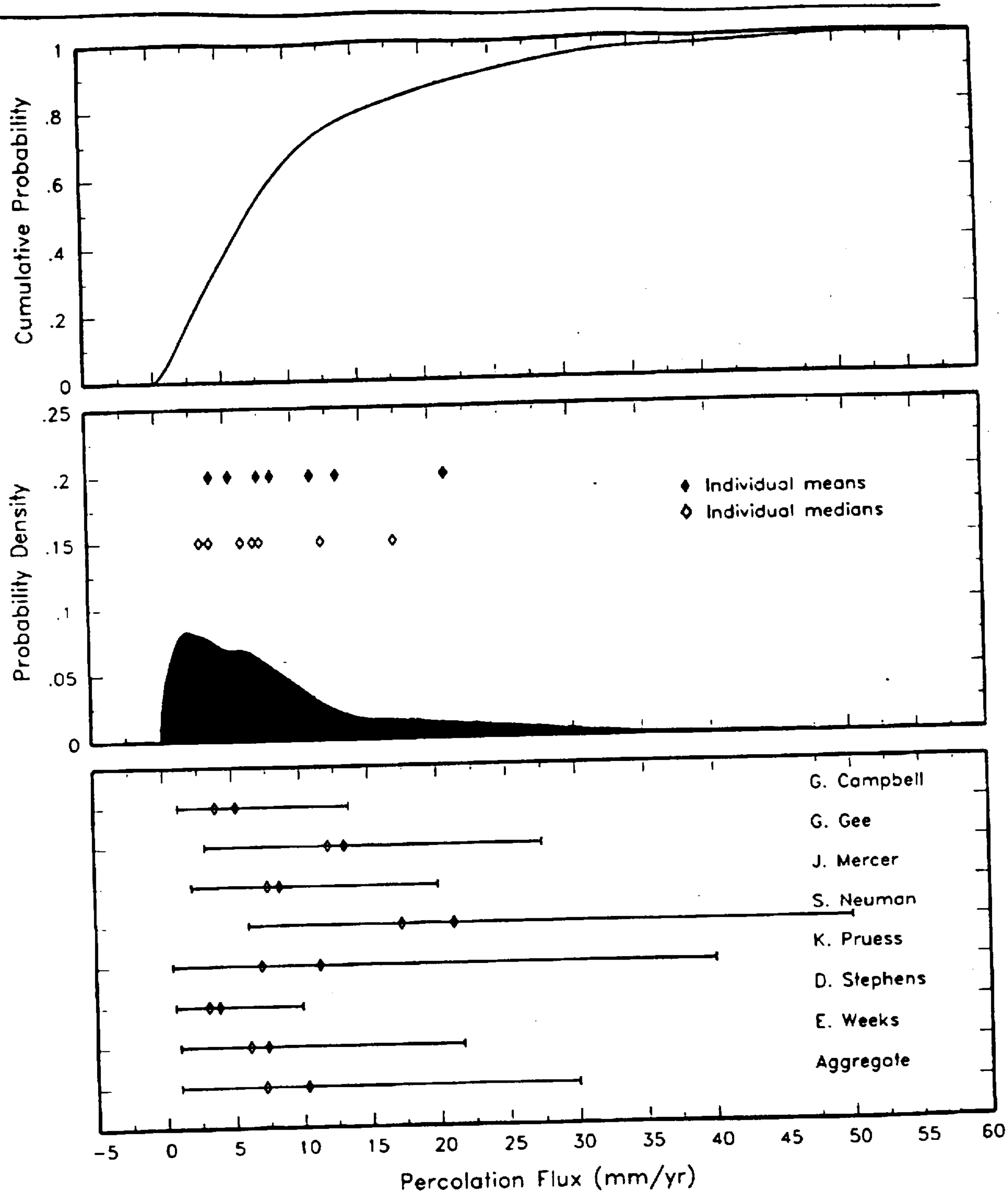

Figure 3-2b Summary of the UZFM elicitation results. Top plot: aggregate cumulative probability distribution for percolation flux across the seven expert panel members. Middle plot: corresponding probability density function for the aggregate probability distribution. Also shown are the mean and median values for the individual expert's distributions. Bottom plot: median, mean, and 5^{th} to 95^{th} percentile range for the seven individual expert's distributions and the aggregate distribution.

4.0 SUMMARY AND CONCLUSIONS

The UZFMEE study is intended to complement the UZ site-scale model while providing assessments that are useful to the total system performance assessment. The UZFMEE experts were given detailed summarizes of the progress being made in various components of the UZ model, as well as calibration issues, available data, and models. The focus of the UZFMEE project was on evaluating the uncertainties associated with the various models, parameters, and components of the UZ site-scale model, as well as providing an independent perspective on the approaches being taken in the UZ model. As such the UZFMEE project is a logical step in the unsaturated zone program for the Yucca Mountain project.

A key mechanism used in the UZFMEE to quantify uncertainties is multiple expert judgments. The procedures for and approaches to eliciting expert judgments, developed by conducting many studies, have been formalized in guidance documents followed in the UZFMEE project. DOE recently developed guidance for the formal use of expert judgment by the Yucca Mountain Project (DOE, 1995), and the Nuclear Regulatory Commission staff has issued a Branch Technical Position (BTP) on use of expert elicitation in the high-level waste program (Kotra et al., 1996). Comprehensive guidance on eliciting expert judgment for seismic hazards recently was set forth in a study sponsored by DOE, the Electric Power Research Institute, and the Nuclear Regulatory Commission (SSHAC, 1995).

The principal steps followed in the UZFMEE project were:

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

The UZFMEE panel addressed a variety of technical issues in characterizing the unsaturated flow system at Yucca Mountain. These issues included those important to modeling the flow system (e.g., spatial distribution of infiltration, temporal pulses of infiltration, lateral flow), as well as those important to the total system performance assessment (e.g., percolation flux at the potential repository horizon, partition of flow between fractures and matrix, seepage into the drifts). In addition, the experts were asked to provide their perspectives on additional data or activities that could help reduce the uncertainties in the UZ site-scale model. The expert's assessments are given in their elicitation summaries (Appendix D) and are summarized in Section 3.

This study was designed to assess the characteristics of the unsaturated zone under *ambient* conditions. Such conditions likely would be most representative of the period following the thermal pulse (first thousand years or so) associated with the emplacement of waste packages. "Ambient" conditions means under a climatic regime that is comparable to that which now exists (the same average precipitation, seasonal distribution of precipitation, solar radiation, and vegetation).

Each of the key issues addressed by the experts is shown in Table 3-1 and discussed briefly below.

Net Infiltration

Net infiltration is defined as water that penetrates to sufficient depth that it is not removed by evapotranspiration processes. All of the experts concluded that net infiltration is the fundamental control on the overall water balance for the UZ system. Likewise, they concluded that, over Yucca Mountain and throughout periods of hundreds to thousands of years, net infiltration varies both spatially and temporally.

Net Infiltration: Temporal Issues

The general conclusion drawn by the experts is that net infiltration is an episodic process linked to major storm events or sequences. The duration of these storm events or sequences ranges from a few days to a few weeks and may be related to snowmelt events. The average frequency of these episodic storm events is judged by the panel to range from annual to approximately once every 20 years. It generally was concluded that between these episodic infiltration events, there is little to no net infiltration.

Net Infiltration: Spatial Issues

The UZFMEE experts generally agreed that the spatial distribution of net infiltration in the Yucca Mountain region is highly variable. Also, the spatial variability generally accords with that given by Flint et al. (1996). However, several experts concluded that this latest map may not account for the potential for significantly higher infiltration beneath washes having relatively thin alluvial cover (less than 1-2 m). The process for this infiltration is postulated to be runoff from the ridge-tops and steep side-slopes toward and into the upper washes, lateral flow within the alluvium and along the bedrock-alluvium contact, and infiltration along faults and fractures in the bedrock. Several experts concluded that this process would modify the Flint et al. (1996) map to show less infiltration along the ridge-tops and more infiltration within the washes.

Net Infiltration: Temporal and Spatial Average

To provide a measure of the uncertainties associated with estimates of net infiltration, the experts were asked to provide their judgments regarding the rates of net infiltration occurring at Yucca Mountain. The estimates are temporal averages (averaged over periods long enough to have captured several episodic infiltration events—generally longer than 50 to 100 years) and spatial averages (averaged over the Yucca Mountain block). The probability distribution functions (PDFs) for this spatial and temporal average are given in Table 3-1 for the five experts who provided an interpretation.

In general, the PDFs for net infiltration are quite broad for each expert and the panel as a whole, reflecting the perceived high degree of present uncertainty regarding infiltration processes, pertinent data, and models. For the five experts who provided an assessment of net infiltration, average values range from 3.9 to 11.3 mm/yr, with an aggregate mean across the five experts of 8.7 mm/yr. Fifth to 95th percentiles range from tenths of millimeters per year to several tens of millimeters per year.

Lateral Diversion

Given certain amounts of net infiltration and its spatial variability, the experts were asked to address the degree to which flow through the hydrostratigraphic units down to the potential repository horizon within the TSw might include a lateral component. In general, all of the experts concluded that a contrast in hydraulic properties across the lithologic interfaces likely would lead to lateral flow, particularly across the TCw-PTn contact. However, there was general consensus across the panel that the nature of the TCw-PTn interface, which appears to be extensively faulted along a series of small faults, means that moisture flowing laterally along the interface will be captured and will flow vertically down the faults. Thus, lateral diversion is suggested to occur over scales of a few meters to tens of meters, but not regionally.

Temporal Behavior of UZ Flow System

The experts agreed that the temporal behavior of net infiltration was characterized by episodic events associated with major storm events or sequences. A related issue is the degree to which the temporal "pulse" associated with infiltration is attenuated as moisture flows through the unsaturated zone. A knowledge of this temporal behavior would assist a decision on whether to use steady-state or transient temporal models for modeling the flow system. Most of the experts concluded that the available data and modeling suggest that both a transient pulse and attenuation occur as water travels through the UZ system. Most of the flux is attenuated through the system, although the fast component may maintain a transient pulse.

Percolation Flux at the Potential Repository Horizon

The experts considered a variety of approaches to estimating percolation flux at the potential repository horizon, including:

- net infiltration
- temperature gradients
- saturations and water potentials
- chloride mass balance
- isotopic evidence
- radiocarbon activities
- perched water/water balance
- fracture coatings.

Percolation Flux Estimates: Temporal and Spatial Averages

Each expert estimated percolation flux at the potential repository horizon, averaged temporally over sufficiently long periods to incorporate extreme percolation events (if any) and averaged spatially over the Yucca Mountain block (Table 3-1). Across the UZFMEE panel, the combined estimate of average percolation flux at the potential repository horizon has a mean value of 10.3 mm/yr, a median of 7.2 mm/yr, and a 5th to 95th range of 1.1 to 30 mm/yr. We believe that this probability distribution represents a reasonable estimate of percolation flux at the potential repository horizon, given our present level of knowledge.

Percolation Flux: Spatial Issues

The estimates of percolation flux discussed above are temporal and spatial averages. Each expert also provided his assessment of the manner in which the percolation flux at the potential repository horizon would be distributed spatially. Because there are no direct measurements of flux at this level, the experts' judgments come from a consideration of the degree to which the various estimation methods provide information on spatial variability.

Partitioning of Total Flux between Fractures and Matrix and between Fast-Flow and Total Flux

Most of the total percolation flux is judged to occur within the fractures of the TSw. In most cases, the experts constrained the matrix flow within the TSw based on the matrix hydraulic properties that have been developed. The relatively low matrix permeabilties led most experts to conclude that the matrix fluxes are approximately 0.3 to 3 mm/yr (the average value being about 1.5 mm/yr). Based on the experts' estimates of flux, the relative contributions to the percolation flux of the fractures and the matrix are approximately 90% and 10%, respectively.

Because of the evidence for low matrix permeabilities within the TSw, the fast-flow component generally is postulated to occur within fractures (which include faults). There was general agreement among the experts that the fast-flow component likely represents a relatively small part of the total flux, although there is uncertainty in this assessment. Generally, the area of the UZ system occupied by the fast-flow component is a small part of the total (<1% - 10%).

Seepage into the Drifts

There was general agreement that a capillary barrier will exist around the drifts that likely will divert moisture traveling in the matrix around the openings. Judgments about the potential and spatial extent of seepage occurring within the fractures differs somewhat across the panel, ranging from a low likelihood of seepage in general to a high likelihood within a small fraction (less than 10%) of the total area of the drifts.

Modeling Issues and Recommendations for Future Work to Reduce Uncertainties

As part of the elicitation, the experts were asked for their judgments about the applicability of various conceptual models for characterizing the unsaturated flow system (e.g., equivalent continuum versus dual permeability models, transient pulses versus steady-state, 1-d versus 3-d models of net infiltration). The purpose was to provide perspectives to the UZ site-scale modelers for consideration in their continuing efforts. Likewise, the experts provided their perspectives on high-priority future data collection or modeling efforts that could reduce significantly the uncertainties related to characterizing the UZ flow system.

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APPENDIX A

BIOGRAPHIES OF EXPERT PANEL MEMBERS

BIOGRAPHIES
MEMBERS OF THE EXPERT PANEL

Dr. Gaylon S. Campbell has been a member of Washington State University's Department of Crop and Soil Sciences since 1971. He teaches courses in environmental biophysics, soil physics, modeling of transport in the vadose zone, and simulation of cropping systems. His research interests include modeling and measurement of hydraulic and thermal properties of soils, plant-water relations, atmospheric transport, remote sensing of canopy properties, inverse methods, and modeling and measurement of transport in soils, plants, and the atmosphere. Dr. Campbell has published extensively in these areas, including a widely used book on environmental physics (1977), a book on numerical methods for models of soil/plant/atmosphere transport (1985), and on environmental instrumentation and simulation of cropping systems. He is a Fellow of the Soil Science Society of America and of the American Society of Agronomy and has been invited numerous times to be a visiting scientist or professor, including at the University of Nottingham, England. Dr. Campbell received his B.S. in physics (1965) and his M.S. in soil physics (1966) from Utah State University in Logan; in 1968 he received a Ph.D. in soils from Washington State University at Pullman.

Dr. Glendon W. Gee is a Senior Staff Scientist with the Water and Land Resources Department of Batelle, Pacific Northwest National Laboratories, Richland, Washington, where he has worked since 1977. Dr. Gee has a wide range of research experience in soil physics. His interests have included the measurement and prediction of recharge at arid sites and the analysis of water and solute transport in unsaturated soils. He has specialized in the hydrologic aspects of waste management, focusing on developing techniques to measure and control recharge and unsaturated water flow and to predict contaminant transport at arid sites. Dr. Gee has conducted research on surface barrier performance in desert environments for more than 15 years and currently serves as the project manager for Surface Barrier Technology at Batelle. He has authored or co-authored more than 160 scientific publications in soil physics and waste management. He has several patents on soil water-sensing devices. Dr. Gee holds adjunct professorships at Washington State University and University of Nevada-Reno. He is a certified professional soil scientist and a Fellow of the Soil Science Society of America, where he served as a division chairman. He received his B.S. in physics (1961) from Utah State University and his Ph.D. in soil physics (1966) from Washington State University.

Dr. James W. Mercer was first president of GeoTrans, Inc., which he co-founded in 1979 in Sterling, Virginia. With GeoTrans (now HSI GeoTrans), he works in all phases of the analysis of geohydrologic transport, including groundwater flow and heat and solute transport in porous media for a range of applications, such as analysis of aquifer resources, aquifer thermal storage, development of geothermal energy, storage of radioactive waste, seawater intrusion, and hazardous waste problems. Prior to starting GeoTrans, Dr. Mercer worked for eight years as a hydrologist with the U.S. Geological Survey. The issues he examined included transport related to storage of high- and low-level radioactive waste, seawater intrusion to coastal aquifers, and multifluid flows in reservoirs. After founding GeoTrans, Dr. Mercer began work for the U.S. Environmental Protection Agency on the Love Canal hazardous waste site, applying his experience with multiphase flow to the dense non-aqueous phase liquid (DNAPL) problems at Love Canal. He has published extensively, including as a co-author of DNAPL Site Evaluation. Dr. Mercer has served on the National Research Council's Water Science and Technology Board and is a member of the U.S. EPA Science Advisory Board. He is a registered professional geologist and hydrogeologist, and is a certified professional geologist in Delaware, Indiana, Virginia, South Carolina, and Florida. He holds a B.S. in geology from Florida State University (1969), a M.S. (1971) and Ph.D. (1973) in geology from the University of Illinois.

Dr. Shlomo P. Neuman is Regents' Professor of Hydrology and Water Resources at the University of Arizona in Tucson. His research group currently 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. 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 about 200 professional papers 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 a M.S. (1966) and Ph.D. (1968) in engineering science (civil/geotechnical) from the University of California at Berkeley.

Dr. Karsten Pruess has worked at Lawrence Berkeley National Laboratory (LBNL) since 1975. He currently is a Senior Scientist with LBNL's Earth Sciences Division and is a Faculty Associate in the Earth Resources Center at the University of California, Berkeley. His research interests involve the physics and engineering of subsurface flow systems, including: engineering of geothermal reservoirs, isolation of nuclear wastes, recovery and storage of oil and gas, environmental protection and remediation, laboratory experimentation on porous and fractured flow systems, and reactive chemical transport in geologic systems. He is the chief developer of the TOUGH family of general-purpose numerical simulation programs. Dr. Pruess served as Associate Editor of the *Journal of Petroleum Technology* and currently is serving on the "Seeing into the Earth" committee of the National Research Council. Since 1985 he has been a lecturer with the Department of Materials Science and Mineral Engineering at the University of California. Berkeley. He has authored or contributed to numerous publications. Dr. Pruess earned his Ph.D. in physics from the University of Frankfurt, Germany (1972).

Dr. Daniel B. Stephens is Principal Hydrologist and President of Daniel B. Stephens & Associates (DBS&A), Albuquerque, New Mexico, which he founded in 1984. DBS&A is an environmental sciences and engineering firm that has about 90 employees. Dr. Stephens formerly was chairman of the Geosciences Department at New Mexico Institute of Mining and Technology (NMIMT) in Socorro. He is an adjunct professor of geology at the University of New Mexico, Albuquerque, and an adjunct professor of hydrology at NMIMT. Dr. Stephens has pioneered in developing methods to characterize the hydrologic properties of soil. He developed a field method that includes capillary effects in determining the saturated hydraulic conductivity of soil from a borehole permeameter. Using extensively instrumented field sites, Dr. Stephens and his colleagues have discovered physical processes that induce significant horizontal flow components to soil-water movement. His other research has focused on field investigations of natural soil-water movement and recharge in semi-arid climates. Dr. Stephens has published more than 30 articles in peer-reviewed journals and has given more than 50 presentations and articles in symposia proceedings. In 1996, he published Vadose Zone Hydrology. In addition to vadose zone hydrology, Dr. Stephens specializes in development of water supplies, application of numerical models, and aquifer monitoring and contamination problems. Dr. Stephens is a certified professional hydrogeologist, a certified hydrogeologist in California, and a registered geologist in California. He received his B.S. degree in geological science from Pennsylvania State University (1971), his M.S. in hydrology from Stanford University (1974), and his Ph.D. in hydrology from the University of Arizona (1979).

Mr. Edwin P. Weeks specializes in field studies of the unsaturated zone for the U.S. Geological Survey. Mr. Weeks has almost 40 years of experience studying groundwater and hydrology for the U.S. Geological Survey. He currently serves as Chief of Unsaturated Zone Field Studies in Denver. Recent experience includes conducting or directing field research on anisothermal vapor transport in unsaturated media, gaseous diffusion and reactions in the unsaturated zone, methods for determining flow properties of unsaturated zones, use of the eddy-correlation method for measuring evapotranspiration, and aspects of topographically affected gas circulation through fractured rock. Previously, Mr. Weeks served as Chief of a major Drilling, Sampling, and Testing project, as well as Research Advisor for Ground Water. He has provided staff training and teaching, as well as technical review of USGS reports . Earlier projects included research on the use of air-permeability techniques to determine *in situ* properties of the unsaturated zone and to determine the effects of groundwater development on stream flow in the Central Sandplain area of Wisconsin. He has performed both spreading and well-injection experiments, a major tracer experiment, aquifer testing, modeling of groundwater flow, and water-balance modeling to estimate evapotranspiration. Mr. Weeks received his B.S. degree from the Colorado School of Mines in 1958.

APPENDIX B
REFERENCES
DISTRIBUTED TO EXPERT PANEL MEMBERS

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APPENDIX C
WORKSHOP AND FIELD TRIP SUMMARIES

SUMMARY
WORKSHOP ON SIGNIFICANT ISSUES AND AVAILABLE DATA

UNSATURATED ZONE FLOW MODEL
EXPERT ELICITATION PROJECT

November 14 and 15, 1996
Lawrence Berkeley National Laboratory
Berkeley, California

The Workshop on Significant Issues and Available Data was the first of three workshops being conducted for the Unsaturated Zone Flow Model Expert Elicitation project (UZFMEE) which is sponsored by U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The goals of this workshop were to: (1) introduce the expert panel members to the UZFMEE project, (2) highlight significant issues related to the unsaturated zone process models for the Total System Performance Assessment (TSPA), and (3) present the various data sets related to the significant issues. The two day workshop revolved around a series of technical presentations and discussions of the various data collected over the past several years to characterize unsaturated zone hydrology at Yucca Mountain.

Copies of the overhead transparencies and slides shown during the course of this workshop are in the UZFMEE administrative files.

DAY 1 - THURSDAY, NOVEMBER 14

Dr. Gudmundur "Bo" Bodvarsson welcomed the workshop participants to Lawrence Berkeley National Laboratory (LBNL) and briefly described his role in the UZFMEE project and in providing input to the TSPA for the Yucca Mountain project. Mr. Tim Sullivan (DOE) described the rational for this expert elicitation and its purpose in characterizing the unsaturated zone process models and quantifying uncertainties for the TSPA.
Dr. Kevin Coppersmith of Geomatrix Consultants then presented a general introduction to the UZFMEE project and reviewed the workshop agenda. He described the expert panel selection process, along with the various types of participation in the project. The members of the expert panel then introduced themselves, and briefly described their areas of expertise. The expert panel members are: Dr. Gaylon Campbell (Washington State University), Dr. Glendon Gee (Battelle, Pacific Northwest National Laboratory), Dr. James Mercer (Geo Trans, Inc.), Dr. Schlomo Neuman (University of Arizona), Dr. Karsten Pruess (LBNL), Dr. Daniel Stephens (Daniel B. Stephens & Associates), and Mr. Edwin Weeks (U.S. Geological Survey[USGS]). The Methodology Development Team (MDT), which is the group that plans and conducts Project activities, consists of: Dr. Robert (Bob) Andrews (M&O/INTERA), Dr. Thomas Bjerstedt (DOE), Dr. Gudmundur (Bo) Bodvarsson (LBNL), Dr. Kevin Coppersmith (Geomatrix Consultants), Dr. Dwight Hoxie (U.S. Geological

Survey), Mr. Edward Kwicklis (USGS), Ms. Martha Pendleton (M&O/ Woodward-Clyde Federal Services[WCFS]), Dr. Roseanne Perman (Geomatrix Consultants), Mr. Tim Sullivan (DOE), and Dr. Robert (Bob) Youngs (Geomatrix Consultants).

Presentations by Bob Andrews and Bo Bodvarsson followed the general introduction. Bob Andrews discussed the objectives of the UZFMEE project and how it relates to the Total System Performance Assessment - Viability Assessment (TSPA-VA) of the waste isolation system. He stated that the DOE wanted the fresh perspective that outside experts would have in evaluating the existing work, and that their approach should focus on "reasonableness" and not conservatism. Bo Bodvarsson then presented an overview of the UZ site-scale model. He discussed the key components of the model (e.g., infiltration rates and fracture/matrix properties), the objectives of the model (e.g., the integration and synthesis of all unsaturated zone data), data inputs, and what the model yields after calibration of the various data sets.

Following a short break, Ed Kwicklis presented a conceptual model of the unsaturated zone at Yucca Mountain. He gave an overview of the hydrogeology of the site, a historical perspective of the project, and discussed the current unresolved issues. Robert Clayton (WCFS) then presented a talk on the 3D geologic framework model of Yucca Mountain. The input data and uncertainty in the subsurface geometry of faults in the model, which was developed by WCFS and the USGS, were discussed.

The afternoon session began with two talks focusing on the fracture and matrix properties of the stratigraphic units comprising Yucca Mountain. Lorraine Flint (USGS) gave the first talk, which focused on the matrix properties of the stratigraphy, and her characterization of 30 distinct hydrogeologic units based on their hydrologic properties. Larry Anna (USGS) then presented a talk on the fracture properties of the Yucca Mountain rocks. He discussed the fracture data and 3D discrete fracture model developed for the repository horizon (Topopah Spring Tuff). He pointed out that east-west-oriented permeability in the repository block is low, relative to north-south and top-to-bottom oriented permeability.

Alan Flint (USGS) continued the presentations with a talk on infiltration rates at Yucca Mountain. He gave an overview of his numerical model, presented a map of net infiltration at Yucca Mountain, and discussed the relative importance of the various data sets used in his model. Joseph Rousseau (USGS) gave the final presentation of the day. He began to discuss the in-situ hydrologic conditions at Yucca Mountain, however, due to time constraints, the remainder of his talk was postponed until 8:00 a.m. the next morning.

Kevin Coppersmith ended the day by opening up the floor for comments and questions by observers.

DAY 2 - FRIDAY, NOVEMBER 15

Joseph Rousseau (USGS) continued his talk on the in-situ hydrologic conditions at Yucca Mountain. He discussed the various data, particularly pneumatic tests, and how the in-situ measurements compare with measurements obtained from sampling. Gary LeCain (USGS) then gave a talk on pneumatic testing in surface based boreholes and in the Exploratory Studies Facility (ESF). He discussed fracture properties and permeability results based on the pneumatic data. Joe Wang (LBNL) gave the next talk, which focused on moisture conditions in the ESF based on data from sensor stations that collect humidity, temperature, and other data.

Following a short break, Perry Montazer (Multimedia Environmental Technology) presented a talk on the various studies conducted by Nye County, Nevada, including simulation modeling. Gary Patterson (USGS) then gave a presentation on the occurrence of perched water at Yucca Mountain. He noted that all zones of perched water occur below the repository horizon, and that the areal extent of perched water at Yucca Mountain is not well constrained. June Fabryka-Martin (Los Alamos National Laboratory) gave the next talk, which focused on the identification of water-flow pathways using Cl^{36} data. Some, but not all, major faults tend to be areas of elevated Cl^{36}/Cl signals.

The afternoon session continued with two presentations on the identification of water-flow pathways. Al Yang (USGS) gave the first talk, which focused on identifying pathways based on the hydrochemistry of the unsaturated zone at Yucca Mountain. He has developed a model that suggests that perched water moves very rapidly through hydrogeologic units via fractures. Zell Peterman (USGS) gave the final presentation of the day. His talk focused on the dating of calcite and opal from veins and fractures in the ESF to relate mineralization to paleohydrological conditions (i.e., past groundwater flux).

Kevin Coppersmith concluded the workshop with a short discussion on the focus of subsequent workshops, and a review of the project schedule. Questions and comments from the observers followed. Topics of discussion included the need to define the specific parameters that will be elicited, how they will be elicited, and the appropriateness of modeling the unsaturated zone as a separate component within the groundwater system.

