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External Peer Review Group Report on Frenchman Flat Data Analysis and Modeling Task, Underground Test Area Project

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EXTERNAL PEER REVIEW GROUP REPORT ON FRENCHMAN FLAT DATA ANALYSIS AND MODELING TASK, UNDERGROUND TEST AREA PROJECT

16 September 1999

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EXTERNAL PEER REVIEW
GROUP REPORT ON FRENCHMAN FLAT
DATA ANALYSIS AND MODELING TASK,
UNDERGROUND TEST AREA PROJECT

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EXECUTIVE SUMMARY

An external peer review panel consisting of six independent technical experts was established to review and evaluate data and interpretations derived in the Frenchman Flat Data Analysis and Modeling Task of the Underground Test Area Project (UGTA) of the U.S. Department of Energy. This Task involves implementation of a groundwater flow and contaminant transport model designed to simulate the maximum extent of contaminant migration over a period of 1,000 years from individual sites of underground nuclear weapons tests in the Frenchman Flat basin on the Nevada Test Site. The review focuses on four draft technical documents totaling more than 1,000 pages which describe the modeling activities on this project. The review addresses strategies and methods employed in these reports, specifically considering the proposed geologic and hydrologic conceptual models, and the groundwater modeling results, identifying significant errors, limitations, or ineffective strategies involved in the modeling work presented in these documents. The review also identifies recommended actions that could address the deficiencies in the modeling work, and includes discussions of the issue of the transferability of the modeling approach to other areas of the Nevada Test Site. The review does not focus on specific strengths of the investigations, though we note that the work is generally regarded to have been carried out in a competent, professional fashion representing the state-of-the-art of practice in this field.

The panel finds that, because of data limitations and ineffective modeling strategies, the very limited extent of contaminant migration (a few hundreds of meters) which was predicted to occur in the alluvial aquifer, though possible, is not established with the degree of confidence that would normally be expected at such contaminated sites. The degree of uncertainty in the model predictions is underestimated primarily because alternative geologic and hydrologic conceptual models are not adequately considered in the uncertainty analysis. Plausible alternative conceptual models, for example, involve localized vertical flows driven down through possible gaps in the confining unit into the Lower Carbonate Aquifer by the 10 meter head differential which exists between it and the alluvium. Such alternative models could involve much more severe consequences in terms of the extent of contaminant migration. There are also concerns that the existing data are not adequate to predict the rate of release of radionuclides from test sites or radionuclide reactions with the surrounding alluvium and volcanic rocks. The exclusion from the study of radionuclides, with classified source term data, compromises the representativeness of the transport calculations, and causes the panel to question whether the predicted doses are either meaningful or conservative. In addition, the inconsistencies among the draft documents in the selection of radionuclides, with unclassified source term data, and in their assumed reactivities, further increases the uncertainty in model-predictions of future radionuclide doses associated with groundwater use.

To address the identified limitations of the current modeling results, the panel recommends a phased, integrated program of modeling and field-data collection, in which decisions on data collection are contingent upon the latest modeling results, and vice-versa. This calls for a decision framework that weighs the cost of data enhancements against the benefits in terms of improved protection of public health and the environment, expressed in terms of defined performance criteria. Suggested data enhancement activities include aquifer testing in the

alluvium, resampling of existing wells for environmental isotopes, alluvium and rock sampling to characterize sorption properties, a reflection seismic survey, and possibly two new wells to determine contaminant conditions and hydraulic properties near detonation sites. Suggested alternative modeling approaches include simpler, smaller scale models which allow better resolution of conditions near contaminant sources and possible vertical pathways into the Lower Carbonate Aquifer via faults, fracture zones, more-permeable sections in the confining layer, or zones of aquitard thinning in areas of block offsets.

Regarding the transferability of the modeling approach to other parts of the Nevada Test Site, the panel can support the transfer of the scientific and engineering thinking that underlies the groundwater modeling efforts to date, but, because of the many possible differences in geologic and nuclear detonation conditions, it questions that the codes and modeling strategy used at the Frenchman Flat Corrective Action Unit can be readily transferred to other sites.