SUMMARY
WORKSHOP ON ALTERNATIVE MODELS AND INTERPRETATIONS

UNSATURATED ZONE FLOW MODEL EXPERT ELICITATION PROJECT

December 18 to 20, 1996
Lawrence Berkeley National Laboratory
Berkeley, California

The Workshop on Alternative Models and Interpretations was the second of three workshops being conducted for the Unsaturated Zone Flow Model Expert Elicitation (UZFMEE) project at Yucca Mountain, Nevada. The project is sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The purposes of this workshop were to (1) present and discuss the key issues and uncertainties associated with assessing the percolation flux at the repository horizon using the unsaturated zone site-scale model developed for Yucca Mountain, (2) present and discuss alternative models for treating particular components of the unsaturated zone flow system and for explaining Yucca Mountain hydrologic data, (3) to discuss and agree upon the specific subjects that will be addressed in the expert elicitations, and 4) to present and discuss elicitation methodology, including methods for quantifying uncertainty. The workshop involved two days of technical presentations and a one-half day session that focused on preparation for the elicitations.

Copies of the overhead transparencies shown during the course of this workshop are in the UZFMEE administrative files.

DAY 1 - WEDNESDAY, DECEMBER 18
A welcome to the workshop was given by Russ Patterson (DOE) of the Methodology Development Team (MDT). Kevin Coppersmith (Geomatrix), MDT member and UZFMEE project manager, then discussed the purposes of the workshop. He also discussed the differences between the proponent and evaluator roles that the experts play in the project, and mentioned that the UZFMEE project procedures follow those established by the Branch Technical Position of the Nuclear Regulatory Commission. Bo Bodvarsson (Lawrence Berkeley National Laboratory [LBNL] and MDT member) then gave a brief presentation on some of the key components and uncertainties in the UZ site-scale model, which included discussion of input and output data, alternative methods of modeling the data, and how the model incorporates data. He also discussed the UZ site-scale model parameter uncertainties, indicating that they are closely related to the conceptual models used and their uncertainties.

Mark Bandurraga (LBNL) began the technical presentations with a talk entitled, "Model Boundaries/Discretization." He discussed the development of the LBNL/USGS three-dimensional site-scale model of Yucca Mountain, including numerical grid issues and the types of geologic data used in grid development. Eric Sonnenthal (LBNL) gave the next presentation, entitled "Submodel of Percolation Flux at the Repository and Development of Fracture Properties for the UZ Model." The submodel is used to investigate flux variation at the repository horizon, or along specific features like faults, in finer grid resolution than the large-scale UZ model. Following a short break, Alan Flint (U.S. Geological Survey [USGS]) gave the final technical presentation of the morning session. His talk, entitled "Numerical Model of Net Infiltration, Yucca Mountain Area, Nevada," gave an overview of the numerical implementation of the conceptual infiltration model.

Following lunch, Stuart Stothoff (Center for Nuclear Waste Regulatory Analyses) began the afternoon session of technical presentations with a talk entitled, "Simulating Infiltration at Yucca Mountain." He discussed the methods used in the simulation model, and the results of the sensitivity analysis. Stefan Finsterle (LBNL) gave the next presentation, which focused on UZFMEE software. He discussed the uses of the TOUGH2 and ITOUGH2 programs. A presentation entitled "Conceptualizations for Fracture-Matrix Interactions" was then given by Christine Doughty (LBNL). She discussed methods, numerical formulations, and the applicability of the Equivalent Continuum Model (ECM) and the Dual Permeability Model (DKM) for conceptualizing fracture-matrix flow and transport. Mark Bandurraga (LBNL) gave the next talk, which focused on rock properties at Yucca Mountain. Characterization of spatial variability, fracture and matrix parameters, and other calibration considerations were discussed.

Following a short break, the technical presentations continued with a talk by Sean McKenna (Sandia National Laboratories[SNL]) entitled "Rock Properties Modeling at Yucca Mountain." He discussed ways of incorporating heterogeneities in rock properties into the geologic framework model. Susan Altman (SNL) then gave a talk entitled, "Results of Incorporating Heterogeneities." Her talk focused on capturing uncertainty in rock property modeling, as well as capturing uncertainty in data on the unsaturated flow system, through the use of geostatistical simulations. Rick Ahlers (LBNL) gave the next talk, entitled "Calibration of the UZ Flow Model Using Pneumatic Data." He discussed the conceptual model, data, modeling, and calibration of pneumatic data at Yucca Mountain. Yu-Shu Wu (LBNL) gave the final presentation of the day. His talk, entitled "Calibration Using Perched Water," focused on perched water data and implications, the conceptual model, model representation and calibration, and modeling efforts.

DAY 2 - THURSDAY, DECEMBER 19

Bo Bodvarsson (LBNL) began the presentations on the second day with a talk entitled, "Calibration Using Temperature Data." He discussed the vertical temperature gradient at Yucca Mountain and the water percolation model developed to model heat flow through the system. Jerry Fairley (LBNL) gave the next presentation, entitled "Conceptual Models of ^{36}Cl Transport." He discussed the alternative conceptual models, and concluded that the preferred model based on ^{36}Cl data is transient, structurally controlled flow. Andrew Wolfsberg (Los Alamos National Laboratory) gave the next talk, entitled "Environmental Isotopes and Radionuclide Migration at Yucca Mountain: Studies Coupling Flow and Transport Processes." He discussed how coupled flow and transport modeling are used to assess ambient flow conditions and predict radionuclide migrations sensitivities.

Following a short break, Stefan Finsterle (LBNL) gave a talk entitled "Validation of Calibration," which compared model outputs with the various measured data. Yu-Shu Wu (LBNL) then gave a talk entitled "Percolation Flux Simulation". He discussed the key issues in percolation flux simulation and a new conceptual flow model. Srikanta Mishra (M&O/INTERA) concluded the morning session with a talk entitled "Uncertainty Propagation Using A Generalized Equivalent Continuum Model," which focused on computing uncertainty in percolation flux at depth.

The afternoon session began with a talk by Clifford Ho (SNL) entitled, "Dual-Permeability Model (DKM): Uncertainty in Conceptual Models of Fracture-Matrix Interaction." He discussed the attributes of the DKM and compared it to the ECM. C.F. Tsang (LBNL) gave the next talk, entitled "Drift Scale Modeling," which focused on a draft-scale stochastic continuum model used to assess spatial and temporal variation of influx to drift. Jack Gauthier (SPECTRA Research) then gave a presentation on the "Weeps Model," which was developed to deal with isolated, fast-flow pathways. He reported that the weeps model is consistent with reasonable interpretations of chemical and isotopic data and appears to be predictive of bulk flow properties (e.g., bomb pulse ^{36}Cl in the ESF).

Following a short break, Linda Lehman (L. Lehman & Associates) gave a presentation on the unsaturated zone modeling studies conducted by the State of Nevada. She also gave a brief historical overview of some of the common assumptions made for conceptual flow modeling in the 1980's and early 1990's. Tetsu Tokunaga (LBNL) gave the next talk, entitled "Film Flow: A Previously Unappreciated Process in Unsaturated Fractured Rock," which focused on continuous films that may create fast-flow pathways through the unsaturated zone. Kevin Coppersmith concluded the days presentations, with a talk entitled "Where Do We Go From Here?" He discussed the scheduling of future project activities and deadlines, and the UZFMEE parameters that will be elicited from the members of the expert panel.

DAY - FRIDAY, DECEMBER 20

The third day of the workshop began with a discussion of the additional analyses and calculations that members of the expert panel would like to have prior to the elicitation interview. The requests included additional geostatistical and uncertainty information from some of the Yucca Mountain Principal Investigators and requests for more detailed information on the TOUGH2 code. Pete Morris (Applied Decision Analysis and MDT member) then presented an introduction to probability assessment to prepare the experts for the upcoming elicitation interviews. His talk focused on using probability to quantify uncertainty, representing and manipulating probabilities, and assessing probabilities. This training session was the final activity of the workshop.

SUMMARY
WORKSHOP ON PRELIMINARY INTERPRETATIONS

UNSATURATED ZONE FLOW MODEL EXPERT ELICITATION PROJECT

February 3 and 4, 1997
Longstreet Inn and Casino
Amargosa Valley, Nevada

The Workshop on Preliminary Interpretations was the last of three workshops being conducted for the Unsaturated Zone Flow Model Expert Elicitation (UZFMEE) project at Yucca Mountain, Nevada. The project is sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The purposes of this workshop were to (1) provide an opportunity for the experts to present and discuss their preliminary interpretations and uncertainties regarding key issues to unsaturated zone flow processes, (2) provide feedback to the experts regarding their preliminary interpretations prior to the elicitation sessions, and (3) allow the experts to question the Yucca Mountain PI's regarding their interpretations and uncertainties.

Copies of the overhead transparencies shown during the course of this workshop are in the UZFMEE administrative files.

DAY 1 - MONDAY, FEBRUARY 3

Kevin Coppersmith began the workshop with a review of the previous workshops, and a discussion of upcoming project elements, including the elicitation interviews, feedback and finalization and documentation of interpretations. He then described the purpose of the workshop and the approach to be followed.

Bo Bodvarsson summarized the questions and requests for information made by the panel during UZFMEE Workshop 2. He addressed the various questions and requests by reviewing the work being conducted, and the documents being distributed to the expert panel, to answer as many of the requests as possible.

The remainder of the workshop consisted of preliminary interpretations by members of the expert panel. Two panel members presented their interpretations on each of five issues: net infiltration, rock properties, major pathways, calibration uncertainties, and alternative conceptual models. Gaylon Campbell and Glendon Gee gave the presentations on net infiltration. Gaylon Campbell began with a discussion of the various ways that estimates had been made of net infiltration in the Yucca Mountain area. He focused on surface water balance measurements and models, and the variability in the various inputs. He discussed the Finite Difference Soil Water Balance (FDSWB) model that he developed, and the various parameters he used in running a 50 year simulation period. His results were a time and space averaged mean flux of 1-20 mm/yr. He then discussed uncertainties in thermal convection calculations, concluding that despite the data uncertainties, calculated values were consistent with other methods and similar to expectations: average flux is 5 to 10 mm/yr, with spatial variation from about 0 to 20 mm/yr. Glendon Gee then discussed aspects of vadose zone water balance for Yucca Mountain. The discussion included general observations on soil properties, plant cover properties, topographic features, and climatic variables; and specific issues of model types used and estimates of net infiltration obtained from various methods (including ^{36}Cl and thermal profiles). Analog areas were then described, including a humid region (where water balances from daily average vs. hourly average precipitation result in order-of-magnitude differences in net infiltration), a Hanford, Washington site, and a Beatty, Nevada site.

DAY 2 - TUESDAY, FEBRUARY 4

The second day of the workshop began with presentations on rock properties given by Dan Stephens and Glendon Gee. Dan Stephens reviewed the rock properties data obtained at Yucca Mountain from laboratory tests on core and field tests. He then focused on scaling issues, and sources of uncertainty from field saturation and potential measurements. The reliability of the van Genuchten formulation for unsaturated hydraulic conductivity was also discussed. Glendon Gee focused on hydraulic property characterization, including the importance of matrix vs fracture properties for hydraulics, vapor flow issues, and hysteresis issues. He discussed lysimeter water storage and drainage estimates from the Hanford site, including the large differences in recharge obtained from using isotopic tracer tests versus lysimeter/N-probe data, and uncertainties introduced by modeling. The expert panel then commenced a general discussion of water potential measurements, with Lorraine Flint discussing some of the rock properties data she had collected and sources of uncertainty.

Major pathways were the next topic of the workshop, and talks were given by Karsten Pruess and Ed Weeks. Karsten Pruess discussed heterogeneity, specifically, the intrinsic variability of permeability, porosity, strength of capillary pressure, and many other factors, and how averages of these factors may be meaningless. He discussed flow focusing and showed different patterns of spatial localization of flow. Finally, he noted uncertainties in parameters, processes and conceptualizations, including the use of the macroscale continuum model versus localized seeps, and the nature of preferential pathways. Ed Weeks reviewed model assumptions regarding major pathways and observations relevant to pathways, and concluded that discrete, high-velocity low-volume fracture flow is a relevant concept. He reviewed isotopic tracer data and the role of faults as major pathways. He concluded that rapid fracture flow is ubiquitous and is only weakly coupled to matrix flow, and that no direct evidence exists that faults are more significant for rapid water flux than fractures in general.

Jim Mercer and Dan Stephens gave presentations on calibration uncertainties. Jim Mercer reviewed the UZ models being used for calibrations, and the calibration parameters. Uncertainties in the various parameters were discussed, as well as the different types of data that provide evidence of fast flow paths at Yucca Mountain. He stated that new information that may become available from the ESF will be extremely useful for calibrating the site-scale model. Dan Stephens began his presentation by stating that convergence of results of different methods of estimating percolation flux is a significant strength of the Yucca Mountain project. He listed calibration uncertainties and how uncertainties in prediction could be reduced. He reviewed some of the different flux values that have been considered reasonable during the past decade, and listed uncertainty implications for both low (< 1-5 mm/yr) and high flux rates.

The final presentations of the workshop were on alternative conceptual models. Shlomo Neuman gave the first talk, and began by stressing the difficulty of modeling the vadose zone. He described his favored modeling philosophy, based on the fundamental premise that a model must be operational, and that if multiple operational models consistent with the experimental data are available, the preferred model should be the least complex and include the smallest number of parameters. For Yucca Mountain, he then discussed major ambiguities/uncertainties in the geologic framework; properties of faults; fractures; layering, heterogeneity and gridding; perched bodies; infiltration; and model calibration. He compared alternative models and their ability to capture various aspects of flow/transport. Ed Weeks gave the final talk and began by reviewing alternate concepts of fracture-matrix interaction and their applicability at Yucca Mountain. He then discussed various concepts associated with air flow and the potential for natural ventilation to remove moisture in the proposed repository. He also considered the weeps models and how it is difficult to reconcile the lack of observed seeps in the ESF with this model.

The workshop concluded with comments from observers. Leon Reiter (NWTRB) noted that the workshop had been fascinating, and that he hoped a feedback workshop could be scheduled. Victor Palciauskas (NWTRB) listed concerns with model grid scale and up-scaling issues. The workshop was adjourned by Kevin Coppersmith.

SUMMARY
YUCCA MOUNTAIN FIELD TRIP

UNSATURATED ZONE FLOW MODEL EXPERT ELICITATION PROJECT

February 5, 1997

The field trip to Yucca Mountain was organized at the request of the expert panel members, who wanted to observe the general setting of Yucca Mountain, bedrock exposed in the Exploratory Studies Facility (ESF) and at the ground surface, and some of the data collection localities for the U.S. Geological Survey (USGS) infiltration studies. Approximately half the day was focused on the ESF trip, and half on surface exposures and data collection sites on Yucca Mountain. The primary goal of the field trip was to provide the expert panel members an opportunity to observe field relationships first-hand and to form their own interpretations regarding important issues to unsaturated flow, such as surface water balance, infiltration monitoring, and nature of bedrock structures. The field trip was led by several earth scientists who have carried out extensive mapping and/or research in the area.

Handouts provided by field gtrip leaders are in the UZFMEE administrative files.

ESF VISIT

The ESF visit commenced with safety training at the Field Operations Center (FOC) and a short visit to the USGS laboratory run by Alan Flint (USGS) located nearby. The group then traveled to the ESF pad and assembled in a conference room where Warren Day (USGS) and Steve Beason (U.S. Bureau of Reclamation) gave short introductory presentations on the geology of the Yucca Mountain block. The group then proceeded into the tunnel by train and were dropped off at Station 28 + 27 near the thermal testing alcove. The group then walked out of the tunnel, stopping at key exposures, test localities, and alcoves to discuss the geology and data collection efforts with Alan Flint, Warren Day, and Steve Beason. Highlights of the trip included examining cooling joints, faults and fractures, and learning about the various tests being conducted to assess rock properties in the ESF.

YUCCA MOUNTAIN VISIT

Drillhole Wash

On the northeast side of Drillhole Wash, at the NRG-5 drill pad, Alan Flint discussed the characteristics of the soil/ Tiva Canyon bedrock interface in the cut slope of the pad. The bedrock contains numerous cross-cutting fractures filled with carbonate, and is overlain by soils that range from about 0.5 to 1.5 m thick.

Split Wash

On the northeast side of Split Wash, near the northern end of the "Imbricate" fault zone, Alan Flint discussed location objectives and data obtained from several neutron probes. Continuing up Split Wash, the group stopped in a narrow part of the canyon between north-facing and south-facing slopes that represent areas with the lowest and highest radiation loads, respectively, at Yucca Mountain. The slopes are characterized by very different vegetation types. Alan Flint described how he would model infiltration with high velocity water movement and low percolation flux on the steep side-slopes of the canyon, and low velocity water movement and high percolation flux along the channel at the bottom of the canyon. Continuing into the north branch of Split Wash, the group observed an outcrop of the Ghost Dance fault described by Warren Day. The fault is marked by carbonate-coated breccia that can be traced across the dark rock covering the surrounding hillslope. Directly below in the ESF, drilling in Alcove 6 has revealed an 11 m wide zone of breccia associated with the Ghost Dance fault. A final stop was made in Split Wash at the Sundance fault, where the fault plane and associated breccia could be observed.

Antler Wash

At the southern end of the "Imbricate" fault zone, Warren Day described the Bow Ridge fault and associated hanging wall deformation on the east side of the fault.

WT-2 Wash

A stop was made at the UZ-7a drill pad, where there is an excellent exposure of the Ghost Dance fault and the adjacent fracture zone in a drill pad cut slope. The fault trace, and offset stratigraphic units, were also observed on the surrounding hill slopes. The UZ-7a well penetrates the Ghost Dance fault.

Yucca Mountain Crest

Warren Day described the geology surrounding Yucca Mountain from the top of the mountain. Various stratigraphic units, faults, topographic features and well locations were discussed.

Fran Ridge

At the southern end of Fran Ridge, an exposure of the Paintbrush Canyon fault was observed. Warren Day reviewed his concept of "horsetailing" (splaying near the surface) faults in the Yucca Mountain area. The expert panel asked Alan Flint questions about his infiltration maps, and future research efforts. Kevin Coppersmith thanked the field trip leaders for their participation and the group departed to return to Las Vegas.

APPENDIX D
ELICITATION INTERVIEW SUMMARIES

ELICITATION SUMMARY
GAYLON S. CAMPBELL
February 6, 1997

OVERVIEW OF UZ FLOW: PROCESSES AND MODELING ISSUES

The TOUGH2 and FEHM site-scale unsaturated zone models of Yucca Mountain developed by LBNL and LANL appear to approximate the primary flow and transport processes occuring within the mountain. The surface water balance (i.e., net infiltration) provides key information for both models, since these models route the water that is supplied at the upper boundary by the net infiltration. During most of the time and over most of the area, precipitation is low; water is stored in the alluvium and removed by evapotranspiration (ET). Significant infiltration occurs only in association with severe storm events or sequences that occur on the order of once in ten years; therefore, infiltration is episodic and occurs as pulses of moisture. Water probably moves through the Tiva Canyon (TCw) unit primarily through fractures, and there is not much attenuation of the temporal pulse. But in the Paintbrush (PTn) unit the pulse likely is damped such that the temporal behavior below the PTn is nearly steady state.

Net infiltration varies spatially as well as temporally, and the uncertainties also vary spatially. I generally agree with the spatial distribution of net infiltration presented by Flint et al. (1996). The areas having low infiltration (e.g., the side-slopes, areas of deep alluvium) are also areas having a relatively low uncertainty in net infiltration. In contrast, the areas of high infiltration (e.g., the ridge-tops and washes) are locations of relatively high uncertainty in net infiltration. The precipitation model developed by Flint et al. (1966) appears to be well designed; it captures the severe storm events that must be considered in developing a meaningful temporally averaged estimate of infiltration. Infiltration averaged over only ten or twenty years in this setting does not provide a meaningful estimate of long-term net infiltration.

Faults and fractures near the faults play a key role in rapid water transport to the repository horizon depth. Mechanisms for funneling and concentrating flow, such as 'horse-tailing' faults (presentation by W. Day at UZFMEE Field Trip) would assist in this process. The presence of ^{36}Cl at depth is best explained by fast-flow in faults and fractures. However, this fast flow is probably a minor component of the total flux because the area containing faults is only a small fraction of the total area. To move water quickly through the PTn, faults and fractures must be present, or focused flow must occur. The capacity of the PTn is so high that it can store significant amounts of water in the matrix and would normally damp out pulses except in areas of concentrated flow.

The evidence is strong that, below a 'level of no return,' there is downward movement of water in Yucca Mountain. Various lines of evidence support this conclusion, including the water stains and mineral coatings we observed in fractures in the ESF (UZFMEE Field Trip), psychrometer measurements that show no matric potential gradient, the perched water bodies deep within the mountain, and the bomb-pulse tracers deep within the mountain. Thermoçouple psychrometer data show a drying zone near the surface, possibly caused by local convection, but I interpret this as a local effect that is not necessarily relevant to defining flow through the deeper layers.

The change in hydraulic properties at the interfaces between the TCw and the PTn, and especially between the PTn and the Topopah Spring (TSw), almost certainly leads to lateral flow. Based on the thickness of the PTn and the presence and spacing of fractures, lateral diversion probably would not occur over more than several tens of meters.

For the bulk of the water and rock in the unsaturated system, the system is usually near steady state. Probably 95% of the flow within the TSw occurs in the fractures, and the fractures and matrix are likely near equilibrium. I consider fracture flow to be part of the overall flow process within the mountain, and not necessarily equivalent to fast paths. I think that fast flow occurs in association with faults, and that this water is not in equilibrium with most of the water in the rock.

Several alternative conceptual models have been used or considered in the UZ site-scale modeling effort for Yucca Mountain. For net infiltration, A. Flint (presentation at UZFMEE Workshop 2) used three approaches to obtain net infiltration values: an empirical model based on neutron borehole data; the Maxey-Eakin equation (an empirical, watershed-scale equation based on rainfall); and a one-dimensional, finite-difference model of the soil-water balance. I prefer the finite-difference model because it minimizes empiricism (important for 10,000-year extrapolations). The other approaches have been useful, however, because they provide more or less independent checks on the reliability of the finite-difference model. There is good qualitative agreement among the models (all predict some net infiltration), and reasonably good quantitative agreement.

For modeling flow within the mountain, a dual-permeability model is almost certainly needed to show the transient nature of flow pulses and the partitioning of water between fractures and matrix. Below the PTn, an equivalent continuum model may be sufficient (although it will not capture the fast-flow component). The present models certainly do not capture all of the complexity of flow in such a medium. No model can ever do that. I see no evidence, however, that the present models are missing significant processes and need to be made more complex. I think there is a good chance that, as we come to understand the processes better, the model for flow within the mountain can be simplified substantially.

There are significant uncertainties in our knowledge of the hydraulic properties of faults and fractures. Inverse modeling using the pneumatic data is allowing some characterization, which is good. I think that additional faults should be added to the model, and the sensitivity to their inclusion should be tested.

The problem of upscaling matrix property measurements on cores to properly represent 100 m^3 grid blocks is one of correctly accounting for fractures and averaging properties. A numerical model is a discrete approximation of the differential equations for flow. We often empirically adjust the material properties in the model to account for the complex processes going on within a grid block, which we are unable or unwilling to describe in detail with the model. The UZ site-scale model uses such enormous grid blocks that a lot of this empirical adjustment must occur. The inverse modeling with the UZ site-scale model is providing empirical adjustments, but one should not be surprised if the matrix properties that come out of the inverse modeling do not exactly match those from the core samples. There are, of course, inconsistencies in the data used in the inverse modeling, and one must use good judgment in deciding which data to honor. I would be concerned, however, if the inverse model required matrix properties much different from the range of values measured on samples.

APPROACHES TO ESTIMATING PERCOLATION FLUX

Net Infiltration/ Surface Water Balance

To evaluate the net infiltration at Yucca Mountain, I obtained weather data from A. Flint (pers. comm.), which were used to produce set of a weather parameters. The weather parameters were then used in a stochastic climate generator to generate 50-year weather sequences for Yucca Mountain. These, in turn, were used in a finite-difference version of the soil-water balance model (Campbell and Stockle, 1993) to determine the components of the water budget, including net infiltration. Computations were made for a range of soil depths and mean precipitation amounts. The results of these calculations were compared with those presented by A. Flint (presentations at UZFMEE Workshops 1 and 2). There seemed generally good agreement between the two. While I am uncomfortable with a number of the assumptions made in the Flint et al. (1996) model (used to produce the most recent net infiltration map), the predicted net infiltration amounts apparently are not sensitive to those assumptions. My model and A. Flint's produced similar net infiltration amounts, even though they are based on different assumptions.

Usually, one would not expect a water balance model to have sufficient accuracy to give useful information about percolation fluxes in the range of mm/yr. Each of the inputs and losses have uncertainties much larger than the net amount we wish to resolve. For example, the mean precipitation at Yucca Mountain is 170 mm/yr. The 99% confidence limits on this value are 30 and 316 mm/yr. The year-to-year variation, therefore, could be almost as large as the mean. These variations bring about large variation in evaporation and transpiration as well. Add to this the spatial variation due to soil depth, rock cover, slope, and aspect, and the variation could be huge. The only reason the water budget calculation produces any useful information is that it is limited by several natural processes. Water moves down readily, but once it is below the root zone of plants, it can't move upward in significant quantities. After evaporation and transpiration have emptied the root zone, the water loss to the atmosphere is zero. Two primary factors therefore determine the net infiltration flux: the water-holding capacity of the root zone, and the frequency with which the capacity of the root zone is exceeded. The capacity of the root zone, which is related to soil depth, was mapped over the surface of the mountain. The frequency with which the capacity is exceeded is determined by the spatial and temporal distribution of precipitation. Detailed studies of precipitation have characterized that input as well as can be expected. Once these two factors are relatively certain, the outcome of the net infiltration simulations become quite certain even when other inputs are very uncertain.

Perhaps the highest uncertainties are associated with infiltration into areas where there is substantial run on, such as in washes. These areas, however, make up only a small fraction of the mountain, so their high uncertainty contributes little to uncertainty in the spatially averaged net infiltration.

From the computations I conducted, I conclude that the net infiltration values of Flint et.al. (1996) are reasonable. I also conclude that their assessment of the relative importance of various factors affecting infiltration (e.g., soil depth, soil properties, root depth) is reasonable. Key sensitivities and uncertainties are the tails of the precipitation distribution, and the thickness and distribution of alluvium.

Additional features that A. Flint (or LBNL) are planning to incorporate in their modeling and their likely effect on the infiltration rate (+ or -) are the following: rocks on side slopes (+), vegetation response to drought (+), runoff added in to washes (+ or -), characterization of TCw unit (+), lateral flow (+ or -), and hysteresis (+ or -). I conclude that the average values probably will increase somewhat over those on the latest infiltraton map (Flint et al, 1996).

There seemed to be considerable concern about using a one-dimensional model to represent a flow situation that is clearly three-dimensional. I am certain that there is lateral flow along the alluvium-rock contact, but the grid blocks in the TOUGH2 model are 100 m wide. I doubt that there is enough lateral flow to transfer significant amounts of water even from one grid block to another. It therefore seems unproductive to spend time developing 2- and 3-dimensional models of surface processes when we have insufficient computer power to implement the spatial detail needed to take advantage of the additional information provided by such a model.

My assessment of the average net infiltration rate over long periods (50-1000 yrs.) and spatially over the repository area ranges from less than 1 mm/yr to 15 mm/yr (5^{th} to 95^{th} percentile, with a mean estimate of about 7 mm/yr. The cumulative distribution for this estimate is given in Figure GC-1. I would not expect this average rate to vary over 100 or 1000 yrs, but 10 yrs is too short to capture the episodic infiltration events. An episodic event might last as long as one month. If the long-term average infiltration rate is 5 mm/yr and an extreme event lasting one month occurs once every 10 yrs, the infiltration associated with that event could be about 50 mm without changing the overall average rate.

Because I know of no evidence for regional-scale lateral diversion, I would expect the average percolation flux at the repository horizon to be about the same as the average net infiltration rate. The spatial distribution of percolation flux at depth is expected to be similar to the spatial distribution of net infiltration, except that the 'high-frequency' variations in infiltration will be dampened by local lateral flow and diffusion (e.g., the profile presented by S. Finsterle at UZFMEE Workshop 2 that compares net infiltration with LBNL model results).

Temperature Gradients/Convective Heat Flux
Convective heat flux is heat that flows through the rock with percolating water, as a result of temperature gradients. If the heat flux density, the temperature gradient, and the rock thermal conductivity are known, the convective heat flux, and therefore the percolating water flux, can be computed. Uncertainties in the water flux estimates result from uncertainties in total heat flux, temperature gradient, and estimates of rock thermal conductivity. Uncertainty in the temperature gradient estimates is negligible, compared to the other uncertainties. The uncertainty in the rock thermal properties is larger, but also probably small compared to uncertainty in the heat flux estimate. The heat flux estimates are from a USGS report by Sass et al. (1988). I do not know how Sass was able to make a heat flux map that is independent of convection effects (I strongly suspect some circular reasoning here), but he may have had some independent information based on his professional judgment. In any case, it is possible to determine the sensitivity of this method to uncertainty in its inputs. An average heat flux over the repository of 36 mW/m^2 would give a net infiltration rate of about 5 mm/yr. A value of 30 mW/m^2 gives 1 mm/yr, and 50 mW/m^2 gives 15 mm/yr of net infiltration. I have no way to assess the uncertainty in the heat flux estimates, but the flux values obtained in this way seem to agree fairly well with those from the water balance calculation. In fact, transects of estimated fluxes based on temperature information seem to match the transects of surface water balance. The two methods appear, therefore, to corroborate each other. I do not have enough confidence in the heat flux estimates, however, to be willing to construct a probability distribution for net infiltration separate from that from the water balance probability distribution. Figure GC-1, therefore, could also represent my probability distribution for net infiltration based on convective heat flux estimates.

Flux Estimates Based on Hydraulic Properties and Water Potentials in the PTn
Because the PTn is highly porous and highly permeable, most of the water flow through this layer is in the matrix. Neither the thermocouple psychrometer data nor the core samples show a matric potential gradient within this layer, so we can assume that flow is the result primarily of the gravitational potential gradient. I made some simple calculations of fluxes through this layer, based on hydraulic properties measured by L. Flint (1996). I assumed a Brooks-Cory unsaturated hydraulic conductivity function, so that:

$$q = K = K_s\,(\Psi_e/\Psi)^{2+3/b}$$

where:
q is the percolation flux, mm/yr,
K is the unsaturated hydraulic conductivity at the prevailing water potential, mm/yr,
K_s is the saturated hydraulic conductivity, mm/yr
Ψ_e is the air entry potential, bars,
Ψ is the water potential, bars, and
b is the slope of a log-log plot of the moisture retention function.

From L. Flint's data I obtained the following: $b = 5.1$, $\Psi_e = 8 \times 10^{-3}$ bar, $K_s = 63 \times 10^3$ mm/yr. The flux calculations from these values are shown below.

Ψ (-bars)	**Flux (mm/yr)**
0.1	100
0.2	17
0.5	1.7
1.0	0.3
2.0	0.05
5.0	0.005

The psychrometer data from boreholes typically show water potentials in the range of -2 to -5 bars, which would indicate very low fluxes. However, the published uncertainties in the psychrometer data are plus or minus 2 bars. I have worked with thermocouple psychrometers throughout my professional career (almost 40 years), so I am well aware of their strengths and limitations. I believe that the psychrometers in the boreholes have not equilibrated, probably because of the packing material that was used to backfill the holes. They are accurate enough to give good information on the matric potential gradient (because the depths are so great, and an equilibrium profile would show such a large change in water potential with depth), but are not good enough to provide the information needed to accurately compute a flux through the PTn.

The water potential data from the borehole samples are also difficult to interpret, because they show considerable scatter. There are two problems with these data. The first is that samples dried in the process of sampling and handling. The second is that the dew point water activity meter used to make the measurements has a maximum possible resolution of 1.4 bars and a measurement uncertainty somewhat larger than this amount. Measurements wetter than -1.4 bars were recorded as 0 water potential. Many of the samples were recorded as zero, indicating that samples were wetter than -1.4 bars, but one cannot know how much wetter.

The most reliable data for estimating fluxes, in my opinion, have come from measurements in the ESF. Unfortunately, sampling the rocks while boring was in progress apparently was not considered (I do not know of any more important data that could have been obtained from the ESF, so I cannot imagine why these data were not collected). A very limited program was undertaken after the rocks had been allowed to dry for some time, and now that considerable drying has taken place, an extensive sampling and measurement effort is planned. We have no published measurements of water potentials from within the ESF, but values obtained from A. Flint (pers. comm.) show water potential in the range of -0.2 to -0.5 bars. These were obtained both with matric potential sensors and with tensiometers. I therefore consider the measurements reliable. They are also much more consistent with the water potentials I would expect at that depth in the mountain. Based on these water potentials and the estimates I calculated in the table above, I estimate fluxes to be between 1 and 20 mm/yr. The PDF from these estimates of percolation flux is shown in Figure GC-2. Eighty percent of the probability density lies between 1 and 10 mm/yr; the extreme values range from 0.01 to 100 mm/yr. The range reflects the large uncertainties associated with the water potential data and the hydraulic properties estimates. I expect the work on the ESF samples during the coming year to drastically reduce these uncertainties. I know of no way to assess spatial variation of flux estimates using hydraulic properties and water potential data.

^{36}Cl Tracer Methods

The ^{36}Cl data from the ESF provide strong evidence of fast transport paths for water and solutes from the surface to the repository horizon. They also suggest pathways for the fast transport and give information on minimum, as well as maximum, fluxes within the mountain. The fact that all bomb-pulse ^{36}Cl was found in the feature-based samples suggests that the fast paths are faults and associated fractures. The fact that many of the samples (feature-based and other) are at modern (<10,000 years old) water concentrations indicates that the transit time is less than 10,000 years for much of the water in both the fractures and the matrix. The fact that many samples were less than bomb-pulse concentrations, but greater than modern concentrations, indicates that much of the water is older than 10,000 years. Some of the water with concentrations above modern water could be the result of mixing bomb-pulse water with modern water, but it seems unlikely that all of them could be the result of that mixing.

To quantify the fluxes, a transport model must be used. The modeling effort presented by A. Wolfsberg (UZFMEE Workshop 2), I thought, did an excellent job of simulating ^{36}Cl transport through the mountain. Only 0.02 % of the flux in faults, at an average flux of 5 mm/yr, is needed to match the ^{36}Cl observations. If the average flux were greater than 5 mm/yr, wash out of the old water would occur, and if the average flux is much below 5 mm/yr, the new water would not yet have reached the ESF.

Based on A. Wolfsberg's analysis, I would estimate a percolation flux that ranges from 1 to 10 mm/yr (Figure GC-3). The most likely value appears to be about 5 mm/yr.

Convection of Radioactive Carbon

This method was described by E. Weeks (presentation at UZFMEE Workshop 3). It is similar to the convective heat transport method in that carbon is assumed to be transported by percolating water within the mountain. If the activity of the carbon, as it enters the mountain, is constant, then the activity at any depth can be computed from the rate of transport to that depth and the rate of diffusion. E. Weeks found that the rate of diffusion was small compared to convection, so he could compute water fluxes by comparing computed activity profiles for different fluxes with measured activity profiles. Fluxes estimated in this way were about 2 mm/yr, and he believed that corrections to his model would perhaps double this value. I have little experience with radiocarbon methods, so I cannot assess the uncertainties. The fact that this number corroborates numbers from other methods adds confidence to the number, as well to the others. The method potentially could provide information about spatial variation of percolation flux, but I have too little information to make those estimates.

Mineral Coatings on Fractures

Z. Peterman (presentation at UZFMEE Workshop 1) described analyses of calcite and opal coatings in fractures. Ages of the coatings were determined and used to estimate a flux of was 2 mm/yr. Again, I know of no way to assess the uncertainty in this value. It has qualitative significance, however, in that it shows significant downward flux at a steady rate during the past 250 ky or so. The number he gives for percolation flux corroborates the numbers from the other methods without influencing the range already established.

Perched Water

The presence of perched water bodies, which were found in essentially all locations under Yucca Mountain where deep enough boreholes were drilled, is strong evidence for downward flow through the mountain. The magnitude of the percolation flux based on perched water data can be established only through modeling, and the value is heavily dependent on the hydraulic properties assumed for the formations under the perched water. I do not recall any estimates of percolation flux based on this method, but understand, from A. Flint (pers. comm.), that percolation fluxes below 1 mm/yr or so do not maintain simulated perched water without unreasonable assumptions about the hydraulic properties of the Calico Hills (CHn) formation below the perched water zone. Increasing the percolation flux to 5 - 10 mm/yr, while using the measured hydraulic properties for the CHn layer, Flint et al. (1996) showed the simulated perched water at locations where it has been observed. The value of these data is more qualitative than quantitative. As the perched water data are examined more closely in the modeling effort, however, useful estimates of percolation flux may result from this method.

Combined Percolation Flux Estimate
Based on my experience and review of the various approaches, I would assign the following relative weights to the approaches to characterizing percolation flux:

Surface water balance	0.3
^{36}Cl tracer methods	0.3
Flux through PTn	0.2
Convective heat flux	0.05
Radiocarbon decay	0.05
Mineral coatings	0.05
Perched water	0.05

As discussed previously, based on available data, I am able to develop percolation flux estimates including uncertainties for the surface water balance, ^{36}Cl tracers, and flux through the Ptn methods. Normalizing the weights for these three methods to unity, the resulting probability distribution that gives the weighted combination of these approaches is given in Figure GC-4.

In terms of spatial and temporal variability, high weight is given to the results of the surface water balance, since I know the basis for that variation, and Flint et al. (1996) have incorporated it into their model. None of the other methods is suited to an analysis of spatial and temporal variation.

PARTITIONING BETWEEN FRACTURES AND MATRIX; SEE PAGE INTO THE DRIFTS

I view the flow system in the TSw as consisting of three components: the matrix flow, the fracture flow, and potentially fast flow within and near faults and areas of focused flow. Roughly 95% of the total flux occurs within the fractures of the TSw, and 5% occurs within the matrix. The fast-flow component carries <1% of total flux. This assessment is based on simulation results from both the LBNL and LANL models (presentations by LBNL and LANL principal investigators at UZFMEE Workshops 1 and 2).

The issue of seepage into the drifts is easily resolved, I think, by providing a small amount of ventilation. The observations in the ESF, as well as several calculations, show that much more water could be evaporated in a year than could be provided, even by the highest flux estimates. The thermal pulse associated with the emplacement of waste will also be effective in keeping water out of the drifts. It is possible that water would not drip into the drift, even without these disturbances, but more work is required before this can be determined with certainty.

POTENTIAL FOR REDUCING UNCERTAINTY

In science one often assumes that uncertainty in a measured value can be reduced by improved measurement methods and/or additional sampling. However, when the underlying process that is being sampled itself is uncertain, new methods and more samples may not reduce uncertainty. In fractile processes, for example, more detailed sampling leads to increased variance. More research over the next year, or even over the next 5 years, could lead to a better understanding of the processes governing water flow within the mountain. From an engineering standpoint, however, I think it unlikely that more measurements (beyond those already underway or suggested for the ESF) will greatly change our understanding. We now know that there is rapid movement of some water to repository level, and that average fluxes are likely to be in the range of 1 to 20 mm/yr range. No amount of research is ever likely to be able to *prove* that fluxes as high 20 mm/yr are impossible. The repository design will therefore have to accomodate fluxes in that range. (Twenty millimeters of water a year over the area of the repository is a trivial amount in a desert; that much water could evaporate in two or three days.)

RECOMMENDATIONS FOR FUTURE WORK

In my opinion, the most critical need at present is for careful measurements of water potential, water content, and hydraulic properties in the ESF and on samples taken from the ESF. These measurements can establish water potentials of the rocks *in situ*, can show whether the rocks and fractures are in equilibrium, and can show whether significant lateral flow is occurring. They can also increase confidence in the estimates of hydraulic properties used in the models. A high priority also should be given to measurement of unsaturated conductivity of the rocks. Several methods should be used and compared because of the large uncertainty in all of the methods.

Additional studies could be conducted to reduce uncertainty in the surface water balance estimates of flux. Additional information should be obtained on plant water uptake, effects of rock cover on slopes, effects of snow, infiltration into washes, and transport of water across and along the rock-alluvium contact.

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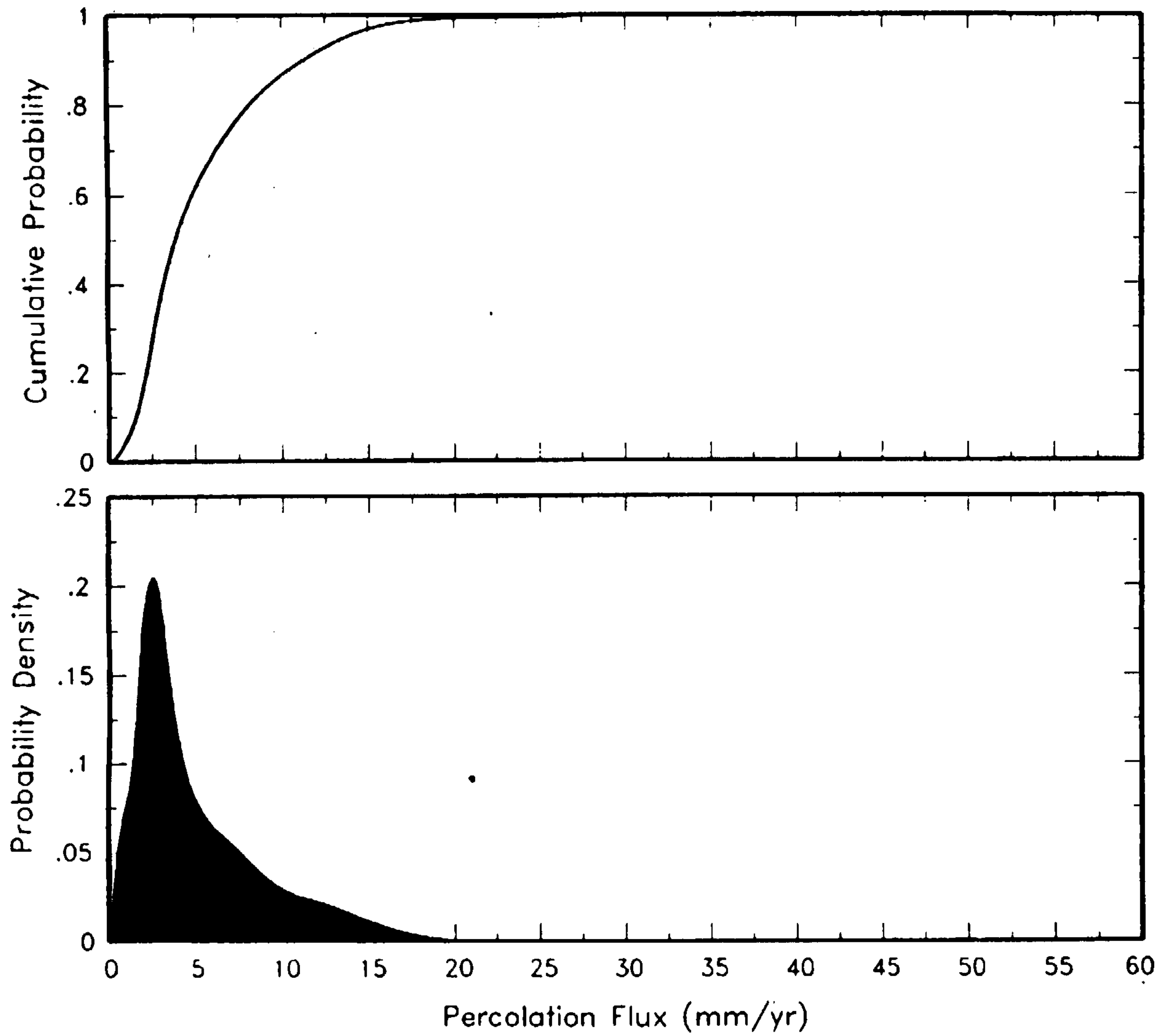

Figure GC-1 Assessed distribution for percolation flux at the repository level developed by Gaylon Campbell based on net infiltration. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

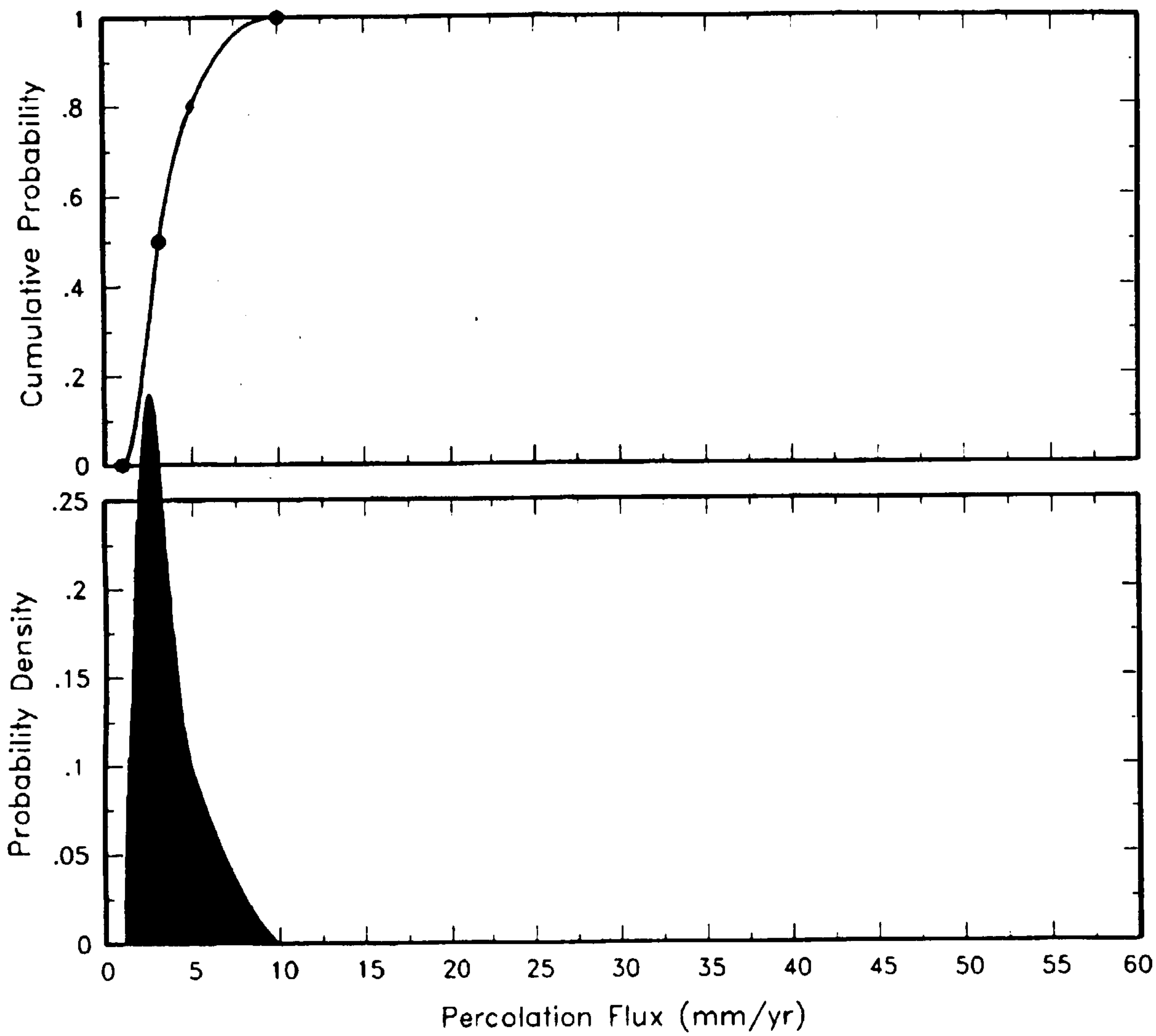

Figure GC-2 Assessed distribution for percolation flux at the repository level developed by Gaylon Campbell based on saturation/water potential data. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

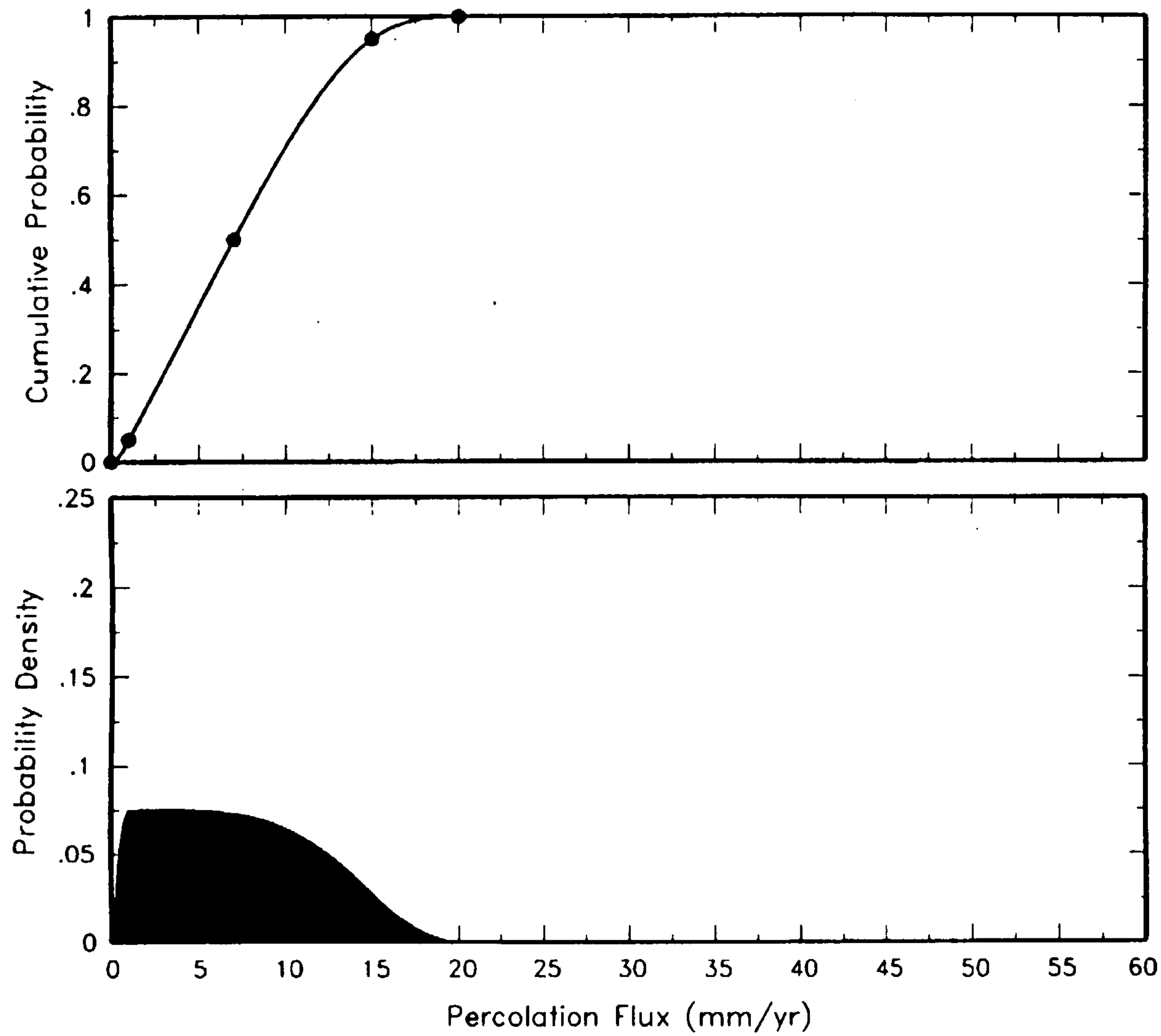

Figure GC-3 Assessed distribution for percolation flux at the repository level developed by Gaylon Campbell based on ^{36}Cl data. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

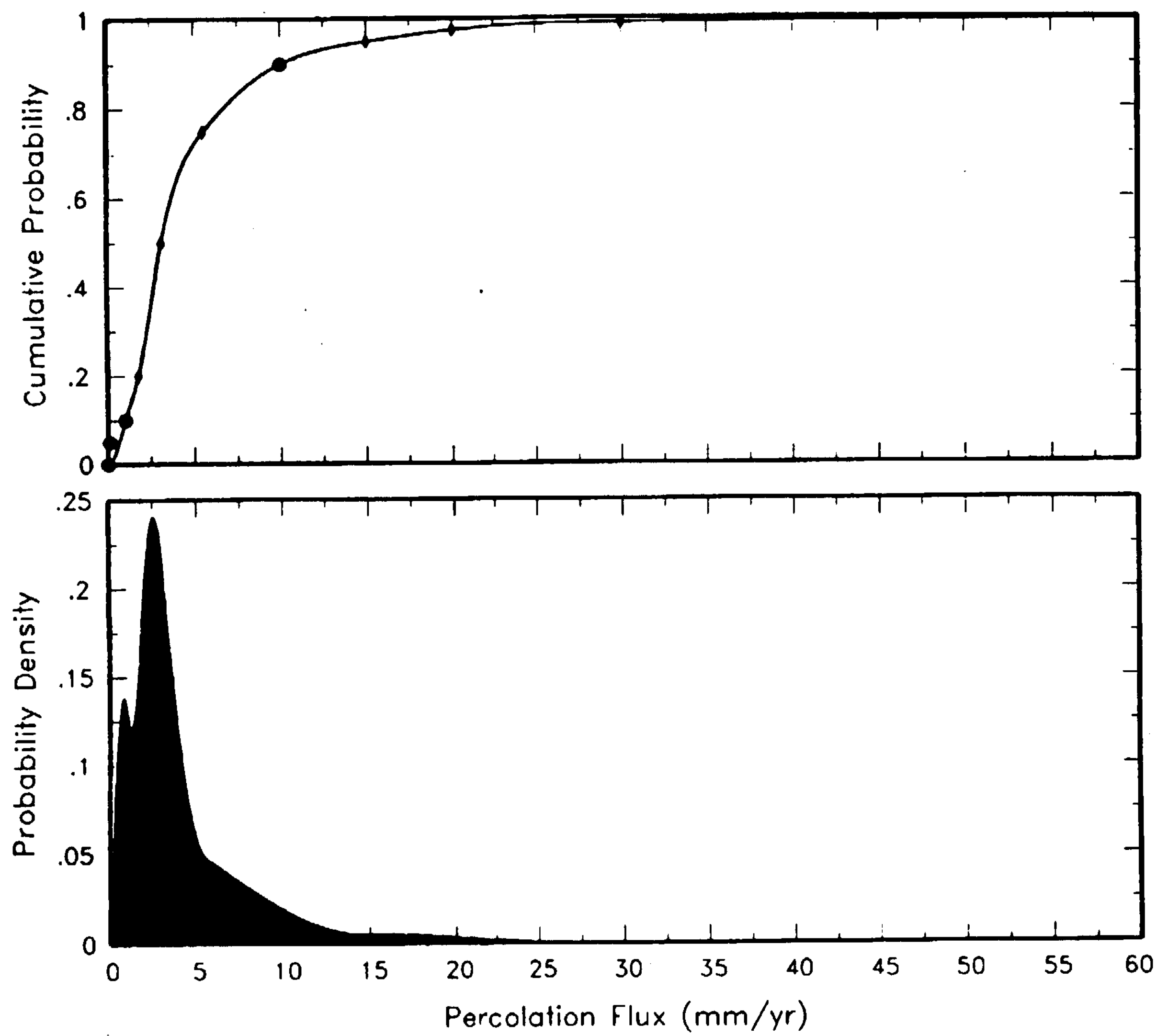

Figure GC-4 Combined distribution for percolation flux at the repository level developed by Gaylon Campbell. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

ELICITATION SUMMARY
GLENDON W. GEE
February 21, 1997

OVERVIEW OF UZ FLOW: PROCESSES AND MODELING ISSUES

There are two major drivers for getting moisture into the unsaturated zone system: episodic rainfall events, and the fault and fracture system within the rocks.