CHAPTER 1

INTRODUCTION

This chapter provides background on this technical review activity, and defines the scope and objectives of the review. The rationale for the approach adopted in the review is discussed briefly, as is the organization of the report.

1.1 Background

Over the past 40 years, 921 underground nuclear detonations were carried out at the U.S. Department of Energy's (DOE) Nevada Test Site (NTS) as part of the United States' program of nuclear weapon testing. Many of these devices were detonated at depths near or below the water table so that there is a significant potential for groundwater contamination by the radioactivity introduced from these detonations. The U.S. Department of Energy, Nevada Operations Office (DOE/NV) has initiated the Underground Test Area (UGTA) Project to evaluate the effects of the underground nuclear weapon tests on groundwater. The State of Nevada's Division of Environmental Protection (NDEP) regulates the corrective action activities of the UGTA Project through a *Federal Facility Agreement and Consent Order*. The individual nuclear test sites have been grouped geographically into six different Corrective Action Units (CAUs). The Frenchman Flat CAU is the most southerly of the units with the smallest number of test sites (10). It is the first CAU to be investigated through implementation of a unit-specific groundwater flow and contaminant transport model designed to simulate the maximum extent of contaminant migration from individual test sites.

As part of the overall groundwater modeling process for the Frenchman Flat CAU (see Figure 2-1 of Volume II, IT Corporation, 1999a), an independent panel of experts, the External Peer Review Group , was chartered, under contract with IT Corporation, to review the groundwater modeling activities for the Frenchman Flat CAU. The members of the panel are:

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Brief professional biographies for each of the panel members are included in the Appendix.

The following four documents provide the basis of the review of the Frenchman Flat groundwater modeling effort:

a) Underground Test Area Subproject
Corrective Action Unit 98: Frenchman Flat Data Analysis Task
Volume I – Hydrostratigraphic Model Documentation Package
IT Corporation, August 1998, Draft

b) Underground Test Area Subproject
Corrective Action Unit 98: Frenchman Flat Data Analysis Task
Volume II – Groundwater Data Documentation Package
IT Corporation, April 1999, Draft

c) Underground Test Area Subproject
Corrective Action Unit 98: Frenchman Flat Data Analysis Task
Volume III – Groundwater Flow and Contaminant Transport Model Documentation Package
IT Corporation, April 1999, Draft

d) Evaluation of the Hydrologic Source Term from Underground Nuclear Tests in Frenchman Flat at the Nevada Test Site: The CAMBRIC Test
Lawrence Livermore National Laboratory (LLNL)
UCRL-ID-132300, March 1999

These four documents, which were provided in April 1999, form the core of the written material that was reviewed by the panel. Several other documents, providing additional background and supporting technical information, were also made available for review. On May 19, 1999, the panel participated in a guided field trip of the Frenchman Flat area of the NTS. At meetings on

May 20 and 21, 1999, in Las Vegas the DOE contractors presented the results of the Frenchman Flat modeling efforts, and discussed various aspects of the UGTA Project.

1.2 Scope and Objectives of the Review

The contract Scope of Work for the External Peer Review Group states that the panel "… will review and evaluate data and interpretations derived during the Frenchman Flat Data Analysis and Modeling Task of the Underground Test Area Project (UGTA) of the U.S. Department of Energy (DOE), Nevada Operations Office…" and indicates that the group is responsible for the following:

a) Review the strategies and methods employed during the data collection, and where appropriate, review the data itself.

b) Review and evaluate proposed geologic and hydrologic conceptual models, and the results of the groundwater modeling efforts.

c) Provide comments about significant omissions, shortcomings, errors, or ineffective strategies used in the preparation of the data analysis and modeling work products.

At the 20 May meeting, the introductory presentation on the modeling effort discussed goals of the peer review in terms of the following series of questions which the review should address in assessing the technical adequacy of the model:

a) Are there fatal flaws?

b) Is the conceptual model correct?

c) Are the physical processes properly incorporated into the model – are the approximations acceptable?

d) Is the level of detail commensurate with the goals of the model?

e) Is the modeled uncertainty inclusive of reality with 95 percent certainty?

The presentations and discussions at the May 21 meeting raised a number of additional issues, pertaining particularly to future modeling-related activities in the UGTA Project, on which the views of the panel are sought. These issues are summarized in terms of the following questions:

a) How can the model be validated and at what scales (basin scale, testing area scale, or test cavity scale) is validation feasible?

b) Is the modeling approach used for Frenchman Flat CAU transferable to the other CAUs?

c) Are there additional wells (or other data) which will be critically important in reducing the uncertainties in the Frenchman Flat model?

The objective of this report is to present the panel's consensus technical assessment of the Frenchman Flat modeling work. The focus of the assessment is on the four primary documents listed in Section 1.1 in relation to the items in the Scope of Work, and the issues reflected in the two lists of questions noted above.

1.3 Panel Approach and Report Organization

The Frenchman Flat CAU was selected for initial study in part because earlier assessments at the regional scale suggest that this CAU is the simplest and least likely of all the CAUs on the NTS to provide a serious threat to human health. It would appear that the strategy is to seek a regulatory decision on the Frenchman Flat CAU before proceeding with the assessment of CAUs on Yucca Flat and Pahute Mesa where conditions are thought to present a more serious threat to off-site contaminant migration. From the perspective of the panel, this strategy is complicated by the apparent desire that the Frenchman Flat study also act as a prototype with some degree of transferability to the other CAUs.

The panel has deliberated carefully over the dichotomy presented by these conflicting goals. We have come to the conclusion that it is our responsibility to assess the Frenchman Flat program on its own merits, irrespective of budget considerations and of its relation to conditions at other CAUs. It is our opinion that if the Frenchman Flat CAU were the only CAU on the NTS, it would merit a full and complete assessment. The Frenchman Flat investigation should not be less intensive simply because other sites are thought to be more problematic. The potential contamination from the Frenchman Flat source areas is at least as worrisome as that which exists at many large Superfund sites across the country. A level of investigative commitment similar to that found at such sites would be appropriate.

The study that we have been asked to review for Frenchman Flat is based almost totally on modeling. It is our opinion, developed more fully below, that the lack of data with which to evaluate contaminant migration predictions leads to unacceptable levels of uncertainty that can only be reduced by further investigative action at the Frenchman Flat CAU. While we concur with the assessment that this CAU is likely to be relatively less threatening than some of the others, we feel that even at this less-threatening site, the requisite proof that this is the case has not been convincingly developed.

In light of the above comments, we have carefully separated our assessment of the subject CAU from the considerations of transferability. In the material that follows, Chapters 2, 3, and 4 deal solely with the Frenchman Flat CAU. All discussion of the transferability issue is postponed until Chapter 5. Chapter 2 provides a summary of the most important issues of concern that have been identified through our review of the four primary documents describing the work on the Frenchman Flat CAU, and Chapter 3 contains the detailed technical review comments on these documents. In Chapter 4 we suggest a rationale for improvements which could address the current weaknesses in the Frenchman Flat modeling work and provide some recommendations based on that rationale.

CHAPTER 2

KEY ISSUES OF CONCERN

This chapter summarizes the major technical concerns which have been identified by the panel in reviewing the three IT volumes and the LLNL report. These items naturally focus on significant weaknesses and shortcomings in the modeling effort, as this is one of the primary purposes of this review. We want to emphasize that the Frenchman Flat groundwater modeling activity is regarded to be uniquely challenging because of the complexity of the geologic setting, the sparseness of the hydrogeologic data, the relative large depth to the water table, and the management and budgetary constraints. Our review does not focus on specific strengths of the investigations, though we note that the work generally has been carried out in a competent, professional fashion using the state-of-the-art of practice in this field. The comments here summarize what the panel finds to be the most important issues. More comprehensive discussions of these issues are found in Chapter 3, which contains detailed review comments on the four primary documents.