Fractures and faults are the most important features to consider; the matrix properties of rock units are of secondary importance. Tracer analyses by E. Weeks (UZFMEE Workshop 3 presentation) indicate that ^{36}Cl matches reasonably well with fault zones. The "horse-tailing" concept presented by Warren Day (Workshop. 3 Field Trip), which suggests funneling through fractures into the deep subsurface, appears a realistic model. A significant amount of water moves from fairly shallow soils into channels that overlie faults and fractures. The areas containing faults and fractures represent 5% or less of the total surface area. These areas, combined with episodic rain/snow (about 250 mm/yr at the crest), may send 150 to 200 mm of water into the fault horsetails (via funneled flow), giving rise to ^{36}Cl and tritium in the subsurface.

Moisture flow within the PTn is more puzzling. Pneumatic responses to barometric changes show higher permeabilities than from core, which measures matrix properties. Therefore, I infer that there is fault-enhanced permeability within the PTn. Accounting for the large spikes in the ^{36}Cl that occur at spacings of about 200 to 700 m requires few faults within the PTn. About 3 of 60 mapped faults in the block are in the UZ site-scale model now; adding more would account for the ^{36}Cl. Horse-tailing within the PTn and consequent concentration within the faults and fractures of the TSw would account for the ^{36}Cl observations.

Net infiltration is dominated by episodic events. Rainfall events that move water below the root zone within the repository occur at most two or three times a year. The rest of the year little or no net infiltration occurs. In some years, net infiltration events may be absent entirely, while during other years (e.g., the El Nino years) they may produce significantly more net downward flux of water into the repository area.

Net infiltration at Yucca Mountain is also highly variable spatially, as illustrated by Flint et al. (1996). A rigorous analysis of the spatial variations of recharge should be a key input to deciding the final location of the proposed repository, as location will determine the integrated recharge number that should be used to analyze the water flow impacts. Ideally, the proposed repository should be sited where net infiltration (recharge) is lowest. This would suggest that locating the repository below alluvium would be preferred over areas where fractures and fault zones are connected to surface exposures and where precipitation is higher. Moving part of the repository to the northwest and away from the Ghost Dance Fault area (as has been suggested) may increase the total recharge to the proposed repository.

Lines of evidence indicate that the mountain is wetter than the matrix data would suggest and that water does not move quickly through the matrix. For example, A. Flint (presentation at UZFMEE Workshop 2) reported that the in-situ tensiometer data in rock were -0.1 to -0.3 bars, suggesting that the rock is already wet in spots, at the tunnel level. The saturated hydraulic conductivities are not high enough to indicate that matrix flow is the dominant process. In addition, the laboratory measured matric potentials seem at odds with the in-situ tensiometer data. Relying more on the heat dissipation data and the tensiometer data, the mountain is seen as wetter than the matrix data suggest.

Lateral flow within the rock is likely. The top of the PTn appears to be a permeability barrier, and textural differences within the PTn itself could lead to lateral flow. However funneling into fracture and fault zones will capture the water moving laterally. Thus regional-scale lateral diversion is considered unlikely. Faults and fracture zones, as long as they are sufficient to hold water, will allow water to flow down to depth. Many of these faults and fractures may go all the way through the section. I am intrigued by T. Tokunaga's work (presentation at UZFMEE Workshop 2) showing fracture flow at low tensions (i.e., very close to full saturation), but it may be difficult to show that these low tensions will be operative at depth. It may be possible within the faults, but it seems unlikely.

APPROACHES TO ESTIMATING PERCOLATION FLUX

The following approaches to estimating percolation flux at the repository horizon were discussed. In the course of the assessments, recommendations were also made regarding the ongoing data-collection and modeling efforts at Yucca Mountain.

Net Infiltration

The net infiltration map developed for Yucca Mountain (Flint et. al., 1996) provides a generalized representation of the infiltration pattern in the area. In the series of maps prepared for the Yucca Mountain project by A. Flint and others (A. Flint presentations at UZFMEE Workshops 1 and 2), there appeared to be a trend toward higher and higher recharge rates, but it is not certain that all of the processes were adequately accounted for in the modeling. Certainly runoff was inadequately addressed, since the modeling was 1D. At a minimum, a 2D watershed model should have been employed. Specific modeling of net infiltration in the Yucca Mountain setting is difficult because no drainage data were obtained directly and thus there is no way to close the water balance correctly. Further, the spatial and temporal changes in evapotranspiration are uncertain, so the entire water balance database is subject to large errors that perpetuate similarly large uncertainties in the drainage estimates.

However, there is agreement on the general pattern of water use and the potential areas of drainage or recharge. Areas containing deep alluvium (> 2 m, and containing a fine-grained component) will effectively store water, and a lower limit of 0 mm/yr net infiltration likely occurs in these areas. Vegetation in the deep alluvium will intercept the water efficiently, and it is likely to be recycled annually (despite the episodic events of high moisture input that could cause local flooding). Roots observed in the cut slope adjacent to the UZ-7A drill pad (UZFMEE Field Trip) extended to a depth of more than 20 feet, demonstrating that plants can remove water from significant depths in alluvium at Yucca Mountain. Recharge in the deep alluvium is likely to be similar to an analog area located near Beatty, Nevada, where studies indicate that in areas of deep alluvium, no significant recharge has occurred over the past several thousand years (Gee et al. 1994; Andraski and Prudic 1997).

Infiltration in the upper reaches of washes, however, is likely greater than the amount shown on published maps. As surface water moves downslope over thin soils, there is a high probability that it will encounter open fractures that will allow funneling and concentrated flow. At higher elevations, the net infiltration rates shown on the published maps may be too high. Runoff, and subsequent interception of water downslope, will shift high net infiltration rates to lower elevations. The potential for some lateral flow also should be considered.

With respect to the proposed repository area, the western side is below an upland part of Yucca Mountain that contains thin alluvium and likely has a higher net infiltration rate than the eastern side of the proposed repository. The eastern side has a thicker alluvial fill, so the net infiltration is expected to be lower. The average net infiltration estimated by A. Flint at 6 mm/yr (presentations at UZFMEE Workshops 1 and 2) may underestimate the actual value. Infiltration is judged to be roughly two times higher (≥ 10 mm/yr) based on more water infiltrating in the upper reaches of the washes, and higher rock permeability based on more funneling of water into fractures below the thin alluvium (there are probably more fractures in the subsurface than can be mapped on the surface).

The probability distribution of net infiltration in the repository area that I developed for a 100-year average, is shown on Figure GG-1. The mode of the distribution is 12 mm/yr, and 95% of the probability is between 2 and 30 mm/yr. The recharge rate I estimated refers to the effective net infiltration that occurs over the repository area (i.e., the water below the root zone, or below about 10 m, where no root uptake is occurring). Vapor flow by convection may occur in some areas on the west side of Yucca Mountain (where large fractures occur and the alluvium is thin). However, E. Weeks' analyses (presentation at UZFMEE Workshop 3) suggest that this mechanism has a minor effect in the central or eastern part of the mountain, accounting for no more than possibly a fraction of a mm/yr water loss. I am not aware of any data that support a hypothesis of significant drying of Yucca Mountain above the proposed repository. Also, the geothermal gradient is too small to move water vapor from depth at any appreciable rate. Based on geothermal gradients of 20-30 °C/km, and typical thermal diffusion coefficients, I calculate that the maximum upward flux from the geothermal gradient is less than 0.1 mm/yr. The only other mechanism for limiting recharge at the repository level is lateral diversion. There is some evidence that lateral movement could occur in localized areas at the base of the PTn, and it might occur in regions where perched water exists. I assume that this is a very small fraction of the total, say 10% or less, and therefore 90% or more of the net infiltration will become recharge at the repository level. I believe that when all the extreme precipitation events are factored in, the long-term average is about 12 mm/yr .

Carbonate-filled fractures in the bedrock probably will not inhibit downward movement of water. Filled fractures, which occur predominately within 10 meters of the surface, open up through wetting and drying. Therefore, measurements of fracture fill permeabilities are not a good measure of hydraulic properties. An example is the water that passes through heavy caliche layers in arid soils.

Water balance modeling in an arid area such as Yucca Mountain has a high degree of uncertainty. Evaporation rates, runoff, drainage, storage and recharge are all difficult to estimate and highly uncertain. Gee et al. (1994) indicate that soil, plant, and climatic variables can cause recharge to vary from near zero to more than 50% of annual precipitation in desert settings. Recharge is not easily modeled, because little is known about the field hydraulic properties that control net infiltration. Episodic storm events clearly drive the system at Yucca Mountain. Moisture storage data from neutron probes on Yucca Mountain are of limited value because spatial and temporal variations may or may not represent fluxes, particularly in relatively coarse or fractured sediments. Even daily measurements may not accurately show the episodic recharge events. In some cases, the boreholes themselves may funnel water. Bedrock permeability and other hydraulic property data collected for the Yucca Mountain Project may vary by factors of 5 or 10, and thus have high uncertainty. Until field data are available to verify the range of uncertainty in numbers, this uncertainty will control estimates of infiltration. A mass balance model with field-measured values is needed to lower the uncertainties. A possible test that could be conducted at the ground surface above the ESF on Yucca Mountain could employ a very long (> 1 km) line source test with a constant drip. Measurement of water infiltration around the drip line might allow inverse calculations of bedrock permeabilities.

Percolation flux at the level of the proposed repository is judged to be essentially the same as shown in the distribution developed above. There could be a small amount of lateral migration, but the input and output amounts in the Topopah Springs unit are judged to be essentially the same.

Temperature Gradients

The advantage of a temperature gradient approach is that thermal data give a bulk number that is an average for a stratigraphic interval and includes both the fast and slow components of flow. However, there are significant uncertainties associated with heat flux. A deterministic value for heat flux could be obtained by combining all of the thermal profiles and carrying their uncertainties through the necessary calculations. An attempt should be made to perform a nonlinear fit to the temperature data to see if temperature profiles contain the expected curvature. Post-Workshop 3 calculations of thermal profiles by E. Kwicklis (pers. comm.) suggest that with properly assumed heat fluxes, recharge rates in the range from 5 to 20 mm/yr are reasonable.

Saturations and Water Potentials

Several issues must be considered in using chilled mirror psychrometers. (1) The instrument range is limited to relatively dry sediments. Specifically, the instrument does not operate well at moisture levels wetter than about -5 bars (99.6% r.h.); and perform best at levels below -15 bar (98.9% r.h.). In this range, a change of ± 0.5% r.h. changes the water potential by as much as 10 bars. (2) Proper handling of core is critical, as a low-porosity core can easily go from 1 to 100 bars if mishandled and dried even slightly. (3) Core having a small surface area may lose some of its original humidity through equilibrating with the outside air (a newer version of the instrument has a better seal to the chamber and can better preserve original humidity); systematic errors tend to indicate a sample is drier than it really is (more randomness in wet samples). The PTn has more surface area, and therefore should provide more accurate data than the Topopah Spring or Calico Hills units.

There are also concerns with the ultra-centrifuge data. (1) The saturated values obtained by this method may have errors because rates of delivery and boundary conditions are not clearly defined for nearly saturated samples (saturations appear too low). (2) In some materials consolidation and changes in pore size distribution can occur and affect flow (this would most likely have the greatest effect on zeolitized or loosely consolidated samples). (3) The head that distributes water in the ultra-centrifuge may not uniformly distribute water to the sample or the sample may allow preferential flow. (4) Care must be taken in quantifying sample water contents. The original data presented by L. Flint (UZFMEE Workshop 1) illustrates some of the potential problems in sample analysis for the ultra-centrifuge.

The recent ultra-centrifuge sample data from L. Flint (pers. comm. to S. Neuman) indicate different (lower) conductivity values for some for the same water contents that were presented for PTn samples in the first workshop. Unit gradient assumptions may not be correct (possible errors of a factor of two or more). Plots of the new data (S. Neuman, pers. comm.) give a range of values with an uncertainly factor of 4, but the mean values would suggest a higher flux in the matrix than originally assumed. These new data (K vs water content) from the ultra-centrifuge indicate 10 to 100 mm/yr flux in the matrix, but more samples are needed to obtain reliable values. The limited data set (only 2 samples) is inadequate for obtaining an accurate assessment. Comparison of more samples by independent methods could provide better confidence here.

Chloride Mass Balance

In this method, averaging is assumed over a large area, and matrix and fracture flows are integrated to obtain a flux average. Flux of a few to about 10 mm/yr can be calculated (using 180 mm/yr rainfall and J. Fabryka-Martin's value of 0.6 mg/l presented at UZFMEE Workshop 1). Measured values in thick alluvium are consistent within the unit (Fabryka-Martin, 1994, Table 4.1). Analysis of near-surface (0-5 m) depths are not useful because of potential interactions and recycling of chloride in the plant root zone. Below the root zone the chloride data should be meaningful.

Isotopic Evidence

The observed spikes in ^{36}Cl and tritium provide strong evidence for fast flow paths in the mountain. The flow velocities required are on the order of 7.5 m/yr (assuming a 40 year travel time and a 300 m repository depth). The spacing of ^{36}Cl spikes is on the order of 100 m. Assuming that about 50% of the spikes are related to faults at the surface, and a 5-to-1 funneling or concentration within the faults (as suggested from horse-tailing), only about 2% of the total surface area is contributing to the fast flow seen at depth. The concentrated flux through these faults is on the order of about 150-200 mm/yr. The net influx of water averaged over the repository area is on the order of 10 mm/yr.

Perched Water

Perched water clearly has a role at Yucca Mountain. The age of the water could be on the order of several hundred years, and thus significantly younger than the ages proposed by Yang et. al. (1997), which are 4,040 to 5,370 yr for SD-9; 2,150 to 2.650 yr for NRG-7A; and 5,260 to 6,260 yr for UZ-14. Although the ^{14}C data indicate an older age, the low chloride concentrations in the perched water relative to surrounding water suggest a younger age. Degassing or some other (unknown) effect may have occurred, resulting in inaccurate age estimates. In addition, mixing of older and younger water could result in inaccuracies.

PARTITIONING BETWEEN FRACTURES AND MATRIX; SEEPAGE INTO THE DRIFTS

Most (as much as 90%) of the percolation flux occurs in fractures in the TSw that are also the fast-flow paths. Roughly 5% of the area contains flow-contributing fractures (from the approximate fault spacing discussed by W. Day in Workshop 3), and some fractures will have flux rates in the range of 150- 200 mm/yr (as indicated by the observed ^{36}Cl "hits").

If flux rates of this magnitude (up to 200 mm/yr) occur over 5% of the area (fractures and faults) and flux values of 2-3 mm/yr occur in the matrix (remainder of the area), then the net infiltration on an areal basis will be more than 10 mm/yr.

The ESF should be completely characterized with respect to ^{36}Cl "hits", and this equivalent seepage number should be applied to calculate the number of seeps in a larger area. Near-saturated conditions are necessary to have any seeps (essentially 0 water tension), while tensions on the order of 200 to 300 cm have been measured (A. Flint's PTn measurements as described in UZFMEE Workshop 3). Based solely on these measurements I speculate that if such pressures persist in a sealed drift, then seepage into drifts will not occur. To my knowledge, no seepage has been observed either in the tunnel or any of the drifts. The lack of seepage may be due to ventilation drying. Testing of a sealed drift will be required to resolve this issue. The probability of seepage into drifts is therefore low based on present observation. Seepage into the actual repository will depend on the steady-state tension values and the actual repository design. A passive ventilation system could be designed to remove more than 30 mm/yr water, thus keeping the repository dry. Evidence from the ESF is consistent with this judgment (despite confounding effects of ventilation), since seeps are not observed even in fault zones. Seepage rates could be tested by injecting water above a sealed-off room in the ESF.

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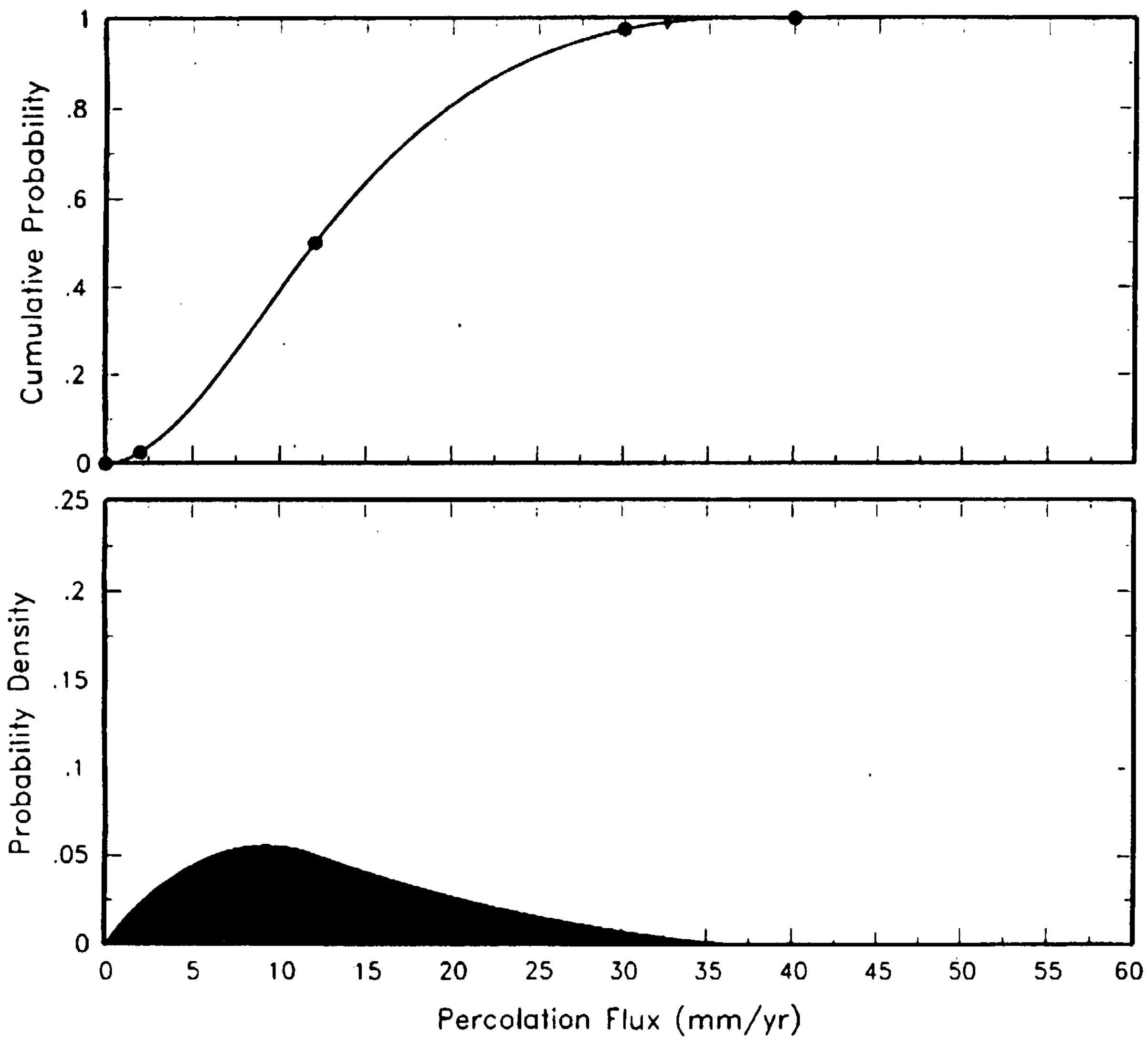

Figure GG-1 Assessed distribution for percolation flux at the repository level developed by Glendon Gee. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

ELICITATION SUMMARY
JAMES W. MERCER
February 7, 1997

OVERVIEW OF UZ FLOW: PROCESSES AND MODELING ISSUES

Those modeling the unsaturated zone (UZ) beneath Yucca Mountain are making a good attempt to model a highly complex system that has spatial and temporal variability. My comments here do not intended to imply that this modeling is deficient; rather, they are directed at the uncertainties in the inputs to the model and are intended to provide some ideas about various enhancements or sensitivity tests that could be conducted.

Beginning with net infiltration, the input of moisture into the mountain is highly spatially variable. I agree with the basic spatial distribution presented by A. Flint (UZFM Workshops 1 and 2), but believe that there could be more infiltration and less storage beneath the washes than has been assumed. The infiltration is also temporally variable, related to episodic extreme storm events or sequences that last for several hours to a week. Therefore, a transient pulse must be considered and, depending on the amount of temporal damping in the system, might call into question the assumption of steady-state conditions deeper in the section at repository depths. The matrix component of the recharge, which is probably less than 1 mm/yr, is best characterized by a steady-state condition. The fast-flow component is a transient phenomenon, as suggested by the observations at Rainier Mesa.

I accept the basic approach being taken to associate infiltration with various subunits: ridge-tops, side-slopes, alluvium, etc. However, there are other features that could focus and increase recharge (e.g., the "horse-tailing" faults described by W. Day at the UZFM Field Trip). The alluvium in the washes likely is very heterogeneous and may allow for rapid water movement and less storage during episodic storm events. Lateral flow within the alluvium and at its base could be an important process for concentrating flow in the alluvial washes.

These processes of focusing flow help the water move through the Paintbrush unit (PTn), although the temporal pulse from infiltrating water will continue to be dampened as moisture moves down through the section to repository depths. The contact between the Tiva Canyon (TCw) and the PTn presents an opportunity for some lateral diversion, but this probably is not significant at a regional scale. The water will flow laterally until it reaches a significant fracture and then will flow vertically. The TCw-PTn contact surface, which is irregular, probably helps focus flow down fractures and faults. Further, there is little independent evidence for lateral flow at this surface where it is exposed to the east. So as water moves through the PTn it is focused in space and dampened in time.

At the Topopah Spring (TSw), a reduction in porosity causes the moisture to spread out and enter into the fracture network that characterizes this unit. Although a dual permeability model probably is needed to characterize the movement of water through the PTn, an ECM-type model could be used for the movement of water in the TSw fracture network, which could be characterized a porous medium. However, allowance must be made for a fast-flow component to explain the presence of ^{36}Cl at depth. In terms of fracture/matrix interaction, there is probably little interaction within the TSw because the matrix permeabilities are so low. Fracture coatings may also reduce the interaction. There is probably more interaction in the PTn.

I interpret the environmental isotope data as suggesting that bomb-pulse tracers are present virtually everywhere samples have been collected (i.e., they are ubiquitous). The radiocarbon, tritium, ^{36}Cl, deuterium, and low chloride in the perched water all suggest fast fracture flow through the PTn. Because the isotopic tracers are ubiquitous, there must be a spreading mechanism and geometry, perhaps the fracture network in the TSw.

Fast flow is probably fault-controlled within the PTn. There are layered welded and non-welded units and/or variable amounts of pumice in the layers of the PTn. Experience with porous media having similar varied, multiple stratigraphic layers shows that it passes water slowly, as heterogeneities tend to disperse the flow. Faults that pass through all of the layers would allow for travel through the system. A weeps-type model may be appropriate for incorporating this type of behavior. It is difficult to see how water moves through the PTn without faults, although faults may not be as necessary for moving water in the TSw.

Air permeability measurements show that the TSw has large fracture permeability, including good vertical permeability. Anisotropy and lack of storage will lead to dispersal within the TSw. Changes from abundant to sparse fractures within different stratigraphic units locally focuses but ultimately spreads the moisture. This model implies that at the TSw there might be multiple small weeps, but these are probably not continuous to the surface unless they are associated with a major fault. This is in contrast to a few large weeps. The lack of seeps in the ESF could be due to the low volume of each weep relative to the ventilation effects. Alternatively, we may not yet have seen a pulse from a large infiltration event travel through to the depth of the ESF.

APPROACHES TO ESTIMATING PERCOLATION FLUX

The following approaches to estimating percolation flux at the repository horizon were discussed. In the course of the assessments, recommendations were also made regarding the ongoing data-collection and modeling efforts at Yucca Mountain.

Net Infiltration

Net infiltration is a temporally and spatially variable process. Long periods of very low infiltration are punctuated by episodic extreme storm events. The episodic events occur about every five years, last from several hours to as long as a week, and probably account for most (perhaps as much as 80%) of the total net infiltration. Therefore, this process should be a pulsed event in the UZ site-scale model. Key uncertainties in the present infiltration modeling are the amount of runoff and the amount of lateral flow.

In terms of the spatial variability of net infiltration, the basic approach taken by Flint et al. (1996) is good. The runoff must to be taken into account. I suspect that there may be too much emphasis on storage in the alluvial washes and that infiltration may be higher in these areas. Lateral flow within and at the base of the alluvium can lead to focused recharge into fractures in the underlying bedrock.

Based entirely on work conducted by others (e.g., A. Flint, L. Lehman, S. Stothoff presentations at UZFM Workshop 2) and no original work of my own, I offer my assessment of the range and uncertainty in the average net infiltration. This is a spatial average over the Yucca Mountain block and a temporal average (averaged over a sufficiently long period, say 100 yr, to have captured several extreme infiltration events). The probability density function and the cumulative distribution function for average infiltration are given in Figure JM-1. The preferred range of values lies between 5 and 10 mm/yr, with extremes that range from 2 to 30 mm/yr. The range between 5 and 10 mm/yr is equally likely; 60% of the probability density lies within this range.

In addition to uncertainties associated with net infiltration, the PDF in Figure JM-1 also is based on consideration of various other assessments given during the UZFM project. These assessments are summarized below.

- For an average precipitation year, net infiltration ranges from zero, for a soil thickness of 6 m or more, to more than 80 mm/yr for a thin soil on a north-facing slope at a high elevation and overlying high-permeable bedrock; infiltration averages 4.5 mm/yr (Flint et al., 1996).

- Estimates of the rate of shallow infiltration along the ESF North Ramp based on the Hudson and Flint (1996) analysis range from 0 to 25 mm/yr.

- Fabryka-Martin et al. (1994) used a chloride-balance calculation at Yucca Mountain to estimate percolation flux rates of 0 to 5.4 mm/yr.

- Based on simulations of Yucca Mountain Brown et al. (1993) indicate that flux values below about 1 mm/yr cause subsurface conditions that are too dry, while those above 10 mm/yr appear too wet.

- Based on measured temperature gradients within the TSw, deep percolation appears to be higher beneath active channels of major drainages, diminishing toward the margins and hillslopes bordering these channels. An apparent heat-flow deficit was accounted for as percolation fluxes beneath the Pagany Wash channel on the order of 10 to 20 mm/yr and on the order of 5 mm/yr or less beneath the hillslopes bordering this drainage.

- For S. Stothoff simulations (presentation at UZFM Workshop 2), the base case used an infiltration rate of 10 mm/yr over the North Ramp and 20 mm/yr over the proposed repository.

- Given a low rate of infiltration, rock properties had to be modified in the UZ site-scale model to account for perched water. With higher infiltration, it was not necessary to modify rock properties. This tends to support the higher infiltration rate.