2.1 Data Limitations

The Value-of-Information Analysis (VOIA) conducted for Frenchman Flat (ITCorporation,1997b) is cited as the basis for the conclusion "…that no additional data were needed to achieve the objectives of the Frenchman Flat CAI." (Volume I, p. 1-4). The panel strongly supports the idea of conducting a VOIA as part of the Frenchman Flat corrective action effort, but questions the basis for the decision that no additional data are needed. Of greatest concern to us is the virtual absence of site-specific data from the underground nuclear test areas where most of the contaminant release and migration are expected to take place. Such an absence of data is unusual for sites of suspected or potential groundwater contamination. This data deficiency throws into question the validity of the analysis of the fate of pollutants, and required corrective action at Frenchman Flat.

a) *Inadequate Data to Define Hydrostratigraphic Framework*
Due to a paucity of drill hole data and the lack of seismic data, the conceptual model of Grauch and Hudson (1995) formed the basis for the hydrostratigraphic framework model for Frenchman Flat, especially for the deeper parts of the basin. Although this conceptual model is plausible, it does not appear to be unique, and cannot be considered a substitute for hard data. Key contaminant migration scenarios were not considered. Of note is the possible vertical movement of contaminants from the alluvial aquifer into the underlying carbonate aquifer through faulted segments of intervening confining units. These possible pathways depend in a critical way on the (virtually unknown) structure and hydraulic properties of these units beneath nuclear test areas at Frenchman Flat.

b) *Inadequate Data to Support Groundwater Flow Modeling*
The available groundwater level and permeability data are inadequate for the direct assessment of groundwater flow directions, rates and travel times in the vicinity of the source areas. They are also insufficient to confirm or constrain estimates of lateral inflows and outflows across basin boundaries, or the assumed patterns and rates of natural recharge and discharge. Recharge is assessed by means of the Maxey-Eakin regional formula, which is acknowledged to be of low reliability. The possibility of local recharge due to preferential infiltration into, and wetting of, nuclear test chimneys (through surficial craters or otherwise) or nearby ditches and depressions is acknowledged but not considered in the analysis. There is no subsidiary data suitable for model validation. In our opinion, the paucity of hydraulic data leads to model predictions that are nonunique and of undetermined accuracy.

c) *Inadequate Data to Define Contaminant Source Terms*
The actual source term data for the radionuclides that may be potentially released from nuclear test cavities at Frenchman Flat is classified and therefore not available for review by the panel. We consider the analysis of release rates of selected radionuclides at the CAMBRIC test site, conducted by Tompson et al. (1999), to be of scientific interest and of potential practical value for the remedial action program at Frenchman Flat. We are; however, unaware of specific site data that would lend direct and decisive support for this model either at CAMBRIC or at other underground nuclear test sites. Without such data, we regard the model and its predictions as having at best tentative site-specific validity. We are also concerned with the possibility that volatile radionuclides might have spread (via prompt injection and/or advection-diffusion) through the vadose zone. There they could decay into nonvolatile daughter products that might find their way into the groundwater. This possibility has not been considered in the Frenchman Flat analysis.

d) *Inadequate Data to Support Advective Contaminant Transport Modeling*
Only one bulk value of effective (kinematic) porosity has been obtained for the alluvial aquifer from analysis of the 17-year long CAMBRIC tracer test. No direct measurements of effective porosity are available for other units in Frenchman Flat. There is little or no site-specific information about retardation coefficients that control sorption and/or diffusion into and out of low permeability materials (lenses of fines in alluvium, matrix in fractured rocks). Hence, there is no adequate database for the conversion of groundwater fluxes into advective transport velocities.

e) *Inadequate Data to Characterize and Predict Contaminant Concentrations*
There is very little information about the presence or absence of contaminants in groundwater, within either the vadose or saturated zones, immediately below and around nuclear test cavities at Frenchman Flat. The only site-specific estimates of dispersivity are those from the aforementioned CAMBRIC tracer test. There is no adequate database to assess existing levels of contamination in the basin or to predict future levels of contamination in terms of radionuclide concentrations and associated dose levels, because initial concentrations are only estimates, and their eventual dispersion and dilution, are undefined.

Generally, the panel thinks that a model is not a substitute for data but a tool to integrate and interpret data. No amount of modeling or uncertainty analysis can make up for the absence of key site information. In the absence of such information, hydrologic and associated uncertainty analyses are largely subjective; hence, their validity remains a matter of conjecture. We think that this is currently the situation at Frenchman Flat.

2.2 Modeling Strategy and Scale

The strategy for modeling the impact of weapons testing at Frenchman Flat has been to create a flow and transport model and to evaluate the predicted pattern of radionuclide migration for the next 1,000 years. Once the contaminant boundary is established by the modeling, it will be possible to evaluate remedial alternatives. A significant emphasis in the modeling is to provide a quantitative evaluation of model uncertainty. This uncertainty evaluation is based on both sensitivity and Monte Carlo analyses.

a) *Modeling as an Appropriate Tool*
   It is appropriate to analyze the potential problem of contamination at Frenchman Flat using mathematical models that capture key physical and chemical processes. This kind of quantitative approach has proven useful in providing a framework for understanding the hydrogeological setting, in identifying gaps in the database, and in providing predictions of long-term behavior. The work that has been completed has created an improved understanding of hydrogeologic issues at Frenchman Flat. While the idea of a model-based analysis is attractive, there are problems in its implementation at Frenchman Flat.

b) *Lack of Confidence in Model Results*
   The panel has concluded that the model has not yielded a defensible and confident assessment of the likely pattern of contaminant migration over the next 1,000 years at Frenchman Flat. The study has treated the end of the “early-site modeling” phase of the investigation as the end of the study. In reality, modeling should move naturally into another investigative-modeling cycle until it becomes clear that the costs of uncertainty reductions from additional field and laboratory work are no longer commensurate with the benefits of improved predictions. As the discussion in Section 2.1 indicates, the quantity and quality of available data are not appropriate to support conclusions concerning the behavior of the source and the finding of limited contaminant migration in the alluvium.

c) *Inappropriate Scales of Models*
   The scale of the modeling at Frenchman Flat appears to be too large to capture likely “failure” scenarios. Important scenarios involve migration from the Alluvial Aquifer (AA) down some nearby fault zone or laterally across zones where the AA and Lower Carbonate Aquifer (LCA) are in contact. The scale of the model and pattern of gridding is such that neither the regional nor the Frenchman Flat model can handle such small-scale defects in the system very well. In addition, there are limited data that would shed light on the localized hydraulic behavior related to the fracture zones.

d) *Cumbersome Linkages between Models*
In the present, data-poor environment of Frenchman Flat, there is not much gained by coupling the Frenchman Flat model to the large-scale regional model. This strategy limits the scope of uncertainty analyses because it is impractical to change key model features (e.g., hydrostratigraphic units) that can contribute significantly to the uncertainty. The need to analyze every trial with both the regional scale and Frenchman Flat scale models is cumbersome and severely restricts the scope of potential analyses. Detailed site-specific analyses with the regional scale model are not helpful in resolving what might in effect be very localized problems.

e) *Need for Local-Scale Modeling*
These scale issues and the difficulties in rapidly constructing different conceptual geological models, point to the need for a simpler, more localized modeling approach that is also more amenable to sensitivity analysis. Most of the scenarios that might lead to contamination of the LCA at Frenchman Flat involve local transport through hydraulic short circuits. These features have not been captured well in the present modeling. The treatment of faulting is rudimentary and not consistent with its possible importance in facilitating contaminant spreading. Smaller, simpler models that can adequately represent plumes in the contaminated portions of the basin and their likely interactions with fault zones are more likely to yield reliable transport predictions.