At higher values of average infiltration, the spatial distribution may be somewhat different. At high values I would expect the distribution to flatten as more infiltration goes into the washes and less into the ridge-tops. This would be due to increased runoff at the exposed bedrock surfaces on the ridge-tops and side-slopes, increased lateral flow into the alluvium, and infiltration into the bedrock beneath the alluvium. At lower average infiltration rates, I would expect the spatial distribution to look essentially the same as presented by Flint et. al. (1996).

As water moves down, it likely will be focused into faults in the PTn. There is probably not much lateral diversion at the top of the PTn because of the faults and irregularities at this surface. The UZ site-scale modeling shows that significant lateral diversion occurs only at low infiltration rates, while at high infiltration rates vertical flow dominates. Therefore, the spatially and temporally averaged percolation flux at the repository horizon would be expected to be the same as the average net infiltration.

The spatial distribution of percolation flux at the repository horizon, however, likely will be much more uniform than the net infiltration distribution. After leaving the PTn, the water will diffuse into the TSw fracture network. The ^{36}Cl is found essentially everywhere, suggesting that water spreads out at depth, perhaps with some local highs near faults. The samples taken for ^{36}Cl are sampling the matrix component, but there likely is ^{36}Cl in the fracture network as well. The ubiquitous fracture distribution and the pneumatic data also suggest a fairly uniform distribution. This suggests a relatively uniform spatial distribution of percolation flux at the repository horizon.

Temperature Gradients

A regional depression in temperature is identified beneath Yucca Mountain. The temperature profiles flatten at the top, as expected from infiltration. However, the temperature profiles appear to be fairly insensitive to various amounts of percolation flux.

Uncertainties exist regarding thermal conductivities, but the primary uncertainty is the heat flux. Therefore, there is not much value in using the temperature data for assessing percolation flux. The UZ site-scale model does not calibrate against this data, but uses it as a qualitative check, which is probably appropriate.

Saturations and Water Potentials

The use of saturations and water potentials, as discussed in the workshop, appears to be a problem because the saturations are not very sensitive to flux. The approach is probably better suited for porous media than for fractured media. There is non-uniqueness between fracture-matrix coupling and flux such that, for particular saturations and water potentials, one can vary the fracture-matrix coupling and get any desired flux. To date, the large-block test at Fran Ridge has produced no usable results related to this. Because of the media involved, this approach may not be fruitful for assessing percolation flux.

Isotopic Evidence

Although the environmental isotopes, particularly ^{36}Cl, provide evidence of fast flow and indicate the spatial distribution of that flow, they provide no means of directly estimating flux. I view these as essentially tracer studies.

An uncertainty in the interpretation of the ^{36}Cl data is the meaning of the intermediate values of concentration. My preferred interpretation is that they represent bomb-pulse, especially since they are found in matrix samples. This suggests that when the fracture/fault component is included, the volumes of water must be larger than used in A. Wolfsberg's model (presented at UZFM Workshop 3). A.Wolfsberg's steady-state model does not account for pulses in the fractures. With pulsing, a greater fraction of water may make it to depth for the same average flux. Perhaps the Wolfsberg model should be run with a pulsed transient component.

The gas radiocarbon studies presented by E. Weeks (UZFM Workshop 3) seem reasonable. They give fluxes that are comparable to those that I assessed based on infiltration rates. The approach assumes equilibrium between the gas and the liquid. Perhaps we should look for evidence of freon in the Calico Hills unit.

Perched Water

A water balance for the perched water bodies should provide a constraint on percolation flux. This can be tested by assuming my assessment of percolation flux and seeing whether it gives a reasonable size for the perched water zone. One can use the hydraulic conductivities from cores for this unit (containing the zeolites) and vary only the percolation flux. The resulting calculated volumes could be compared with existing estimates of volumes. It would also be fruitful to consider the contribution to the perched water that might come from infiltration and lateral flow from Solitario Canyon. I think that the UZ site-scale model provides a good vehicle for these types of 'what-if' assessments to provide constraints on percolation flux.

PARTITIONING BETWEEN FRACTURES AND MATRIX; SEEPAGE INTO THE DRIFTS

At the repository horizon, most of the flow (perhaps 90%) will be in the fractures and the rest in the matrix. Fractures are ubiquitous, and fracture flow occurs at many locations. It is not clear how much, by volume, is represented by the fast flow component. The UZ model is the best tool for separating the fast component from the slow and for evaluating the relative contributions of both to the total flux at the repository horizon. A temporal pulse should be included in the net infiltration; we can then see how it is dampened at depth, and which volumes maintain the transient. Sensitivity analyses should make it possible to assess the amount of flow required to get a pulsed flux through the PTn; perhaps several faults are required.

I would expect that water seeps into the drifts at many locations through film flow along the wall of the drift, which is a relatively rough surface. Hetergeneities near the wall will lead to localized breakthrough. Mineral coatings within lithophysal cavities are a good natural analogue to this process. In terms of the volumes of the total flux that will enter the drifts, the modeling that is being conducted appears to model well the fracture-matrix system.

More dual-permeability calculations probably are needed, but these are already planned for incorporation into the UZ site-scale model.

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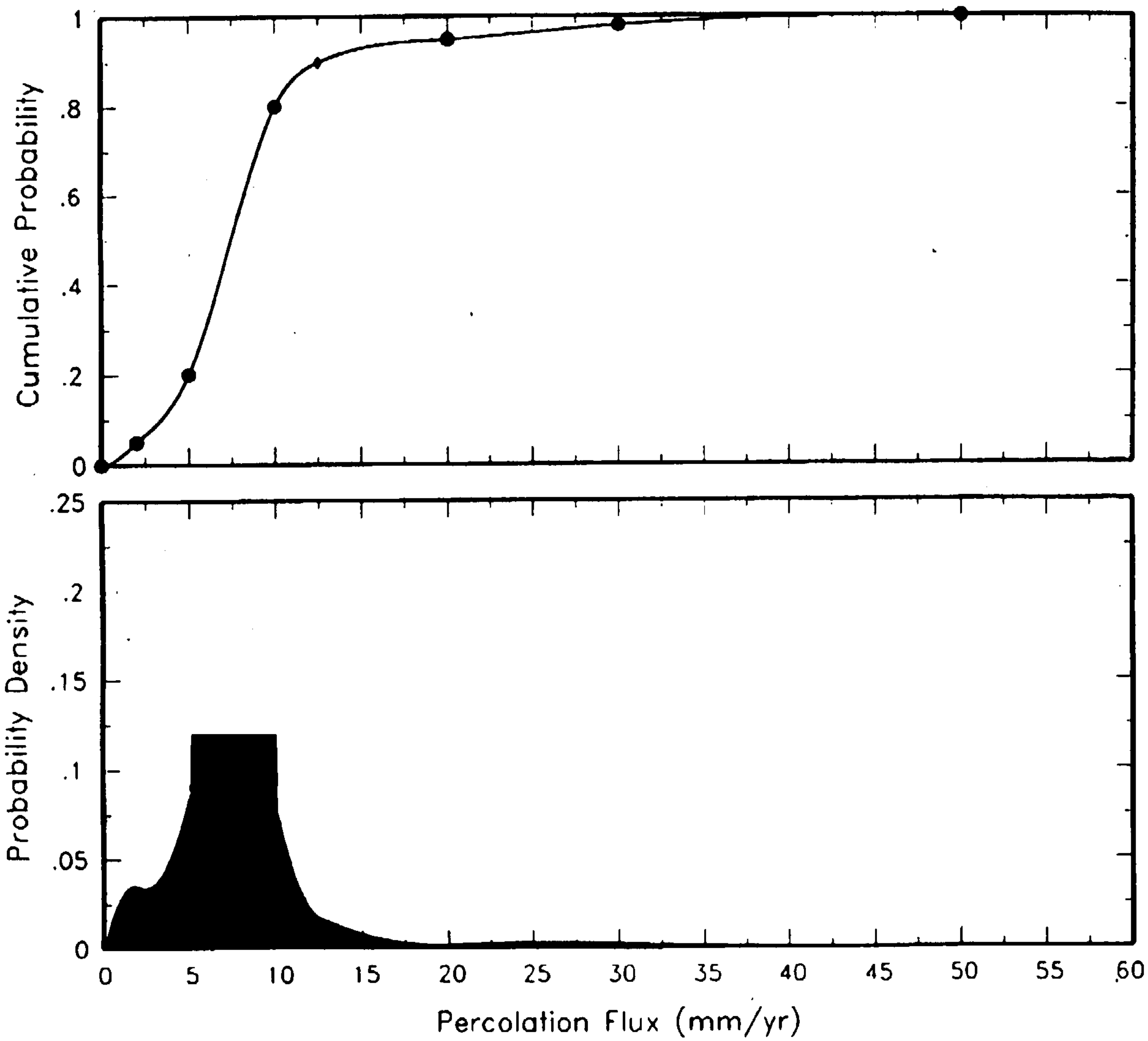

Figure JM-1 Assessed distribution for percolation flux at the repository level developed by James Mercer. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

ELICITATION SUMMARY
SHLOMO P. NEUMAN
February 19, 1997

INTRODUCTION AND CONCEPTUAL FRAMEWORK

The reliability of percolation flux assessments at Yucca Mountain depends on the choice of model and the availability of suitable data. There is no precedent for the assessment of subsurface flow conditions in a large, unsaturated, fractured (or porous) rock complex such as Yucca Mountain under semiarid (or other) climatic conditions. Thus there is no experience to indicate how reliable any model (conceptual, mathematical, or computational), and any particular set of data, would be in generating such assessments. There is, however, a rich body of accumulated generic knowledge about some of the key physico-chemical processes that govern fluid flow (as well as mass and energy transport) in unsaturated media (mainly porous), and about climatic and hydrogeologic controls on these processes, which together with site-specific data should allow one to make intelligent inferences about subsurface flow and transport conditions at Yucca Mountain. For these inferences to be scientifically credible, they should be based as much as possible on theories and models that are directly supported by, and compatible with, available experimental and site-specific data.

One of the better-understood subsurface processes in both saturated and unsaturated, porous and fractured rocks is that of heat flow. If there was a sufficiently large and reliable set of data concerning temperature, terrestrial heat flux, and ambient heat conductivity (preferably also heat capacity) across Yucca Mountain, such data could in principle be used to help render credible estimates of subsurface fluid fluxes across the mountain at various scales, including percolation fluxes across the repository horizon. Although some such data exist for Yucca Mountain, they may not be of sufficient quantity or quality to allow reliable estimation of these fluxes (more on this later).

One of the least-understood processes at Yucca Mountain is the mechanism by which atmospheric precipitation (rainfall and snow melt) is transformed into deep percolation below the root zone. Attempts to assess the space-time distribution of deep percolation on the basis of near-surface measurements and models have, in my view, been unconvincing. To my knowledge, nowhere (neither in fractured nor in porous terrains, neither in humid nor in arid environments) have such measurements and models been verified to yield reliable estimates of net infiltration on a scale comparable with that of Yucca Mountain, and with the space-time resolution attempted at this site. It is my belief that neither the models nor the data used to generate net infiltration maps across the surface of Yucca Mountain can be fully relied upon to provide credible estimates of net rates at which water enters the mountain, or of their space-time distribution. I especially doubt the premise, which underlies current infiltration maps, that net infiltration rates are higher along hilltops than along washes. The reasons for my assessment will be explained in some detail later. In the meantime, I conclude that the key to unraveling the nature and rates of subsurface flow at Yucca Mountain lies not at and near but at depth below ground surface.

If I were merely to guess at the bulk mean annual net rate of infiltration at Yucca Mountain, I would expect it to constitute between 5% and 30% of mean annual precipitation rate. Whatever the actual rate of net infiltration at the site may be, it constitutes an upper bound on bulk mean annual percolation flux within the interior of the mountain. I will attempt to estimate the range of bulk mean annual percolation fluxes within the mountain by examining conditions at depth. As will become clear, these estimates fall close to the above range.

Among the more reliable models applied to, and data available for, Yucca Mountain are those concerning pneumatic monitoring and air injection tests. Although there is considerable uncertainty about the nature of flow within fractures and faults at the site, there are strong indications that the pneumatic monitoring and air injection test data from welded tuff units represent conditions within fractures and faults that are at relatively low water saturation and thus are open to the flow of air. These data reveal a pneumatically interconnected network of fractures and faults that conducts air with relative ease across considerable distances within the Tiva Canyon (TCw) and Topopah Spring (TSw) welded tuff units, although not always with equal ease in each direction. The two sets of data provide self-consistent information about the permeability of this network which, considering the low water saturation in fractures and faults, probably is close to the intrinsic permeability of the network. Although our own work at the Apache Leap Research Site indicates that one should be able to estimate the air-filled porosity of fractures from a type-curve analysis of single-hole pneumatic injection tests, I am aware of no such estimates for Yucca Mountain (the air-filled porosity used to calculate permeabilities from pneumatic monitoring data at Yucca Mountain is that of the rock matrix, not of the fractures; this is justifiable because of the long time scale of these data relative to the time scale of typical single-hole air injection pressure transients).

Because matrix permeability of TCw and TSw rock samples is known from laboratory measurements to be lower by several orders of magnitude than the permeability of fractures and faults, one may conclude that flow in these units is dominated by fractures. Although field observations at TCw outcrops reveal many fractures that are filled with secondary minerals, these minerals do not seem to impede the ability of TCw fractures and faults to conduct fluids across this unit. The TCw appears to be so permeable that once infiltrating waters have migrated below the root zone, they can move with relative ease downward through fractures and faults. As the matrix is at relatively high ambient water saturation at depth, there is little opportunity for water to move into it; most of the percolating water is expected to move through fractures and faults. The same is expected to happen within the

TSw. Unfortunately, there is no information that would allow one to evaluate directly the modes, rates, and directions of water flow through fractures and faults within the TCw and TSw units (How much of this flow takes place in open fractures, how much in secondary minerals that fill them? How much of it is spread across wide areas of a fracture; how much is concentrated in narrow channels and rivulets, formed along fracture planes and/or along fracture intersections? How much flow occurs in capillary films? What are the associated flow rates? What are the mechanisms and parameters that determine the answers to these questions? How do they vary in space-time?). I propose to seek an answer to the question of percolation flux through Yucca Mountain by focusing on matrix-dominated flow within the Paintbrush nonwelded (PTn) unit that lies between the TCw and TSw.

That flow within the PTn occurs largely through rock matrix is evident from the fact that its matrix has comparatively high porosity and permeability; that saturation within the PTn matrix is sufficiently low to cause water from fractures and faults to imbibe into the matrix, thereby attenuating flow within the former; that fracture density within the PTn is relatively low; that faults within the PTn are relatively narrow and thus difficult to identify; and that the unit has a pronounced capability to attenuate the propagation of pneumatic pressure signals across it. Yet the discovery of bomb-pulse isotopes (^{3}H and ^{36}Cl) in waters within and below the PTn implies that at least some of the water that flows through it must do so at relatively high velocities. Given that bomb-pulse isotopes have been found within the PTn matrix, this rapid flow cannot be confined to fractures or faults but must occur (at least in part) through the matrix. As will be seen later, mean flow rates and seepage velocities through the PTn matrix are insufficient to account for the aforementioned bomb-pulse isotopic signatures. The only way to account for these signatures is to postulate preferential flow through relatively narrow channels associated with locally elevated hydraulic conductivities. These channels need not be confined to fractures or faults; it is in principle possible for preferential flow channels to develop within the PTn matrix due to (a) focused infiltration that concentrates water along narrow flow paths; (b) buildup of saturation along these flow paths, which may not have time to fully dissipate between successive infiltration events, so that antecedent paths act as channels of elevated hydraulic conductivity during subsequent events; (c) spatial variations in matrix permeability; and (d) instability and fingering due to contrasts in material properties between the PTn and the overlying TCw unit (Chen et al., 1995). The preferential flow channels may either persist or adjust themselves dynamically to variable conditions of infiltration at the surface. Regardless of whether distinct preferential flow channels develop within fractures, faults, or the matrix, I will show below that the rock volume they occupy is so small as to make it extremely unlikely that they can be observed in the field.

There is no clear-cut evidence to either support or deny the existence of lateral flow within or above the PTn. Although I expect some such lateral flow to take place, I doubt that it is extensive because of the dampening effect of heterogeneities on a variety of scales, most notably those associated with fractures and faults. For this reason, my calculations below assume that flow within this unit is essentially vertical.

"BACK-OF-THE-ENVELOPE" CALCULATIONS OF PERCOLATION FLUX AND VELOCITY

The conceptual framework described above makes it possible to conduct a "back-of-the-envelope" calculation of bulk mean annual vertical percolation flux (from now on referred to merely as percolation flux) through the PTn and TSw units at Yucca Mountain. It also makes it possible to assess mean vertical velocity (from now on referred to merely as velocity) along fast-flow paths and the relative volume of void space occupied by these paths, which also represents the probability of encountering fast paths within the rock. Although I recognize that flow rates and velocities at the site may range broadly in space-time, I consider it useful for the purposes of this simple calculation to speak of two distinct rates and velocities, one representing the bulk rock and the other fast-flow channels. Because there is no evidence for extensive lateral flow either within the PTn or within the TSw at or above the proposed repository horizon, I likewise think it reasonable to consider only vertical flux and velocity in these units for this calculation.

Lower Bound on Percolation Flux
Table 7 in Flint (1996) contains summary information about the matrix properties and state variables within seven units of the PTn. From this table one calculates an average porosity ϕ of about 0.4, average saturation S of about 0.5, and geometric mean saturated hydraulic conductivity K_s of 3.25×10^3 mm/yr for the PTn matrix. L.E. Flint (pers. comm., Feb. 17, 1997) gave me an unpublished table of two replicate relationships between hydraulic conductivity and water content for two samples of matrix from the PTn, recently determined with a centrifuge apparatus (surprisingly, no other direct experimental data about the variation of hydraulic conductivity with water content and/or saturation appear to be available for Yucca Mountain). From these, one can derive a geometric mean relative hydraulic conductivity at $S = 0.5$ which, when multiplied by the above value of K_s, yields an estimated K of about 6 mm/yr for bulk ambient hydraulic conductivity within the PTn matrix. Laboratory and borehole measurements of pressure head and saturation within the PTn suggest that ambient vertical flow is gravity-dominated and controlled by a mean hydraulic gradient close to one. This yields a mean ambient downward flux q_m through the PTn matrix of about 6 mm/yr. Considering that this estimate disregards the effect of fractures, faults, and fast-flow paths within the matrix; that it therefore cannot account for the observed bomb-pulse isotopic signatures at depth, as will become obvious; and that it is based on small laboratory samples without taking into account the well-established tendency of permeability to increase with scale, the estimate clearly is low, thus constituting a lower bound for percolation flux through both the PTn and the underlying TSw units.

My conclusion that 6 mm/yr constitutes a lower bound on percolation flux seems to agree with calculations performed at two ESF stations by Fabryka-Martin et al. (1996) on the basis of ^{36}Cl data. Their Tables 8-5 and 8-6 imply that a minimum infiltration rate of 5 mm/yr is required to reproduce observed bomb-pulse signatures at these stations.

Upper Bound on Percolation Flux

Based on measurement of moisture conditions within the Exploratory Studies Facility (ESF) at Yucca Mountain, J.S.Y. Wang (pers. comm., Feb. 18, 1997) established that, during weekends when the ventilation system is shut off, average moisture flux from the rock into the ESF is about 50 mm/yr. Given that measured moisture conditions within the PTn matrix appear to vary little with time, it is reasonable to assume that the PTn effectively attenuates temporal variations in bulk percolation flux, which therefore remains relatively stable within the PTn and the underlying TCw units. The above flux rate of 50 mm/yr can be considered representative of long-term ambient conditions in the presence of an unventilated drift. Fluxes into the ESF typically are much higher during the week, when ventilation increases pressure gradients between the rock and the drift. It seems reasonable to assume that ambient percolation flux within the rock, in the absence of a drift, does not exceed the recorded weekend moisture flux into the ESF and probably is considerably lower. The recorded moisture influx of 50 mm/yr can be considered an upper bound on percolation flux within the PTn and TSw units.

Percolation Fluxes in Matrix and Fractures at Repository Horizon

Based on Birkholzer et al. (1996) and Wang (presentation at UZFMEE Workshop 2), matrix permeability k in the TSw at the repository horizon can be represented by 5×10^{-18} m^2. Since the matrix there is nearly saturated, this corresponds to an ambient hydraulic conductivity K of about 1.5 mm/yr. Hence, considering again a unit mean vertical hydraulic gradient, the lower and upper bounds on percolation flux through fractures and faults in the TSw at the repository horizon are, respectively, 4.5 mm/yr and 48.5 mm/yr.

Velocity Along Fast-Flow Paths in PTn and TSw

The available record of bomb-pulse isotopic signatures allows one to estimate velocity as $v = d/t$ where d is depth of bomb-pulse sample and t is associated travel time from the surface. Given that bomb-pulse samples were found at various depths within the PTn matrix and at the repository (ESF) horizon within the TSw, it is reasonable to consider that bomb-pulse isotopes also might have reached the bottom of the TSw unit. This yields d values ranging from approximately 100 m (representative depth at top of PTn) to 450 m (representative depth at bottom of TSw) in the repository area. Considering that bomb-pulse isotopes were released into the atmosphere between 1952 and 1963, t ranges from approximately 30 to 40 years. Hence the corresponding velocity ranges from approximately 2.5×10^3 to 1.5×10^4 mm/yr.

Within the matrix of the PTn. percolation flux was estimated to be about 6 mm/yr at an ambient volumetric water content (porosity times saturation) of about 0.2. This yields a velocity of about 30 mm/yr, which is much too slow to account for the bomb-pulse isotopic signatures. To explain these signatures, it is necessary to postulate the existence of fast-flow paths within the PTn, associated with preferential channels of elevated permeability and/or antecedent water content (and thus elevated hydraulic conductivity) within fractures and faults and/or within the matrix. Similar fast-flow paths must develop in fractures and faults (but probably not the matrix) within the TSw.

It is important to mention that the existence of fast flow paths does not imply that rock openings along these paths (whether in fractures, faults, or the matrix) must be saturated with water, only that the saturation is large compared to the bulk of the associated fractures, faults, or matrix. The existence of such paths therefore does not mean that one would encounter visible seeps of water in an underground opening such as the ESF, although the formation of such seeps is possible.

The background velocity of 30 mm/yr calculated for the PTn matrix implies that it takes an average of 13,000 years for water to propagate to a depth of 400 m, excluding fast paths. This agrees with the reconstructed production rate of $^{36}Cl/Cl$ ratios in the atmosphere shown on Figure 2-2 of Fabryka-Martin et al. (1996), which shows elevated ratios prior to about 10,000 years at the end of the Pleistocene, and the large number of corresponding ratios their Figure 5-1 shows within the ESF.

Effective Porosity and Probability of Fast Paths Within PTn and TSw

The effective porosity ϕ_f of fast-flow paths is defined here as the pore or open fracture volume occupied by fast paths per unit bulk volume of rock. It can be interpreted as the probability of encountering a fast-flow channel within the rock.

The ϕ_f can be computed as the ratio between percolation flux q_f associated with fast-flow paths and the corresponding velocity v. Within the TSw, q_f was found to range between 4.5 and 48.5 mm/yr; v was found to range between 2.5×10^3 and 1.5×10^4 mm/yr. Hence ϕ_f ranges approximately between 3×10^{-4} and 2×10^{-2}.

It appears impossible with available data to calculate a lower bound for q_f within the PTn. An upper bound for q_f of 44 mm/yr is obtained by subtracting the previously established lower bound on percolation flux within the PTn of 6 mm/yr from the upper bound of 50 mm/yr. This yields an upper bound for ϕ_f within the PTn of slightly less than 2×10^{-2}. The actual value is expected to be much smaller.

Let A_f be the average cross-sectional area of pore or fracture void space associated with a fast-flow path, and let N_f be the corresponding number of such paths per unit bulk cross-sectional area. Then $\phi_f = A_f N_f$. It is clear that one cannot evaluate A_f or N_f without knowing one of them.

The total area of the ESF in plan view is about 8,000 m x 8 m = 64,000 m^2. The corresponding cumulative area of pores and fracture voids associated with fast paths is thus between 3×10^{-4} and 2×10^{-2} times 64,000 m^2, or between 19.2 m^2 and 1,280 m^2. It is important to stress once again that (a) the individual area of any given fast path cannot be predicted in this manner, and (b) these areas may not manifest as visible seeps. In fact, given that saturated conditions are not needed for fast flow to take place, it is not surprising that few if any visible seeps have been identified along the periphery of the well-ventilated ESF.

Optimum Estimates for TSw

Under the assumed unit mean hydraulic gradient, percolation flux is directly proportional to hydraulic conductivity K. It is common to consider K as being lognormally distributed, in which case so is percolation flux. This is the basis for the lognormal probability density function, and cumulative probability distribution, of total percolation flux within the TSw depicted in Figure SN-1. The parameters of these functions were obtained by allowing a 5% probability that the percolation flux is less than the lower bound of 6 mm/yr; a 95% probability that it is less than the upper bound of 50 mm/yr; and a 50% probability that it is less than or exceeds the geometric mean of these two bounds, which is approximately equal to 17 mm/yr. Clearly, this latter value constitutes my best estimate of total ambient percolation flux through the repository horizon, based on data to which I had access.

Temporal and Spatial Fluctuations in Percolation Flux

Given the buffering effect of the PTn, I expect small temporal fluctuations in mean annual percolation flux across the repository horizon. I expect mean annual percolation flux across the repository horizon to vary spatially because of spatial variations in net mean annual infiltration rate at the surface, medium heterogeneity, and the fast-flow paths. I expect both temporal and spatial fluctuations to increase in amplitude as temporal and spatial resolutions (frequencies) increase. This is due to the intermittent and focused nature of net surface infiltration, the fact that medium heterogeneities are expected to occur on various scales (Neuman and Di Federico, 1997), and the possibility that fast-flow paths may be associated in part with unstable fingers (Chen et al., 1995; Chen and Neuman, 1996).

PROSPECTS FOR REFINING THE ABOVE CALCULATIONS

The above back-of-the-envelope calculations are only as good as the data that enter into them. The largest source of uncertainty in these calculations stems from having only two sample measurements as a basis for surmising values of PTn matrix hydraulic conductivity at ambient water content or saturation. My most urgent recommendation is to create a large and reliable database concerning the hydraulic properties and states of the PTn matrix at ambient conditions. Such a database would enable one not only to improve my calculations but also to estimate the spatial variability of flow conditions within the PTn matrix and to assess quantitatively the uncertainty associated with such estimates.

My calculation in principle could be refined with the existing database by constructing more detailed models that take into account a larger variety and number of available data concerning surface and subsurface conditions at Yucca Mountain. Indeed, models have been developed that simulate one-, two-, and three-dimensional flows through the mountain under a variety of assumptions and reproduce with some fidelity selected space-time measurements of state variables such as water saturation and pressure head, pneumatic pressure, temperature, and the presence of perched water. Unfortunately, predictions of percolation flux rendered by these models may be no more reliable than those obtained by the above back-of-the-envelope calculations. This is so because (a) many of these models are driven by surface maps of mean annual net infiltration, the reliability of which is open to question; (b) all models (these and mine) are limited by a lack of measurements concerning key matrix properties such as the variation of hydraulic conductivity with saturation (the data quoted earlier are the only ones available, regardless of model type); (c) all models suffer from limited information about the number, location, geometry and material properties of fractures and faults; (d) all models suffer from limited information about the variation of state variables within fractures and faults; (e) attempts to determine net infiltration rates and fluxes by calibrating models against measured values of state variables have suffered from apparent lack of sensitivity to such rates and fluxes. As crude as the above back-of-the-envelope calculations may be in comparison to more detailed models, they nevertheless offer a number of advantages, including (a) simplicity; (b) transparency; (c) avoiding reliance on questionable net infiltration data; (d) avoiding reliance on unknown fracture and fault properties; (e) avoiding reliance on unknown conditions within fractures and faults; (f) avoiding speculation about processes that control fluid, solute mass, and energy transfer across fracture-matrix interfaces; (g) avoiding calibration; (h) ability to define upper and lower bounds on percolation flux; (i) ability to define uncertainty in percolation flux by means of a quasi-subjective yet data-based probability distribution function; (j) ability to differentiate quantitatively between slow and fast-flow regimes, fluxes, and velocities; (k) ability to define upper and lower bounds on the effective porosity of (relative rock volume occupied by) fast-flow paths; and (l) associating the latter with the probability of encountering fast-flow paths within the rock. As mentioned earlier, these calculations could be greatly improved, refined, and qualified if a larger and more reliable set of data becomes available about the hydraulic properties and states of the PTn matrix under ambient conditions.