2.3 Model Implementation
Given the complexity of the physical setting and the modeling strategy, it should not be surprising that opportunities exist to improve the modeling approach. The panel has identified a significant number of issues that need to be addressed as modeling work at Frenchman Flat continues. This section describes the most important modeling issues and how they contribute to our lack of confidence in the model assessments.

a) *Calculational Errors Related to the Size of Grid Blocks*
The large grid blocks contribute to several different kinds of errors in the model calculations. Source concentrations are artificially diluted because the cells are larger than the actual contaminant sources. In addition, numerical accuracy considerations require that the size of the grid blocks be comparable to or smaller than the longitudinal dispersivities. The resulting tendency to exaggerate dispersive mixing also causes concentrations to be underestimated. Another problem with large grid blocks is that they require averaging faults, block-faulted aquitard structures, and their hydraulic properties over grid blocks in a way that tends to suppress the effect of localized vertical pathways.

b) *Nonunique Flow-Model Calibrations*
One cannot be very confident about the uniqueness of the base-case calibration in the flow model, given the paucity of data related to the parameters and the measured hydraulic-head values. Confidence in the calibration is usually developed using a verification step that independently evaluates the calibrated model. At the very least, the calibrated and verified model should assist in confirming some key model assumptions (e.g., decrease of hydraulic conductivity with depth). One might explore whether other types of data might be available and useful in strengthening confidence in the Frenchman Flat model. The chemical and

isotopic data have potential in this respect, although they are in short supply and suffer problems in their spatial distribution and resolution.

c) *Absent Calibration/Verification of the Mass Transport Model*
   Calculations with the mass transport model are highly uncertain because data are not available for model calibration/verification. In Section 2.1, the panel has noted its concern that the database for Frenchman Flat is inadequate for a confident analysis. It is our opinion that there may be unexploited chemical data that could be developed further for model calibration.

d) *Lack of Consistency in Mass Transport Data*
   The panel is aware that the calculations in Volume III are a proxy for subsequent calculations with the classified data. However, we note a lack of consistency in the geochemical data among the various IT report volumes and the LLNL source-term study. The list of radionuclides of concern changes from report to report. There is also a lack of consistency in the choice of distribution coefficients (or retardation factors) between the LLNL and IT reports. These problems add uncertainty to the results of the model calculations.

2.4 Quantification of Uncertainty

Although the Frenchman Flat modeling work includes state of-the-art efforts to quantify the uncertainty in the predicted contaminant transport through sensitivity and uncertainty analyses, we do not feel that the actual uncertainty in the predictions is adequately evaluated. It cannot be said that the modeled uncertainty is inclusive of reality with 95 percent certainty. The actual uncertainty is likely to be much larger than that calculated because a number of factors have not been adequately addressed or impose limitations on the analysis.

a) Uncertainties in the Conceptual Model
   Essentially only one conceptual model was explored quantitatively in the modeling calculations. There are plausible alternative conceptual models involving, for example, localized vertical flows driven down through possible gaps in the confining unit into the LCA by the 10 meter (m) head difference that exists between it and the alluvium. Such alternative models could have severe consequences for the extent of contaminant migration. There needs to be strong evidence to exclude the possibility of such vertical transport pathways, or clear evidence that the consequences are not severe, before it is appropriate to neglect them. We do not see such evidence.

b) Model Complexity Impediment
   The complexity of the iterative coupling between the regional and CAU-scale models imposes major operational and computational burdens that make it impractical to explore the influence of the full range of parameters in the sensitivity/uncertainty analyses. The analysis does not address the influence of several potentially important sources of uncertainty including the source term, the dispersivities, distribution coefficients, and recharge/boundary fluxes.

c) *Ill-determined Parameter Variation*
The data describing the variability of many of the parameters are limited and provides little basis for prescribing the parameter ranges that have been assigned in the uncertainty analysis. The hydraulic conductivity data have been treated in a statistically inconsistent fashion which underestimates the variability. Because a relatively small degree of input variability has been prescribed, the results reflect only very limited effects of parameter uncertainty. Consequently, we do not feel that the analysis adequately quantifies the uncertainty even if the chosen conceptual model is correct.

d) *Inappropriateness of Spatial Variability Analysis*
The influence of intraformational spatial variability of hydraulic conductivity is likely to be small compared to that associated with uncertainties in major hydrogeologic features as reflected in alternative conceptual models. We do not find the approach used to describe the spatial variability within the geologic model to convincingly represent geologic reality, and the data available to characterize intraformational spatial variability are so limited as to render the small calculated effects quantitatively meaningless.

e) *Calibration Discrepancy in Uncertainty Analysis*
The different realizations of parameters used in the Monte Carlo simulations do not generally produce solutions that honor the measured head values. We are uneasy with this inconsistency.