Calculations Based on Temperature Gradients

One important way to complement the above back-of-the envelope calculations is to calculate percolation fluxes through Yucca Mountain on the basis of temperature and heat flux data.

Several attempts to do so have been reported to the panel, but I question whether they are not based on reliable data about ambient heat fluxes within the unsaturated zone, and rock heat conductivities (and capacities) at ambient water saturations. Two primary methods of calculation have been reported, one based on values of heat flux measured in the saturated zone under conditions different from those that prevail in the unsaturated zone. (Whereas in the saturated zone advection is largely horizontal, in the unsaturated zone it is largely vertical; one cannot be sure that vertical heat flux in the saturated zone is equal to that in the overlying unsaturated zone.) The other method is based on fitting computed first- and second-order spatial variations in temperature to measured values. The first method is sensitive to errors and uncertainties in heat flux, heat conductivity, and first-order spatial variations in temperature. The second method is sensitive to errors and uncertainties in first-order spatial variations in heat conductivity and both first- and second-order spatial variations in temperature. Although some sensitivity analyses have been performed following the elicitation interviews, in none of the reported calculations have errors and uncertainties been quantified through a transparent statistical analysis of the available data. Prior to the interviews, available heat flux data were on the one hand assumed to represent heat conduction, and on the other hand used to calculate an advective percolation flux. In such calculations the advective term seems to be merely a residual error in the equation. As matters stand, it is not clear that the available temperature-related data base allows one to assess percolation fluxes at Yucca Mountain with a reasonable degree of certainty.

Additional Comments on Net Infiltration

Near-surface processes that generate net infiltration at Yucca Mountain are complex and difficult to quantify. There is little doubt that net infiltration varies with large frequencies and amplitudes in space-time, but the details of this variability remain highly uncertain. Existing estimates of net infiltration are based in part on measurements of space-time variations in water content by means of neutron probes in shallow boreholes at a few sites across the mountain. Even if one could obtain reliable estimates of net infiltration at these sites, one still would not know how infiltration varies spatially between the sites.

Unfortunately, even at measurement sites the available assessments of net infiltration are suspect. A visit to some of these near-surface installations reveals that distances between neutron monitoring boreholes often appear too large to obtain a clear picture of shallow flow conditions before, during, and after storm events. In particular, the apparent downward propagation of elevated moisture signals, observed in some boreholes during and after storm events, has been interpreted consistently as an indication of downward flow and has been used to assess vertical net infiltration rates. In reality, such signals often reflect lateral, and not only vertical, movement of an advancing moisture wave. This is what one may expect in a wash that contains alluvial material when runoff from surrounding bedrock slopes seeps into the alluvium along its margins, and then propagates through the alluvium in a direction controlled in part by the slopes of the underlying bedrock. The concept of lateral flow along the bedrock-alluvium contact is supported by the finding of bomb-pulse ^{36}Cl at the base of the alluvium in borehole UZ-16, but not within the alluvium. Shallow, lateral subsurface flow may also take place along hillslopes in bedrock terrain due to a phenomenon similar to that which causes a thatched roof to divert rainwater laterally away from the underlying structure. No such lateral flows were considered when preparing net infiltration maps published for Yucca Mountain. Not only was near-surface flow taken to be everywhere vertical, but rates of infiltration into bedrock were often based on permeabilities that had not been measured but had instead been predicted theoretically on the basis of fracture geometry data such as densities and apertures. Unfortunately, it is now well established that such predictions lack a firm basis in theory and experiment (Neuman, 1987) and therefore generally are unreliable.

Many other important sources of error and uncertainty affect the available estimates of net infiltration rates at Yucca Mountain, including low space-time resolution of storm events; neglect of surface runoff; relatively poor understanding of, and ability to quantify, processes that control water uptake by plants from soils and fractures; poor definition of processes and material properties (such as spatial variations in near-surface bedrock permeability) that contribute to the generation of focused infiltration and corresponding fast-flow paths; and the transient nature of infiltration processes.

Comments on Chloride Mass Balance

The approach used to date assumes that all chloride available at the soil surface enters the mountain, even though some may wash away at the surface or remain stored in the soil. This notwithstanding, percolation flux rates computed by J. Fabryka-Martin (presentation at UZFMEE Workshop 2) for the PTn on the basis of chloride mass balance are of the same order as those computed above on the basis of Darcy's law.

Additional Comments on Bomb-Pulse Isotopic Signatures

Bomb-pulse isotopic signatures provide unequivocal evidence for the existence of fast-flow paths to the repository horizon and perhaps below. They also allow one to assess velocities of fast-flow paths.

Comments on Perched Water and Associated Water Balance

The evidence for perched water near the TSw and nonwelded Calico Hills (CHn) contact is convincing, but its lateral continuity across the site remains unknown. Pumping tests conducted in perched water suggest that some of it may form distinct saturated bodies of finite volume.

As the age of the perched water is 5,000-10,000 yrs, it clearly is not sustained entirely by fast flow through the overlying units. It is unclear to what extent it is supported by vertical flow from above and by lateral flow. However, the recorded occurrence of younger perched water in the CHn beneath older perched water is difficult to explain without invoking lateral flow.

It should be possible to extract from pumping test data in perched water bodies information about the drainable porosity (specific yield) of the fracture system within which they reside. This would provide a lower bound on the total porosity of this system, and an estimate of its effective (kinematic or transport-related) porosity.

It is my view that current UZ site-scale models lack the data and the resolution required to conduct a meaningful examination of conditions that control the development of perched zones at Yucca Mountain.

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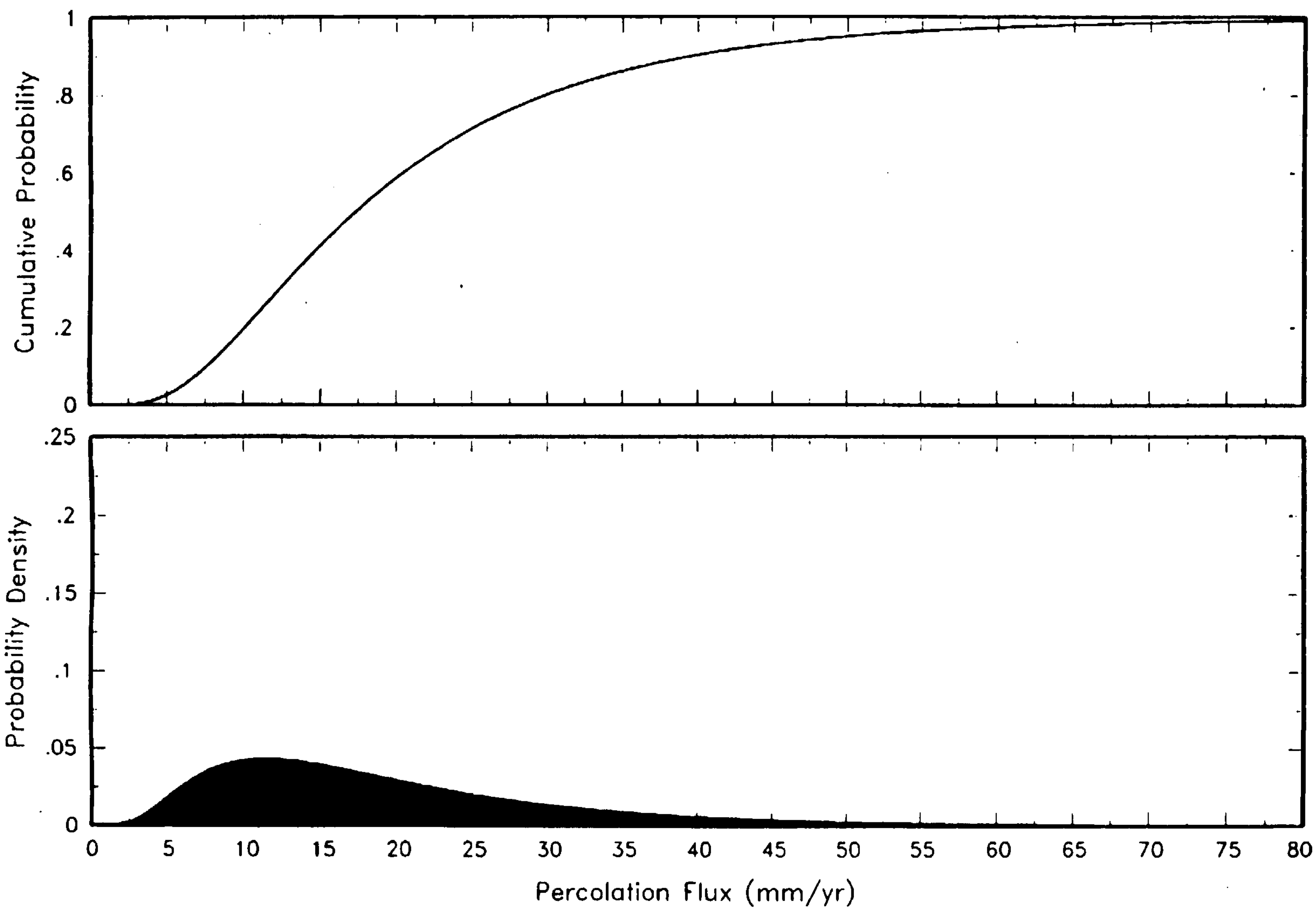

Figure SN-1 Assessed distribution for percolation flux at the repository level developed by Shlomo Neuman. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

ELICITATION SUMMARY
KARSTEN PRUESS
February 10, 1997

OVERVIEW OF UZ FLOW PROCESSES AND MODELING ISSUES

The unsaturated flow system at Yucca Mountain is very complex. Heterogeneities exist at all scales. If unsaturated flow in this system could be described by a simple Richard's equation, water would be expected to enter both the matrix and the fractures, and the two would be in (near) equilibrium. We know, however, that at least some water flows through the fractures and has limited contact time with the matrix. Therefore, we have a slowly flowing component of moisture in the matrix and another component that migrates in the fractures. We do not know whether the system is at steady state. It may not be, because some of the response times to transient perturbations are very slow (capillary flow in the matrix, non-isothermal effects), and there is evidence that episodic pulses of moisture can pass quickly through the system. For moisture to become part of percolation flux, it must pass through the "point of no return" beyond which evaporation and transpiration are no longer operative. Capillary barriers deeper in the section can divert some of the moisture. However, this mechanism probably occurs only in limited areas of from meters to at most hundreds of meters, and is not expected to be regionally significant.

We can consider two end-member conceptual models: (1) a major fraction of the total flow occurs as fast-path flow, or (2) only a minor fraction travels in fast paths and the rest occurs as slow flow. The available data do not provide an unequivocal assessment of which end-member is applicable, only that both processes are occurring. Important to both models is the stability in space and time; that is, do seeps or local flow paths stay in place through time? Environmental isotopes provide evidence of fast-flow velocities on the of order of 10 m/year, but not of the fluxes or flow volumes that are occurring. A scientific approach would dictate that we include all aspects and components of the flow system; an engineering approach would suggest that we concentrate on localized flows, as larger flow velocities and flow volumes are more relevant for site suitability.

Conceptual uncertainty exists with respect to fracture-matrix interaction. A scientific approach would demand that we represent the system realistically; an engineering approach would suggest that we consider different approximations that focus on different aspects. Simple flow and transport models based on transit time distributions, such as Jury's transfer function model (1982), the "weeps" model of Gauthier et al. (1992), and Chesnut's lognormal model (1992), offer an alternative to the sophisticated finite-difference approaches. The latter are based on volume-averaging concepts having uncertain applicability to the Yucca Mountain system. Therefore, it would seem prudent to keep transit time-based models as an alternative engineering approach and see if the more complicated models give similar answers. A weeps-type model also could be embedded in a more complex model to deal with the behavior of certain hydrogeologic units and compare with predictions of finite-difference models.

The current LBNL and Los Alamos unsaturated zone (UZ) site-scale models use (integral) finite-difference and finite-element methodology and employ "macroscale continuum concepts." This includes a continuum description of flow (one or several interacting continua) by means of multiphase extensions of Darcy's law, and volume-averaging on the scale of grid blocks or larger (tens to hundreds of meters). Volume-averaging is done for hydrogeologic properties and for initial and boundary conditions. It has not been established that this type of approach is able to capture those aspects of the Yucca Mountain hydrogeologic systems that are most relevant to unsaturated flow. In fact, I am skeptical that it can. If an important component of flow is localized in preferential pathways, then much of the flow system volume may not participate, and volume averages may be meaningless.

Transient processes as well as processes having small-scale spatial variability should be represented in the UZ modeling. It is reasonable to expect secular or episodic variations in infiltration. Piston-type displacement through the Paintbrush (PTn) would take too long, and the volumes of water that would have to be displaced would be too high to account for the presence of environmental isotopes at depth. For environmental tracers to pass through the PTn requires a conceptual model where weeps occur, each possibly having a small volume. My reading of the data is that the environmental tracers appear localized at depth, different from E. Weeks' assessment (presentation at UZFMEE Workshop 3) that they are ubiquitous. I agree with Weeks' arguments regarding the maximum seepage volume that could be present without causing dripping into the ESF. This concept could be further developed to place a limit on the number and volume of seeps. The Los Alamos modeling presented by A. Wolfsberg (UZFMEE Workshop 2) does not consider phenomena at the scale of individual weeps (presumably, on the order of 1 m) and assumes a continuum.

The transient component that is induced from the infiltration events probably is significantly dampened as it passes through the PTn and other layers having different hydraulic properties. It therefore may be reasonable to use a steady-state model for flow at the repository depth, but this is still uncertain. Fast flow through the PTn does not require faults or fractures, if it behaves like a sand where minor heterogeneities can funnel flow to factors on the order of 100 and cause fingering in soils (Kung, 1990a, b). In many cases the ^{36}Cl shows are not clearly associated with identifiable faults. The pneumatic data do not provide strong evidence for the lack of fractures in the PTn.

The present modeling considers the interface area in the description of fracture-matrix interaction. This would be appropriate if fracture flow occurred in something approaching uniform distribution throughout the fractures, but is questionable in a system where localized flows occur along preferential pathways. The impact of fracture coatings on flow are poorly understood; qualitatively, they probably reduce imbibition.

The role of faults in moisture flow also is not understood. Perhaps the model should include more geologic complexity and should include faults, particularly major faults having large stratigraphic offsets. However, arguments can be made that faults provide zones of both high and low permeability. Thus the incorporation of faults, without a better basis to characterize them, simply adds to the uncertainty. Using a range of fault properties in the model and sensitivity analyses could help to design field experiments that could determine fault properties (e.g., by injecting water and tracers into fault zones above the ESF).

Up-scaling of rock properties is an important source of uncertainty in the UZ modeling. For example, the characterization of matrix permeabilities from plug samples, which is routine in the oil industry (Christie, 1996), will miss aspects such as fractures through the system. Fracture properties for Yucca Mountain have come largely from the pneumatic data, and matrix properties from plug samples. The gas permeability data are at the scale required for the LBNL grid blocks, but uncertainties in the relationship between gas and liquid permeabilities must be considered. The present understanding allows for sensitivity studies and bounding calculations of fracture behavior. Infiltration can be pushed to increasingly higher values, and the behavior of the system assessed for a variety of fracture properties to identify those that are unreasonable.

The program has made a commendable effort to include a variety of calibrations to elements of the model. However, the ability to calibrate unsaturated zone flow models at Yucca Mountain is severely limited by the large range of space and time scales of many of the important flow processes.

APPROACHES TO ESTIMATING PERCOLATION FLUX

The following approaches to estimating percolation flux at the repository horizon were discussed. In the course of the assessments, recommendations were also made regarding the ongoing data-collection and modeling efforts at Yucca Mountain.

Net Infiltration

The uncertainty in net infiltration is quite large, as shown by the range in average values that have been advanced in the past few years. The significant spatial and temporal variability of net infiltration may be more important than the magnitude of average flux. As a percentage of precipitation, the amount of net infiltration can rise steeply during severe storm events.

Based on the estimates that have been discussed and the models developed, the most reasonable estimates of both spatially and temporally averaged net infiltration lie within the range of 1-10 mm/yr. However, given the large uncertainties, a prudent (conservative) range of estimates may vary from - 0.1 mm/yr (i.e., the long-term average has evapo-transpiration processes slightly exceeding precipitation) to 50 mm/yr (i.e., nearly one-third of nominal average annual precipitation). My estimate for the probability density distribution of average percolation flux is summarized in the following table.

Table 1. Estimated Probability Distribution for Average Percolation Flux.

Percolation Flux Interval (mm/year)	Integrated Probability for Interval*
- 0.1 - 1	10 %
1 - 10	60 %
10 - 30	20 %
30 - 50	10 %

* probability density assumed constant within interval

I judge the uncertainty associated with percolation flux to be very large. Accordingly, my estimate was not developed from a formal quantitative procedure, but was based on the following qualitative judgements: (1) there is a small but non-zero probability that average percolation flux is very small, below 1 mm/year, or even negative, reflecting a regime of overall slow drying; (2) the most probable average percolation flux is in the range of a few millimeters per year, with values from 1 to 10 mm/year judged about equally probable; (3)†there is a substantially smaller but significant probability that percolation flux may be in the range of 10 to 30 mm/year; (4) a yet smaller but non-negligible probability exists for percolation flux to exceed 30 mm/year and be as large as 50 mm/year. The probability density function and cumulative density function to express this uncertainty in average net infiltration is given in Figure KP-1.

The temporal distribution of net infiltration is expected to be concentrated in a few isolated major storm events or sequences, which average perhaps 1 or 2 per year or fewer. Between these events, the average net infiltration is probably very low and may well be negative. An estimate of average net infiltration must capture the severe events as well as the intervening periods.

The spatial distribution of infiltration likely is quite variable. Net infiltration may even be negative for certain regions and for certain time periods; however, this is not my area of expertise. Lateral overland flow and concentration of flow in channels/washes would appear to be an important process. The factors that are being used to constrain the spatial distribution in A. Flint's modeling (Flint et al., 1996) (e.g., topography, vegetation, soil depth, slope aspect) probably are themselves correlated to a significant degree. The spatial distribution likely is nonlinear, such that the spatial pattern of net infiltration will vary as a function of total average infiltration. Just how it would change is not clear, but areas of high infiltration may become even more pronounced at higher precipitation rates.

Mechanistic models of net infiltration may not have a high reliability, but they should be helpful in building a model and integrating it into the UZ flow model. Given the temporal variability that we have seen in the net infiltration estimates, the monitoring and data collection should continue in order to develop a more defensible appraisal of long-term system behavior.

Estimates of percolation flux at the repository horizon would be expected to have the same average values as net infiltration. Lateral diversion and concentration—although very important locally over scales of perhaps 100 m—is not expected to cause significant diversion of net infiltration at the regional scale. The spatial distribution of percolation flux at the repository horizon may or may not be similar to the net infiltration map. The washes may localize infiltration, and locally high darcy velocities may persist to depth; in other cases, high infiltration locations may get redistributed at depth. It is also possible that heterogeneous structures may be present that funnel spatially distributed infiltration into localized fast preferential flow paths. There are mechanisms that could increase as well as others that could decrease spatial variability of percolation flux with depth. Existing variations may be damped out while new variability may develop from medium heterogeneities. At present we simply do not know the net outcome of these competing mechanisms.

Temperature Gradients

The use of temperature data to estimate percolation flux is probably the most robust approach. It has advantages over isotopes because it provides a volumetric average rather than just a velocity. At the local scale, temperature gradients can be measured to get information on local seeps. At the scale of the mountain, it can provide an average estimate of percolation flux at the scales needed for modeling. Deep boreholes throughout the unsaturated zone are needed to develop information on temperature gradients. Admittedly, because of sparse data, there are uncertainties in the gradients, thermal conductivities, and the nature of basal heat input. The temperature data can constrain percolation flux, but my perception is that current assessments based on such data are model-dependent (e.g., need to make assumptions about basal heat flux) and therefore highly uncertain.

Saturations and Water Potentials
This is outside my area of expertise, particularly related to the reliability of field measurements. There appear to be significant uncertainties in measurements of water potentials.

Chloride Mass Balance
The chloride mass balance approach assumes a mixing process. I picture the flow field as non-uniform and having variable amounts of mixing. Therefore, any assessments based on a mixing model would appear to have large uncertainty.

Isotopic Evidence
The observation of environmental tracers at depth is the strongest evidence for fast travel. However, it is difficult to translate this information on flow velocities into flux rates. The analysis by A. Wolfsberg (presented at UZFMEE Workshop 2) does not provide a constraint on flux, because the Los Alamos model uses volume-averaged macroscale continuum concepts (dual permeability, spatially distributed flow) whose applicability is questionable.

E. Weeks' analyses of ^{14}C gas (presentation at UZFMEE Workshop 3) shows that a large range of percolation flux values would be consistent with the measurements. Therefore, the method, although not unique by itself, could be used with other methods to arrive at better-constrained flux values. Cross-correlations between tritium and ^{14}C seem to be consistent.

Perched Water
It is important to understand the perched water bodies. Why are they there? How much water flows in and out? I am unaware of quantitative estimates of percolation flux for the perched water in the Calico Hills beneath the repository horizon.

Fracture Coatings
I am not familiar with this area. It appears that coatings may permit a minimum estimate of flux, since water flowing through a fracture would not always generate precipitate.

PARTITIONING BETWEEN FRACTURES AND MATRIX; SEEPAGE INTO THE DRIFTS

Matrix conductivity is about 0.3 mm/yr (corresponding to a permeability of 1 microdarcy) for the Topopah Spring (Tsw). Therefore, if percolation flux exceeds this value, most of the flow in the TSw must be in the fractures. The fracture flow is subject to diffusive and advective exchange with the matrix. Only a small part of the fractures may be carrying the fast component of flow. The remaining slow component occurs in both the fractures and matrix.

Addressing the issue of flow into the drifts, ventilating a drift would cause drying around the wall and development of suction pressures. As a result, matrix flow into the drift would cease, and fracture flow would diminish near the wall. This process can be modeled readily.

Assuming an unventilated drift, the matrix rock beyond the drift wall typically would have a slightly negative matric potential, which would stop the matrix component of flow. However, water flowing in the fractures should be capable of entering the drift. The spatial distribution of seeps into an unventilated drift would be expected to be approximately the same as for undisturbed conditions.

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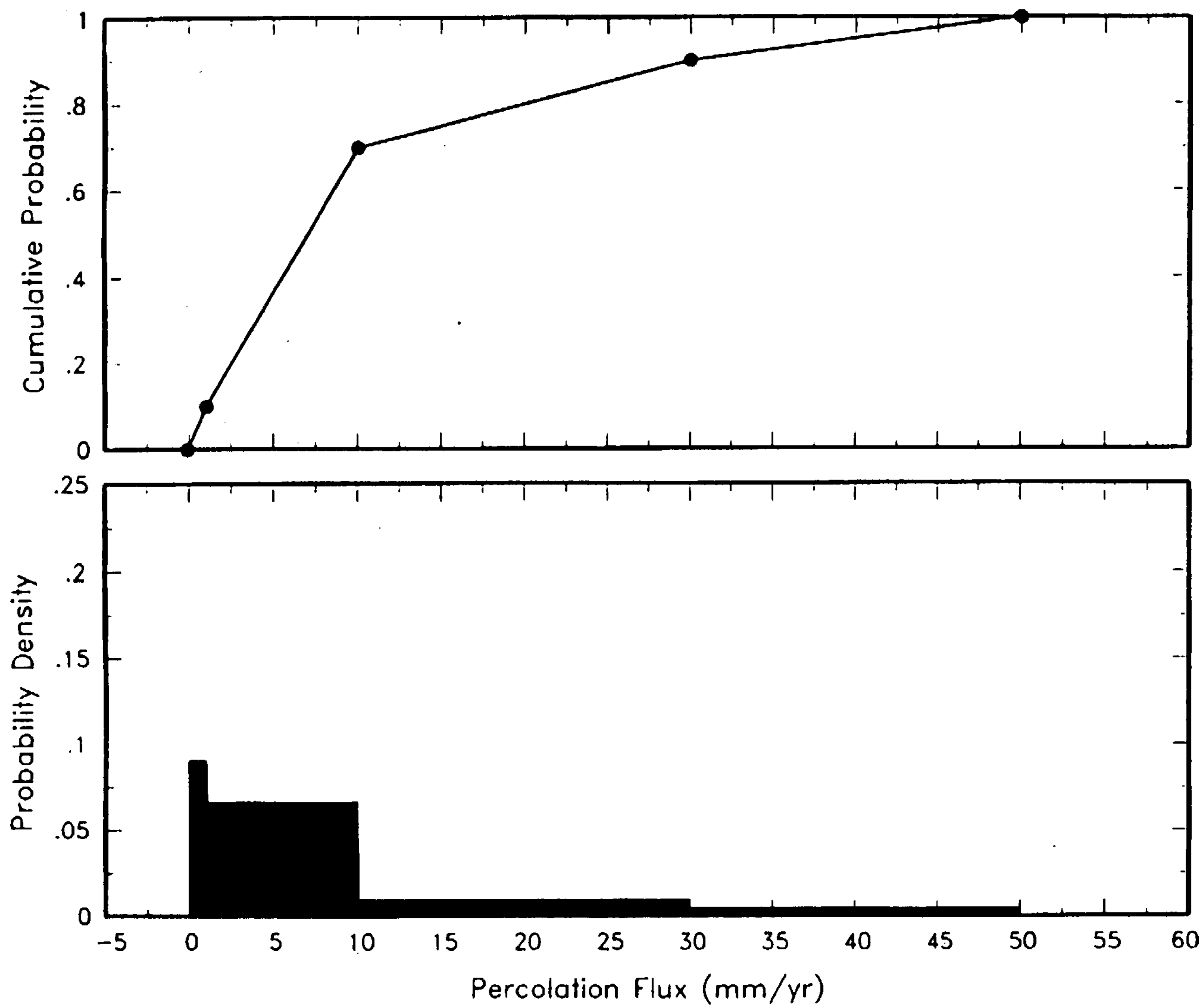

Figure KP-1 Assessed distribution for percolation flux at the repository level developed by Karsten Pruess. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

ELICITATION SUMMARY
DANIEL B. STEPHENS
February 20, 1997

OVERVIEW OF UZ FLOW: PROCESSES AND MODELING ISSUES

The hydrologic system at Yucca Mountain is one of unsaturated flow in fractured rock within an arid environment, which is one of the most difficult settings to characterize (after karst). Infiltration probably occurs as short bursts associated with severe storm events. The scarce vegetation and highly fractured rock enhance the likelihood of infiltration. Little is known about the plumbing of the mountain that would explain the presence of perched water or the overall water balance.

Net infiltration is the primary factor in understanding the moisture conditions in Yucca Mountain. In addition to the information presented on infiltration studies, I will rely on my intuition and experience for the components important to infiltration. I expect that the relatively flat, poorly vegetated ridges with exposed rock will be areas of moderately high infiltration provided there is sufficient contact time between the water and the rock. The steep side-slopes appear capable of carrying water down into the washes, where most infiltration is expected to occur. At the alluvium-bedrock interface at the base of the slopes in the channels, there likely will be underflow, at least seasonally. Underflow at the base of alluvium is common in mountain-front areas and is related to bedrock topography and the permeability of the bedrock. Variable thickness, heterogeneities in the alluvium, and irregularities in the bedrock-alluvium interface likely will provide long contact times for the concentrated subsurface flow beneath the washes to infiltrate eventually into the underlying bedrock. Fractures, faults, and their density beneath the washes therefore are important, as are the locations where water will be in contact with the rock for the longest period. The infiltration of precipitation through the alluvial flood plains and terrace locations is likely to lead to lower net infiltration to bedrock than the infiltration beneath the channel because of the heavier vegetation and larger storage on the flood plain.

Direct observation of the spatial variability of net infiltration in general and the underflow process in particular may be difficult. Experiments such as the transect of heat dissipation probes in Split Wash are a good idea. I am not familiar enough with the spatial distribution of neutron holes to know if they are capable of capturing the runoff concentration and infiltration beneath washes. Trenches may have to be dug and TDR probes drilled into bedrock to obtain information on the processes in bedrock hillslopes. As discussed below, one approach might be to monitor thoroughly a small watershed and use the results to calibrate net infiltration models for the rest of the mountain.

Although net infiltration is occurring practically all of the time, it is concentrated temporally during extreme storm events. The largest infiltration events are those that occur about every decade to a few tens of years. Between extreme infiltration events, the plane of zero flux moves down in the soil profile. Because there is always a positive hydraulic gradient, water is always going down; the question is simply how much. By far, most of the infiltration occurs during extreme storm events. Transient pulses associated with these high infiltration events, although dampened as they move downward through the hydrologic system, have propagated to near the repository horizon, primarily in fractures. In addition to the infiltration occurring directly over Yucca Mountain, infiltration into rock on the eastern side of Solitario Canyon may be very important. Percolation to the Calico Hills zeolite zones and water build-up at fault barriers may contribute to the perched water observed beneath the repository horizon.

Fracture flow is the principal mechanism for percolation in the Tiva Canyon (TCw). The areas of concentrated infiltration are expected to be the fractured parts of the TCw lying beneath the washes and, to a lesser extent, beneath the ridge-tops. At the contact with the Paintbrush non-welded unit (PTn), percolating water through fractures will diffuse into the matrix. Some degree of lateral diversion also likely will occur at the top of the PTn. However, the faults and interface irregularities within the upper PTn likely will diminish the amount of lateral flow. At the Topapah Spring welded unit (TSw) where near saturation occurs, moisture will enter the fractures and faults. The presence of ^{36}Cl and other environmental isotopes at repository depths and below verifies that a "fast-flow" component of infiltration is present. From the standpoint of partitioning of the net infiltration volume between the fractures and the matrix, over the long-term and across the mountain most of the total volume of flow could be occurring in the TSw matrix, although this is uncertain. The matrix may convey most of the flow volume because the fast fracture flow apparently is episodic and occurs in fractures and faults that comprise a very small part of the rock mass (0.1%-1%).

It is also possible that virtually all of the water movement in Yucca Mountain, at least in welded units, occurs via fracture flow having both fast and slow paths. Fast flow would occur briefly following storms or snowmelt, whereas slow flow would occur at other times in fractures that are only partly water-filled. I suspect the importance of the slow fracture flow component has been overlooked and should be included in the conceptual model along with slow matrix flow. Data collected to date do not provide a clear picture of the relative importance of fracture and matrix flow.

APPROACHES TO ESTIMATING PERCOLATION FLUX

The following approaches to estimating percolation flux at the repository horizon were discussed. In the course of the assessments, recommendations were also made regarding the ongoing data-collection and modeling efforts at Yucca Mountain.

Net Infiltration

Although the quantification of net infiltration is uncertain, it provides perhaps the best vehicle for estimating the average percolation flux at the repository horizon. A surface water balance has been developed to quantify net infiltration. Extending this approach to compute net infiltration from a water balance of the perched water and the regional water table may also be valuable.

Based on experience elsewhere, I estimate the net infiltration over long time scales for Yucca Mountain would be a few percent of total annual precipitation (1-5% is expected, perhaps as high as 20% is possible in places). This would be a spatially and temporally averaged value. In reality, there undoubtedly will be regions of relatively high and low infiltration; and most of the infiltration will occur over short periods during severe storm events or sequences.

Based on the data and interpretations presented for Yucca Mountain, as well as my experience at other locations in the arid southwest, I would assess the average infiltration at Yucca Mountain to lie between 1 and 10 mm/yr. The estimated probability density function (PDF) and cumulative density function (CDF) for my assessment are given in Figure DS-1. Note that the average net infiltration rate is averaged both spatially over the Yucca Mountain block and temporally over approximately the 100-yr period that A. Flint used in his most recent assessment (Flint et al. , 1996). This period presumably includes several of the severe storm events that result in higher infiltration, which I estimate to occur every 20 yrs or so.

The spatial variability of net infiltration over the Yucca Mountain block is considerable. Figure DS-2 is a diagrammatic north-south cross-section of the relative amounts of net infiltration in various topographic positions at Split Wash presented to me by A. Flint during the UZFMEE Field Trip. Not shown are the areas of thick alluvium farther east; here I agree with A. Flint that net infiltration is very low, except in the channel. Figure DS-2 compares the approximate relative values given by A. Flint with those I interpret for different topographic positions. Infiltration on the relatively flat ridge-tops that lack vegetation and have thin-to-no soil is very high according to A. Flint, but only moderate in my assessment. I think that snowmelt probably is the dominant mechanism for infiltration in these areas. The water contact time with the exposed bedrock on the ridge crests probably is too brief during severe storm events to provide high relative rates. The steep side-slopes are likely not responsible for significant infiltration because overland flow and interflow through the thin soils convey water to the base of the slopes, where it infiltrates into the flood plain soils. In the washes, the highest rates probably occur as a result of convergent surface and shallow subsurface flows, which create ephemerally perched groundwater at the bedrock-alluvium contact. Irregularities on the bedrock surface, variations in the thickness of the alluvium, and other heterogeneities within the alluvium allow for longer contact times for ephemerally perched groundwater on the bedrock. Locally, faults and fractures within the bedrock beneath the washes probably give rise to the highest rates of deep infiltration.

The average percolation flux at the repository horizon probably is very similar to the average net infiltration rate. It could be less, depending on the amount of lateral flow within the section, particularly at the top of the PTn. No doubt some amount of lateral flow does occur there, but the irregular nature of the PTn -Tiva Canyon boundary and its faulted nature may preclude significant lateral flow at the boundary over distances of more than a few hundred meters. Moisture that does not infiltrate into the PTn matrix may be diverted laterally because of a contrast in hydraulic properties until it encounters a fracture or fault, where it may flow vertically into the TSw. The occurrence of ^{36}Cl at depth indicates that fast paths, most likely faults and fractures, occur within the PTn. Net infiltration into the TSw could also occur in Solitario Canyon and contribute to the percolation flux at the repository horizon, although this contribution is likely insignificant. The ESF affords an excellent opportunity to install water potential sensors to better evaluate in detail the average percolation flux and how it is distributed spatially.

Because the dominant flow processes down to the repository horizon are vertical, the *spatially averaged* percolation flux at this level probably is quite similar to the *average* net infiltration. However, the spatial distribution of flux at depth probably will look somewhat different from the net infiltration map of Flint et al. (1996). The deep spatial distribution will be a function of heterogeneities of hydraulic properties within the section and the dip of stratigraphic units, as indicated by numerical modeling. Within the TSw and at the repository horizon, the distribution of fracture networks is an important control on the spatial distribution of moisture that would enter the repository. At these levels, vertical flow is expected to dominate. The areas having high percolation flux rates generally will lie below the highs in net surface infiltration (e.g., channel bottoms connected to fault and fracture zones), and the low percolation rates will occur below the areas of low infiltration. However, the high-amplitude variations in net infiltration will appear to be smoothed out at depth.

Regarding water balance modeling for net infiltration, I have low confidence in the Bucket model. It is inadequate for the level of detail being considered in this analysis. The concept of "field capacity" has no physical significance. Likewise, at the local scale the simple notion of varying infiltration as a function of topography following the Maxey-Eakin model is unsatisfactory to me unless it can be shown within a local watershed, e.g., north-south transect in Split Wash, that there is an orographic effect or some basis for precipitation to vary with elevation. The Maxey-Eakin method was developed for entire watersheds and was not intended for points within a watershed. The neutron probe data used for calibrating the soil-water budget models should be examined for reliability. It is unclear why some data sets were retained and others discarded. Nevertheless, the neutron probe data alone probably are insufficient for calibrating or validating the soil-water budget models.

I suggest that a fruitful approach to net infiltration modeling and calibration would be to thoroughly instrument and study a small drainage basin. The goal would be to examine the meteorological data and surface and subsurface infiltration processes so that net infiltration models for the Yucca Mountain Project could be further developed and calibrated for application to other parts of the mountain. The local scales would be consistent with the scales that are needed for the detailed understanding being sought for unsaturated flow within the mountain. The small watershed could be thoroughly instrumented and studied, including rain gauges, detailed mapping of fractures (beneath the alluvium at some locations), nests of piezometers in the alluvium and bedrock, and detailed mapping of the depth to bedrock. Measurements could be made of surface flow during storm events and subsurface flow along the bedrock-alluvium contact using trenches, buried pan lysimeters, and TDR probes. Part of the watershed ideally should overlie part of the ESF, where other instrumentation (e.g., tensiometers, neutron probes, heat dissipation sensors) is monitored and pore water is sampled for geochemistry. A goal would be to develop a complete local water balance, throughout at least a few years, to assess the amounts and spatial distribution of infiltration within this local watershed. The information gained on the relative importance of various processes would serve as calibration for models that would include the entire Yucca Mountain block.

It should be noted that the various estimates of net infiltration all appear to be quite similar, even though they are derived from different data sets and models (e.g., temperature, water potentials). This is encouraging. The Yucca Mountain program has taken a multipronged approach to assessing the percolation flux by using every bit of data that is available, with exception of data on the perched and regional aquifer. This should be commended and continued. The uncertainties at present are large, reflecting the difficulties in evaluating this type of hydrologic system. The uncertainties can only be reduced by continued, properly focused field studies (which include characterizing hydraulic properties by laboratory and field methods) followed by modeling efforts.

Temperature Gradients

I have not studied the temperature data or modeling efforts in any detail. There appears to be considerable uncertainty in the thermal conductivities and heat flux, yet the models give fairly consistent estimates of percolation flux, in the range of 5-10 mm/yr. The measured temperature profiles seem to be matched by models using a fairly wide range of percolation fluxes. Therefore, the results should be viewed in the context of other data.

I understood from the field trip that in developing the Flint et al. (1996) net infiltration map, a narrow ribbon of relatively high net infiltration of 10 mm/yr along the active channel of the washes was derived from heat flow data of Rousseau et al. (1996), rather than from an evapotranspiration-based soil-water budget. Perhaps this helps explain some of the similarity of the fluxes obtained by the two methods.

Saturations and Water Potentials

There are several reasons for the inconsistent and frequently poor agreement between measured and model-predicted potential and saturation data. These include errors in field measurements as well as modeling errors. Modeling errors apply to the conceptual model and input hydraulic properties. Regarding the latter, no measured unsaturated hydraulic conductivity data were used in the modeling, only estimates calculated from moisture retention and saturated hydraulic conductivity.

Using variably saturated flow models to estimate flux has considerable value if accurate unsaturated hydraulic conductivities are used. I am surprised that no measurements of this critical parameter have been used in the UZ flow model. Actual measurements could greatly reduce uncertainties in important aspects, such as lateral versus vertical flow or matrix versus fracture flow. Huge uncertainties are associated with using saturated hydraulic conductivities and various estimation models (e.g., van Genuchten properties) to predict the saturation profiles. The models that estimate hydraulic conductivity may be inappropriate for the processes that operate here with matric potentials <1-2 bars. As a result, simulations calibrated to the saturations and water potentials are virtually insensitive to percolation flux. The approach taken in the UZ flow modeling of calibration using the combined temperature, pneumatic, and saturation data, is a good idea. The UZ flow model generally is working well, but it is unknown which flux values give the best match to the pressure and saturation data.

Suggestions that could make this approach more useful are the following: measure unsaturated hydraulic conductivity in the laboratory and field where possible; rather than fit the van Genuchten function to saturated hydraulic conductivity, fit the function using hydraulic conductivity at a saturation closer to ambient saturation; optimize flux estimates on a borehole-by-borehole, layer-by-layer basis; and obtain more accurate *in situ* measurements of water potentials using tensiometers and heat-dissipation probes.

I also have doubts about the field measurements of potential and saturation and the use of these to calibrate or validate the numerical models. The field data most likely reflect matrix conditions, given the sparse network of fractures relative to the scale of the field measurement. I envision that the water-conductive fractures that receive periodic surges in infiltration, and hence highly variable potential, occur at the boundaries of large matrix blocks. Consequently, there may be steep water potential and saturation gradients within these matrix blocks. The spatial variability of potential and saturation within the matrix could help explain the large scatter in field data. Whatever the reason for the scatter in data used for model calibration and validation, results of a numerical model to predict net infiltration without measured hydraulic properties seems fraught with uncertainty.

Chloride Mass Balance

Because of preferential flow in fractures in Yucca Mountain, it will not be helpful to use the chloride mass balance approach for separating the fracture from the matrix flow. This approach has been used for alluvial settings or areas that have few fractures. However, the approach could be useful in assessing the flux due to diffuse infiltration through soils in a watershed or in the PTn, if there is little lateral flow and few sources of chloride other than precipitation. This inexpensive approach is worth trying at Yucca Mountain to augment other methods.

Perched Water and Water Balance

I do not know why the program has not looked more closely at developing percolation flux from a perched water balance and overall regional groundwater water balance. In light of L. Lehman's report (presentation at UZFMEE Workshop 2) that regional water table and precipitation oscillate with 2-3 year periods, an evaluation of water level data to quantify recharge seems potentially useful. Regional modeling conducted previously (Czarnecki and Waddell, 1984; Czarnecki, 1985; Czarnecki and Luckey, 1989) could provide another source of percolation flux information, particularly if the isotope data that are now available can be incorporated.

The observed low chloride in the perched aquifer could be consistent with episodic fast flow. The perched water analysis conducted by E. Kwicklis (Rousseau et al., 1996), which used residence time and volume of water to estimate seepage rates to and from the perched water body, is the type of modeling that should be continued. Fundamentally, the perched water must be explained. There could be a significant contribution to the perched water from infiltration and lateral flow from Solitario Canyon. This would explain the presence of younger water below older water beneath Yucca Mountain.

Additional work that might be fruitful includes an infiltration study of the Solitario Canyon watershed and the development of hydrographs of the perched water ascertain whether it is accumulating or draining.

PARTITIONING BETWEEN FRACTURES AND MATRIX; SEEPAGE INTO THE DRIFTS

The partitioning of the total percolation flux (by volume) at the repository horizon between fractures and matrix is uncertain. The UZ flow model now predicts that from 10% to 70% will be in the fractures, as a function of various parameter sets (e.g., flux levels, rock properties). The model results appear reasonable. Probably over the mountain and over long periods, most of the total flow volume, or at least a significant portion of it, occurs in the matrix component of the TSw. The velocities and flow per unit area are much higher in the fractures, however, for only relatively brief periods.

In terms of the components of the flux, the fast-flow component (as represented by the isotopic evidence), is likely a small component of the total flow volume. I agree with the basic bimodal shape to the LBNL travel-time curve for flow velocity to the repository (i.e., in the first pulse [fast fracture component], a small percentage of flow reaches the repository within years or tens of years, explaining the ^{36}Cl data; at the peak of the second pulse [matrix and/or slow fracture component], travel times are on the order of hundreds of thousands of years). The transient "pulse" of fast-flow moisture may be a relatively small part of the total volume of deep water movement. On the other hand, just the opposite could be true, based on the wide range of modeling results reported to date.

Seepage into the drifts (assuming ambient temperature conditions and no ventilation) will occur through fractures and not matrix. Because of the dry rind around the drift, where hydraulic conductivity would be very low, most of the matrix flow will be diverted around the drifts. Only when fractures are locally saturated and under sufficient hydraulic head will water enter the drifts. This is expected to occur at a limited number of locations: probably within a small percentage of the total number of available fractures, and therefore a small percentage (< 1%) of the total area. The WEEPS model is intriguing in its representation of this process. The TOUGH2 model should predict a limited number of seeps into the drifts. The observations at Rainier Mesa may provide a possible analogue for localized seepage, and it may be useful to validate TOUGH2 for this scale and type of problem by using it to simulate flow into Rainer Mesa tunnels.

To make the site UZ flow model more credible, additional field data should be gathered, including tension infiltrometer or an instantaneous profile in the PTn, perhaps from measurements in an alcove of the ESF. The model should be able to predict the key observations of seepage in the ESF, such as the wet area at station 75+00.

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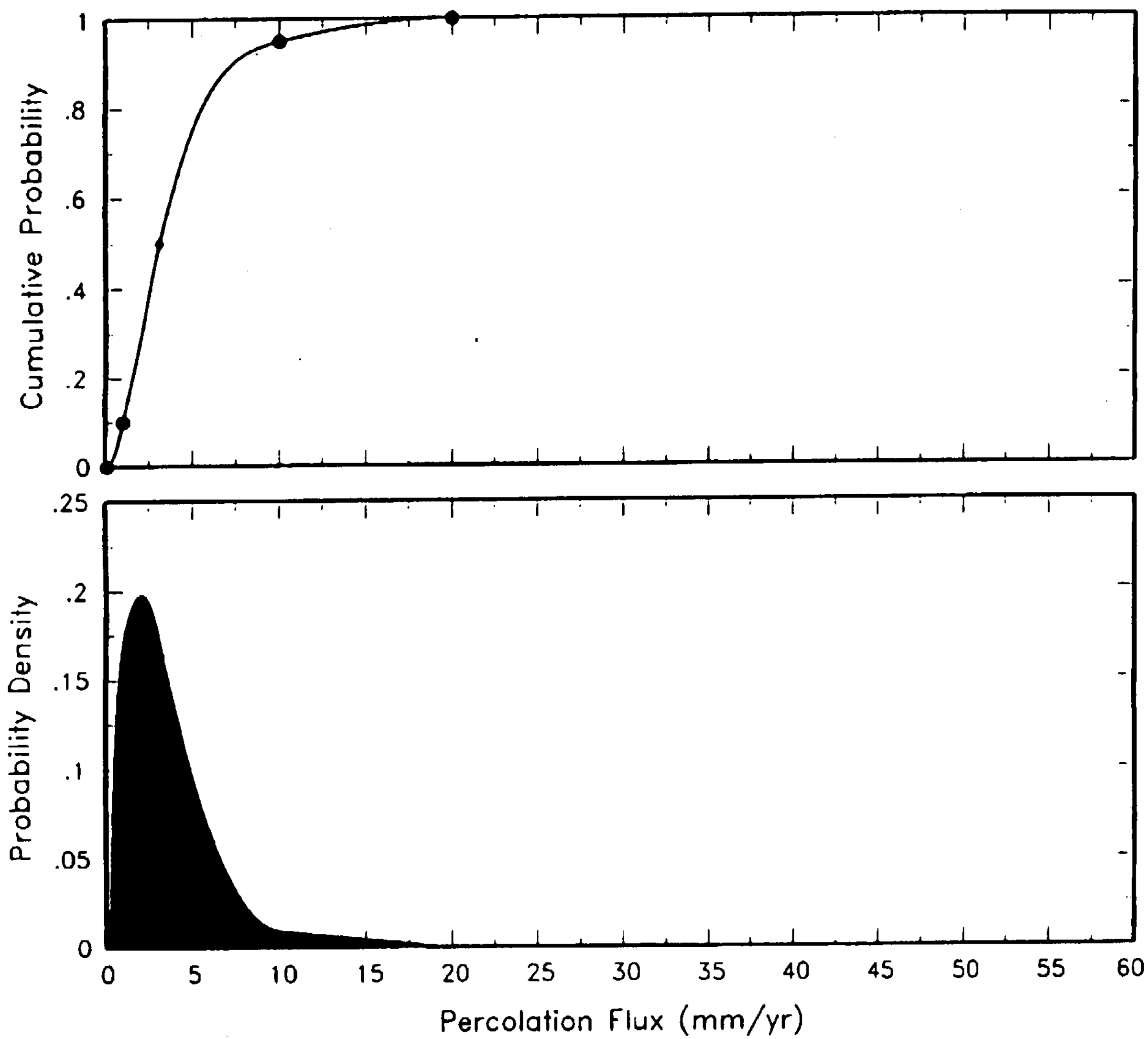

Figure DS-1 Assessed distribution for percolation flux at the repository level developed by Daniel Stephens. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

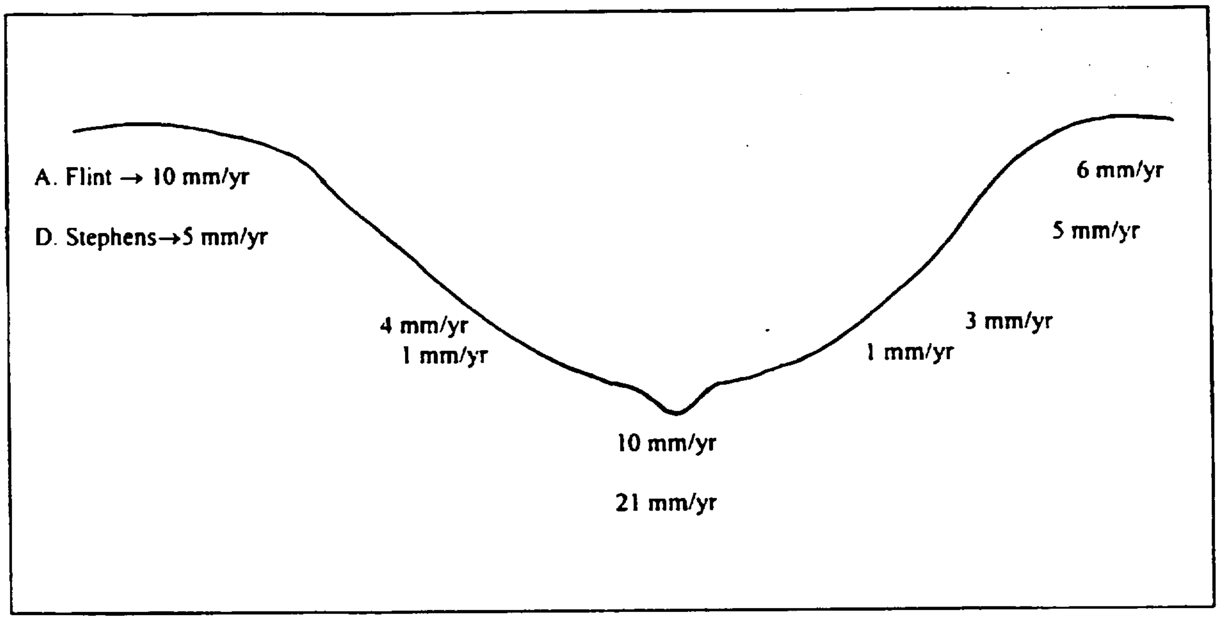

Figure DS-2 Diagrammatic north-south cross section of Split Wash showing estimates of the infiltration associated with the flat ridges, steep slopes, rock-covered lower slopes, and channel of the wash. Approximate net infiltrations are estimated by A. Flint (upper number) and D. Stephens (lower number).

ELICITATION SUMMARY

EDWIN P. WEEKS

February 18, 1997

OVERVIEW OF UZ FLOW: PROCESSES AND MODELING ISSUES

Several lines of evidence point to the ability of the flow system to move water quickly down to the water table. Chloride concentrations measured in water collected from neutron holes following precipitation (about 6 mg/L) are similar to those in surface water and in perched water at depth. This similarity in chloride concentrations near surface and at depth suggests that surface runoff accumulates in washes and moves through fractures in bedrock to pass quickly through the unsaturated zone. Therefore, washes and open bedrock fractures beneath them probably play important roles in focusing flow and may be underestimated in the infiltration modeling.

Air-permeability tests and air-pressure monitoring analyses of the Paintbrush unit (PTn) show its permeability to be about 100-200 millidarcies, values that are similar to those determined from cores. These permeabilities, which are equivalent to hydraulic conductivities of 30-60 meters/year, suggest that a significant amount of water could move through the PTn under gravity drainage. Water movement through the PTn probably occurs as localized flow both through fractures and faults and through the matrix, depending on whether fractures in the Tiva Canyon unit (TCw), which provide the deep percolation to the PTn, continue through that unit or not. If the fractures are discontinuous at the TCw-PTn contact, the matrix permeability of the PTn should be sufficient to allow water to percolate through a limited area with only localized perching. The top of the PTn is an irregular surface, and localized perching may occur in depressions on that surface. However, as observed in the ESF, the top surface of the PTn contains numerous faults having small offsets that, combined with significant matrix permeability of the PTn, would limit the extent of lateral flow. These observations, and the lack of evidence such as perched water at the upper PTn contact encountered in boreholes, or paleo-spring deposits at the upper PTn contact exposed in outcrop, indicate that significant lateral diversion of water at the TCw-PTn contact is unlikely.

Chlorine-36 (^{36}Cl) detected at bomb-pulse concentrations at depth confirm the ability of preferential flow paths, which probably connect from the surface to the perched water bodies, to carry flow at fast rates. However, these rapid fluxes may represent a small volume of flow relative to a much slower component of more diffuse percolation. In the vadose zone within the PTn and Topopah Spring (TSw) above the ESF horizon is a total depth of water of about 35 m, including a depth of about 30 m in the PTn. The bomb-pulse ^{36}Cl data indicate travel times of 20-40 years, implying a piston-flow displacement rate through the PTn of about 1 m/year or 3 mm/day. Such a flux rate, which is larger than the potential evaporation rate within the tunnel, would indicate that, if such piston flow were occurring over any significant area, seeps should be seen in the ESF at the locations where high ^{36}Cl activities were observed. Thus, the fast component of flow must bypass most of the volume of water stored in the PTn, as well as the volume stored in the TSw. This flow probably results from temporary perching at or near the top of the PTn that allows for transient flow through the PTn. The flow must occur as a transient pulse that moves through both units with little matrix interaction. The volume of water moving in these pulses may be only a small fraction of the total water flux through the system. In addition, the measured ^{36}Cl activities that are greater than previous background levels may represent a small amount of bomb-tagged water diluted by a much larger volume of older water, as pointed out by J. Fabryka-Martin (presentation at UZFMEE Workshop 2). This dilution would account for the fact that high ^{36}Cl activities are sometimes found without a correspondingly high tritium activity.

At UZFMEE Workshop 3, I presented an analysis of the minimum seepage flux rates required to produce seeps in the ESF. These estimates were somewhat arbitrary and probably too low. I believed that small seeps would be readily apparent during fracture mapping. However, on visiting the ESF (UZFMEE Field Trip), it was clear that large volumes of water are used in the mining process, and that "wet spots" would likely be attributed to residual moisture from the mining operation, even if they truly represented "weeps". The minimum fluxes are 10 times larger than those detected at Stripa, Sweden (Chesnut, 1992), which were obtained by placing plastic sheets over 2-square-meter areas within the tunnel. The plastic covers, however, may be effective in "magnifying" the detectability of the seeps by a factor of more than 10. More reliable estimates of the minimum detectable seepage rates might be obtained by finding out what size seeps were observed at Stripa before the plastic sheeting was employed, as ventilation practices probably are similar in most mines.

As water flows into the TSw, it could either disperse into the matrix or concentrate in the fracture network. If water enters the TSw as concentrated flow, the TSw could disguise a small areal source. If flow enters more uniformly, it could become more concentrated within the fracture network. Temporally, there is probably some damping within the TSw. However, any fracture flow would have to be somewhat episodic and not steady-state.

T. Tokanaga's work (presentation at UZFMEE Workshop 2) on film flow is for a narrow range of potentials that are near zero; thus, they are close to having water in the fractures anyway. Unless the fluxes are very high, the applicability of his results to the TSw is questionable.

APPROACHES TO ESTIMATING PERCOLATION FLUX

The following approaches to estimating percolation flux at the repository horizon were discussed. In the course of the assessments, recommendations were also made regarding the ongoing data-collection and modeling efforts at Yucca Mountain.

Net Infiltration

So many variables and uncertainties are involved in the water balance analysis that the usefulness of net infiltration to estimate percolation flux is doubtful. I will, therefore, rely on other indicators. In terms of spatial variability, I agree that the areas of thick alluvium and terrace deposits east of Fran Ridge will be areas of essentially zero infiltration. Plant density is sparse along the ridge at Yucca Mountain crest, intuitively suggesting that high infiltration would occur. However, studies of gas flow and of tracer arrival at well UZ-6s indicate that the uppermost microunits of the Tiva Canyon tuff (the caprock and upper cliff units) have quite low fracture permeability. Hence, significant overland runoff may occur from these units, and the estimates of 20-40 mm/year of deep percolation along the crest may be high. The water may be recharged into washes instead. This runoff, as well as runoff from other areas of bedrock outcrop, will enter the washes as side-flow, and will tend to migrate down the alluvium-bedrock contact. Where this percolating water encounters open fractures, substantial focused flow will occur that may persist to great depth. Data on moisture contents obtained from the neutron holes may not be useful for infering lateral movement of water along the bedrock-alluvium contact. Given these issues, I would expect the net infiltration map to be somewhat smoother than the Flint et al. (1996) map, with lower highs on the ridges and higher rates in the washes.

Temporally, to get water below the root zone and to overcome storage capacity, a rare large rainfall event is needed to cause significant net infiltration. A storm or sequence of storms lasting several days is required. In winter, precipitation events generally are of low intensity, but long duration. After soil moisture is replenished by winter rains, some evapotranspiration begins as previously dormant grasses begin to grow. Thus, winter recharge events likely occur as a result of anomalously intense winter storms, or storms of unusually long duration. In summer, sudden thunderstorms may occur after a long period of dry weather. The desert vegetation becomes dormant during periods of prolonged drought. Thus, these summer storms might be effective in causing recharge if they are of sufficient magnitude. The frequency of these events would likely be once every few years. A. Flint's modeling results (presentation at UZFMEE Workshop 1) show that five events occurred in the Beatty precipitation record between 1964 and the late 1980s of sufficient magnitude to have produced deep percolation at Yucca Mountain had they occurred there. This seems like a plausible number of recharge events. More severe events might be expected within increasingly longer recurrence intervals. During the intervening time between these events there is essentially no net infiltration.

At the level of the repository, I would expect the spatial distribution of percolation flux to look like a subdued replica of the distribution of infiltration. Water will flow vertically through the TCw, might show a minor lateral component through the PTn, and will flow vertically through the TSw.

Temperature Gradients
See attached "Thoughts on Temperature Analysis, Yucca Mountain," by E. Weeks, dated February 2, 1997. I endorse the temperature methodology for assessing percolation flux and believe that it is robust. However, its application to Yucca Mountain is limited because of data limitations, particularly the large spacing of temperature measurements in the unsaturated zone and uncertainty in estimates of heat flux in the saturated zone. I became convinced of the applicability of the temperature profile method to estimate recharge late in the elicitation process, and did not go back and review calculations by E. Kwicklis (presentation at UZFMEE Workshop 1) or by B. Bodvarsson (presentation at UZFMEE Workshop 2). If one takes the Sass et al. (1988) estimates of saturated zone heat flux in the areas underlain by thick alluvium (the consensus estimate is that recharge is zero in these areas), and applies that heat flux to the area under Yucca Mountain, a recharge of 12 to 30 mm/yr can be estimated based on heat flux in the unsaturated zone. It seems likely that the saturated zone heat flux beneath Yucca Mountain is less than that beneath the basins because of the phenomena occurring within the saturated zone, thus making these flux estimates unreliable. However, the above estimates might be valid, and they are the basis for the low-probability estimate of high flux ranging from 10 to 30 mm/yr shown in Figure EW-1.

Saturations and Water Potentials
Uncertainties in modeling water saturation and potentials preclude strong constraints on the flux estimates. Saturations apparently can be matched using any flux desired. Water potential estimates determined from cores differ from those determined *in situ*. Although the *in situ* data presumably are more reliable, they still may not represent equilibrium conditions. Flux estimates are very sensitive to small differences in water potential values, making them questionable.

Chloride Mass Balance
The assumed values of 0.6 mg/L of chloride in precipitation (presentation by J. Fabryka-Martin at UZFMEE Workshop 2) and 6 mg/L in the saturated zone show only an increase of a factor of ten. Comparison of surface water chloride concentrations with perched water suggests that water moves through the section without picking up much chloride, despite high chloride content in the PTn. This suggests that the system is recharged primarily by fracture flow. These observations do not provide a constraint on percolation flux.

Isotopic Evidence
The presence of ^{36}Cl at depth shows only that some water gets to depth in a short time. However, radiocarbon activities of dissolved inorganic carbon provide a way of dating water from a few hundred years to about 40,000 years. Radiocarbon is mobile in both the liquid and gas phases, and gaseous diffusion should tend to smooth and integrate the radiocarbon signal, averaging the radiocarbon activities of matrix and, presumably, both fast and slow components of fracture flow (based on the assumption that the gas and liquid-phase radiocarbon contents remain in local equilibrium). Gas samples from the TSw show decreasing radiocarbon activity with depth, which is matched by a model of a few mm/yr percolation flux. Although the estimates derived from this model range from about 1 to 10 mm/yr, this variation may represent uncertainty in the method, as opposed to true areal variability.

The middle of the range (1-10 mm/yr) of average percolation fluxes that I assess (Figure EW-1) is based on this approach. This is a spatially and temporally averaged estimate for the Yucca Mountain block over tens to hundreds of years.

Perched Water
E. Kwicklis (in Rousseau et al., 1996) used a mixing (box) model of radiocarbon activities measured in water samples collected from some of the perched water bodies to estimate mean residence times of 4,000-11,000 years, depending on the assumed extent of calcite-water radiocarbon exchange. These residence times would result from percolation flux rates of 0.01-02. mm/yr, values that I used in the probability distribution (Figure EW-1) for the range 0-1 mm/yr. Water squeezed from cores collected from beneath the perched water bodies, however, provide radiocarbon ages that are much younger (500-1,000 years). Possibly, these young ages represent lateral flow from infiltration in Solitario Canyon, but the young dates also raise doubts about the validity of estimates of low flux from the mixing model. Another puzzle is presented by chloride data, which show concentrations of 4-6 mg/L in the sampled, freely draining water, while water squeezed from cores collected from the perched water zone indicate concentrations as high as 100 mg/L. These results indicate that the chloride is not diffusing from the matrix into the free water even over thousands of years. This seems impossible.

Fracture Coatings
From Z. Peterman's data (presentation at UZFMEE Workshop 1) on the rate of calcite deposition in lithophysal cavities and fractures, I calculated a flux rate that would provide the necessary rate of calcite deposition. The calculation is based on outgassing of CO_2 in response to increasing temperature with depth, assuming that the water was saturated with calcite. For a temperature gradient of 0.025 degrees C/m and a recharge period of 10 Ma, I obtained a flux rate of 2 mm/year to deposit the calcite. Although this estimate fits into the range provided by other methods, it seems unlikely that calcite would precipitate from rapid

pulsed recharge to the extent needed to get the ^{36}Cl to the repository horizon. Hence, the estimate should be thought of as a lower bound to the recharge estimates, rather than a reliable estimate by itself.

PARTITIONING BETWEEN FRACTURES AND MATRIX; SEEPAGE INTO THE DRIFTS

In the TSw, the low matrix permeabilities can carry about 1 mm/yr of flux. The rest of the flux occurs in the fractures. It is unknown how much of the flux in the fractures is the fast component and how much is the slow component. If percolation fluxes are as high as 5-10 mm/yr, a significant fraction may occur as pulses following extreme precipitation events. Such a temporal distribution of high flux would be compatible with the lack of observed weeps into the tunnel, as it would imply that we have not been looking for weeps at the right time.

The matrix component of the flux will go around the drifts because of capillary barrier effects. However, I would expect most of the fracture component to enter the drifts, as the fractures tend to be vertical to subvertical. Fractures and faults have been mapped nearly everywhere; I interpret the ^{36}Cl as being essentially everywhere. Therefore, there are many opportunities for water to flow into the drifts, yet no seeps have been observed.

Most likely only a few of the total number of fractures are accommodating the flux, perhaps 1% - 10%. The presence of many fractures accommodating the flux, as opposed to a few carrying large volumes, is consistent with the lack of observed seepage into the ESF, although the period of observation has been short. I would expect less than 1% - 10% of the total area of the drifts to see seepage. I have little basis to comment on the degree to which it is possible to identify those fractures that might flow. The calcite coatings suggest that the same fractures support flow over time. Perhaps the spatial distribution is best modeled as a random process.

THOUGHTS ON EXPERIMENTS TO REDUCE UNCERTAINTY

Estimates of deep percolation flux probably are best constrained by relatively large-scale experiments in the ESF. I am not familiar with the details of the proposed niche studies, but I understand that these will be sealed alcoves in which humidity buildup and/or "weeps" will be observed. My biggest concern regarding these experiments is whether the niches will be large enough to capture representative seepage conditions into the tunnel. Any attempt to make such observations in the ESF itself, however, would have the handicap that tunnel ventilation has likely resulted in sufficient dryout of the wall rock that several years would be required before ambient conditions were recovered (based on data from J. Wang's presentation at UZFMEE Elicitation Panel Workshop 1). However, a possible approach to identifying larger weeps might be to install a substantial number of plastic sheets along the roof and walls of the ESF, similar to the experiment conducted at Stripa, Sweden (Abelin et al., 1991; Chesnut, 1992). In that experiment, 1 m x 2 m plastic sheets were installed on the roof and sides of a drift mined in granite, and water inflow to the sheeted areas was monitored. Chesnut (1992) reports detections of inflows of as little as 2 mL/day to a given sheet. (Abelin et al. provide the data in a graphical format from which minimum fluxes are hard to identify.) The Stripa facility is below the water table, so water in the rock is under positive pressure, and capillary barrier effects are absent. At Yucca Mountain, capillary barrier effects may divert water around the drift, but larger weeps that represent slow fracture flow should be detectable. However, matrix flow might be diverted by capillary barrier effects, and episodic flow would be detected only if the timing is right. I have no idea what kinds of experiments might be conducted to confirm that a significant fraction of the deep percolation occurs in episodic events. Good fortune might be the best hope.

A second effort might be to obtain better temperature logs from the unsaturated zone at sites for which previous logs were obtained by measurements at 30-50 m intervals. The wide spacing of readings makes it difficult to determine temperature gradients across fairly uniform areas of the section.

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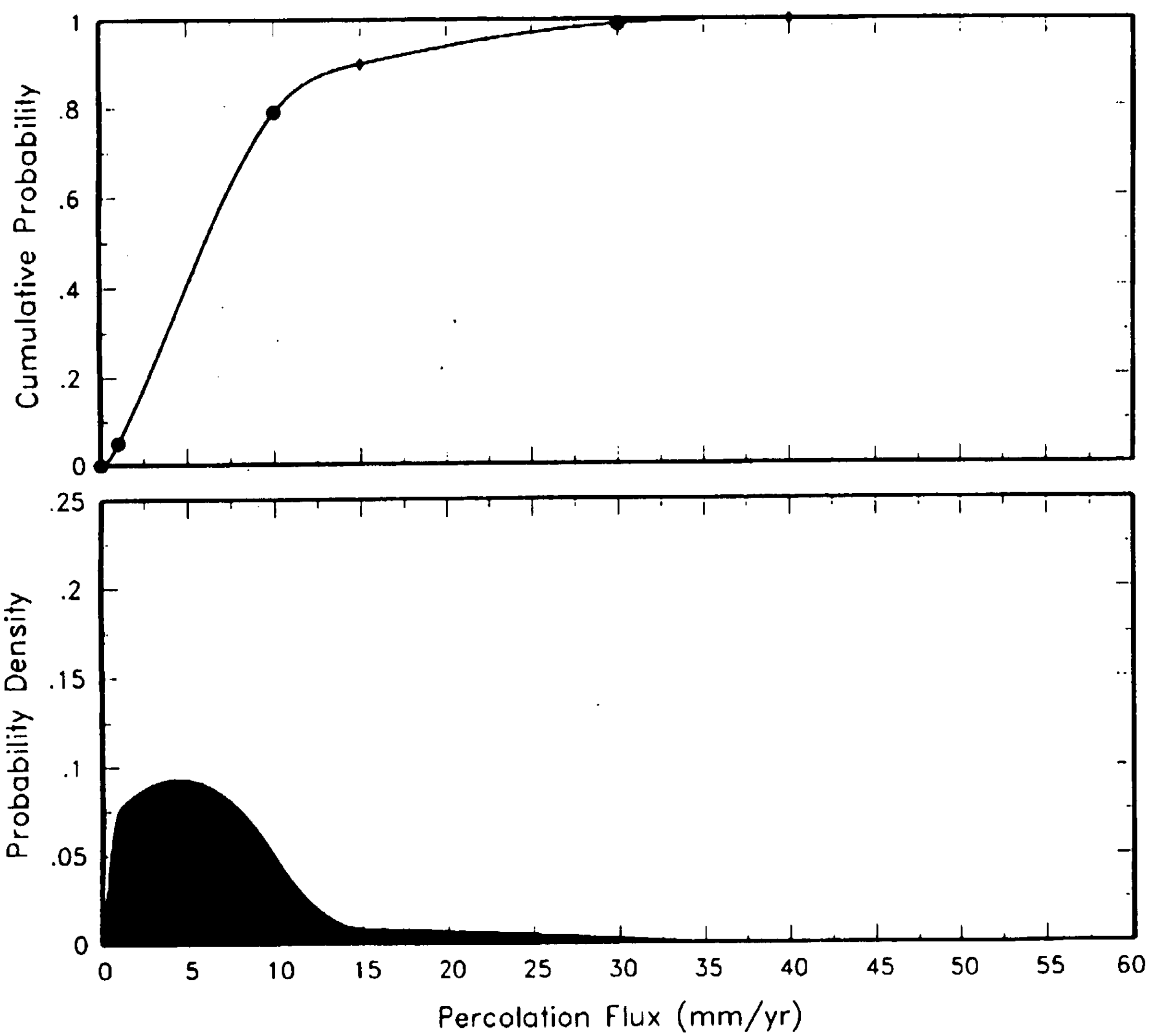


Figure EW-1 Assessed distribution for percolation flux at the repository level developed by Edwin Weeks. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

Thoughts on temperature analysis, Yucca Mountain

E. P. Weeks

Much emphasis has been placed on the analysis of temperature profiles with depth to estimate deep percolation. Thinking has developed that the bottom boundary condition should be that of specified flux, rather than the specified temperature of Bredehoeft and Papadopulos' (1965) solution for the equation of steady 1-D flux through a uniform porous medium subject to a geothermal gradient. Their differential equation is:

$$k\frac{d^2T}{dz^2} = \rho c v\frac{dT}{dz}, \qquad (1)$$

where k = thermal conductivity, W/m·K; T is temperature, K; ρ is water density, kg/m^3; c is thermal heat capacity of water, J/kg·K; and v is Darcy velocity, m/s.

This equation is of the form $y''+ay'=0$, and has the solution:

$$T = C_1\exp(-\alpha z) + C_2, \qquad (2)$$

where α is $\rho cv/k$, 1/m.

We are interested in the solution for the boundary conditions $\frac{dT}{dz} = -C_0$ at z=0 and $T=T_L$ at z=L. But $\frac{dT}{dz} = -\alpha C_1\exp(-\alpha z)$, so $C_1=C_0/\alpha$. $T = \frac{C_0}{\alpha}\exp(-\alpha z) + C_2$, and

$T_L = \frac{C_0}{\alpha}\exp(-\alpha L) + C_2$. Thus, $C_2 = T_L - \frac{C_0}{\alpha}\exp(-\alpha L)$, and the equation becomes:

$$T = \frac{C_0}{\alpha}[\exp(-\alpha z) - \exp(-\alpha L)] + T_L. \qquad (3)$$

The physics behind the assumption of T_L being specified arises from the context that the near-surface energy balance ensures that the infiltrating water will adapt to a temperature approximated by the annual mean air temperature before percolating to depth. This seems likely, in that, even if snowmelt supplies the infiltration, solar radiation and the large rock heat storage term will supply sufficient energy to warm the water, particularly when it is considered that this energy is sufficient to evaporate much more water than falls. Also, a situation in which the cold water infiltrated to some depth quickly, the low temperature induced at that depth would be resupplied by thermal conduction from the warmer surface.

Equation 3 was evaluated for assumed values of flux rate to produce synthetic temperature logs that could be used to test Ed Kwicklis/Bo Bodvarrson methods. The simulated profiles are based on a 200-m thickness of Calico Hills (CH) overlain by 250 m of Topopah Spring (TS). Thermal conductivity for the CH is 1.3 W/m·K and for the TS is 2.0 W/m·K. The logs were created in a three-step process. First, a simulation of the CH was made assuming an arbitrary upper temperature to determine the heat flux leaving the top of the unit. This heat flux was used to compute a temperature gradient, C_U, for the TS, and the log segment for the TS simulated to have a top temperature of 19 °C. The temperature profile for the CH was then shifted so that the temperature at the top of the unit exactly matched that simulated for the base of the TS, and the segments were combined. Three profiles, based on deep percolation rates of 0, 10, and 20 mm/yr, were prepared.

How do we determine the deep percolation flux v from the temperature logs? As I understand Bo's approach, we take the known (or independently estimated) heat flux at the base of the section minus an estimate of heat flux leaving the top of the TS, based on the average temperature gradient through that unit in the equation:

$$v = \frac{Q_H - \left[k\frac{\Delta T}{\Delta z}\right]_{TS}}{\rho c \Delta T_x}, \qquad (4)$$

where Q_H is the known heat flux, W/m^2. For the 10-mm/yr percolation flux, ΔT for the TS is 6.1 °C, and Δz is 250 m, so the average temperature gradient in the TS is .0244 K/m. What do we use for ΔT_x? Here, it seems that it should be the temperature drop from the base of the CH to the midpoint of the TS, as we are using the average gradient across that unit to determine the outgoing heat flux. Thus, ΔT_x would be 9.04+3.05 or 12.09 °C. Substituting,

v=(.065 W/m^2-.0488 W/m^2)/(4.2X10^6 J/m^3·KX12.09 K), or 3.19X10^{-10}m/s.

This translates to 10 mm/yr exactly (at least to the number of decimal places I kept).

A second approach, based on Ed Kwicklis' method, is to substitute the heat flux computed from the average temperature gradient and thermal conductivity of the CH for Q_H:

$$v = \frac{\left[k\frac{\Delta T}{\Delta z}\right]_{CH} - \left[k\frac{\Delta T}{\Delta z}\right]_{TS}}{\rho c \Delta T_x} \qquad (5)$$

For the 10-mm/yr flux rate, the temperature drop across the CH is 9.04 °C, so the heat flux is 1.3X(9.04/200) or .0588 W/m^2. The term ΔT_x for this approach should be equal to the temperature drop from the midpoint of the CH to the midpoint of the TS, or 7.57 °C. Substituting these values also returns a flux rate of 10 mm/yr. Thus, the methods are completely equivalent if the ΔT_x term is correctly selected.

Similar analyses were made using a flux rate of 20 mm/yr, with exactly the same results. This redundancy occurred because I used improper values for ΔT_x in my initial calculations, resulting in an erroneous indications of error increasing with percolation rate.

Finally, we look at Ed Kwicklis' theory in which the heat fluxes are evaluated based on temperature gradients across short depth intervals at the base of the CH and at the top of the TS to obtain the $\Delta T/\Delta z$ terms shown in the numerator of Equation 5. In this case, ΔT_x is the total temperature drop across the two layers, or 15.14 °C. From the simulation output, the temperature gradient at the top of the TS is .0244 K/m, so the outgoing heat flux is 0.0449 W/m^2. (and of course the incoming heat flux is 0.065 W/m^2). The flux rate of 10 mm/yr is again perfectly captured, so that Ed is completely correct in his arguments.

I conclude from this that so long as ΔT_x is evaluated as the difference in temperature between the midpoints of the two line segments of whatever length used to determine incoming and outgoing heat flux, the suggested methods are equivalent and should provide accurate (within the limits of the data) estimates of deep percolation. For Bo's method, the bottom heat flux is assumed to be determined for an infinitesimal thickness at the base of the CH. In theory, the above conclusions regarding the temperature difference between line-segment midpoints should be equally applicable to heat flux measurements from below and above the water table, apparently as done by Bo/Ed? This will only be true if the 1-D assumption of heat flow can be made, but provides very plausible values of deep percolation flux for wells G-1 and H-1, which seem to have better-behaved saturated-zone temperature profiles than many of the other wells. That's as far as I went with that analysis.

Reference

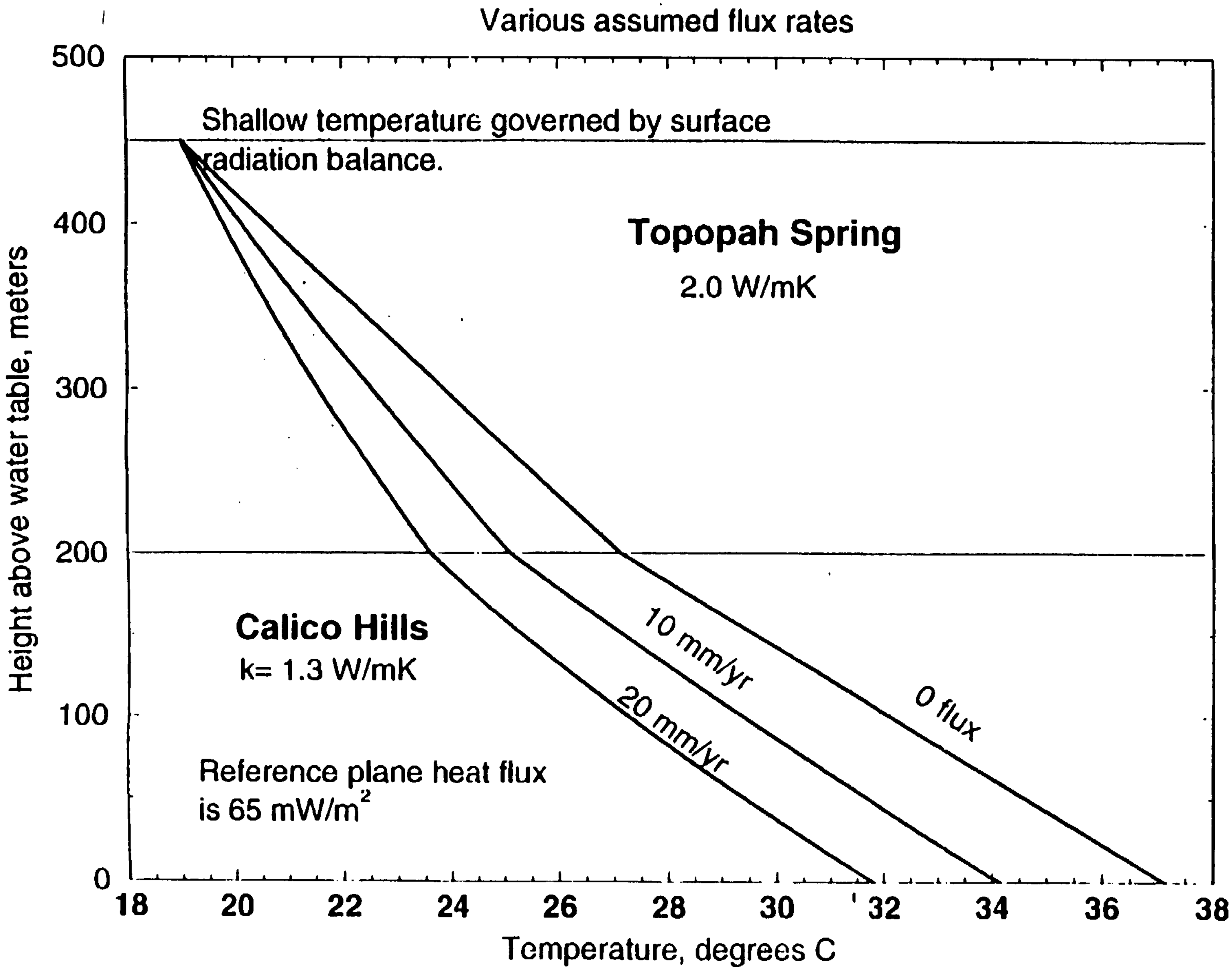
Bredehoeft, J. D. and Papadopulos, I. S., 1965, Rates of vertical groundwater movement estimated from the Earth's thermal profile: Water Resour. Res., v. 1, no. 2, p. 325-328.

APPENDIX E
QUALITY ASSURANCE

QUALITY ASSURANCE

The Unsaturated Zone Flow Model 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 Technical Document Preparation Plan for this expert elicitation project; this plan is maintained as a controlled document under document identifier B0000000-01717-4600-00004. 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 this guidance has been successfully applied in other comparable assessments.

Synthetic Temperature Logs



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TRW

TRW Environmental Safety Systems Inc.

1180 Town Center Drive
Las Vegas, NV 89134
702.295.5400

WBS: 1.2.3.1.2.9
QA: N

Contract #: DE-AC01-91RW00134
LV.PP.TAG.06/97-055

June 9, 1997

Stephan J. Brocoum, Assistant Manager
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Yucca Mountain Site Characterization Office
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North Las Vegas, NV 89036-0307

Attention: Technical Publications Management

Dear Dr. Brocoum:

Subject: Completion of Level 3 Fiscal Year (FY) 1997 M&O Milestone SP24BM3, "UZ Site Flow Model," Work Breakdown Structure (WBS)1.2.3.3.1.2.9

Three copies of the above-referenced deliverable are being submitted for deliverable acceptance review in accordance with YAP-5.1Q. This action completes delivery of Milestone SP24BM3. A second YAR form is also included for the related deliverable SP2445M4. This YAR may be approved when acceptance of SP24BM3 is complete.

If you have any questions regarding this deliverable, please contact Dwight Hoxie at (702) 295-5740, or me at (702) 295-5604.

Sincerely,

Larry R. Hayes

Larry R. Hayes, Manager
Site Evaluation Program Operations
Management and Operating Contractor

LRH/clt

Enclosures:
(1) Deliverable Acceptance Review Form
(2) Participant Planning Sheet
(3) Milestone SP24BM3

cc with Enclosures:
S. H. Hanauer, OCRWM HQ, RW-2
M. D. Voegele, M&O, Las Vegas, Nevada
LV RPC = 773 pages

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