2.5 Hydrologic Source Term and Radionuclide Sorption

The overall approach used in the LLNL and IT source term and sorption studies is reasonable. These studies have made optimal use of sparse, available site data. However, the panel has specific questions and concerns related to the methodology and the implementation of key chemical processes in the transport model. Questions and concerns related to the hydrologic source term and radionuclide sorption are summarized here and discussed in detail in Section 3.4.

a) *Exclusion of Radionuclides with Classified Source Term*
Only radionuclides with unclassified source term data are considered in the LLNL and IT studies. We have no way of knowing what affect radionuclides, whose source term is classified, such as long-lived and highly mobile ^{237}Np (the daughter of ^{241}Am) might have on study conclusions. We suspect that the inclusion of these radionuclides will almost certainly increase predicted radionuclide doses from groundwater.

b) *Hydrologic and Related Source-Term Assumptions*

In the absence of data, many assumptions have been made to facilitate the source modeling. Some assumptions are appropriate, others are not. Questionable hydrologic assumptions related to the source term and transport modeling include:

(1) The assignment of a lower hydraulic conductivity to the exchange volume than to the alluvium;
(2) The neglect of dispersion and diffusion along and between streamlines which provides no mechanism for the mixing that can be expected to affect chemical reactions in the aquifer; and
(3) The often arbitrary and unsupported selection of parameters used to describe aquifer geometry, flow and transport, and reactions involving radionuclides.

The CAMBRIC radionuclide source term has been used in Frenchman Flat CAU-scale transport modeling. The results may or may not be conservative or applicable to other tests in Frenchman Flats because:

(1) The source term is inserted as a mass rate of contaminant into a single large grid cell, which effectively dilutes the source;
(2) All detonations in the Frenchman Flat CAU are assumed to take place at the water table with no radionuclides assumed retained in the unsaturated zone;
(3) It seems likely that volatile radionuclides and their daughter products could have been driven considerable distances beyond the cavity by "prompt injection"; and
(4) The source term of the CAMBRIC test which is in alluvium, may not be comparable to the source terms of other tests in the Frenchman Flat CAU at least one of which is in tuff.

c) *Radiochemical Aspects of the Hydrologic Source Term*

A general purpose of the LLNL CAMBRIC source term study is to provide transport parameters for selected radionuclides for use in IT's Frenchman Flat CAU scale transport modeling described in Volumes II and III. However, there are significant differences between the two studies with regard to the radionuclides chosen for study and the reactivities (e.g., K_d values) assigned to those radionuclides. These inconsistencies make the results of the two studies uncertain and not comparable. Specific concerns and observations related to radiochemical aspects of the hydrologic source term as described by Tompson et al. (1999) are summarized below.

(1) *Determination of total inventory of radionuclides and their partitioning among glass and rubble zones.* Estimates of the total amount of radionuclides (the radiologic source term) and assessment of their partitioning are based on limited data, as is the radionuclide makeup of the hydrologic source term. We suspect that these features will be different for large versus small tests, and shallow versus deep tests (relative to the water table),and for tests at Frenchman Flat in the alluvium versus in tuff.
(2) *Development of a model describing radionuclide releases from the melt glass.* The reactive surface area of the glass determines the initial and long-term release rate of radionuclides such as ^{239}Pu, ^{241}Am, and ^{155}Eu to the groundwater. This parameter; however, is an important uncertainty in the modeling calculation and determines the

initial and long-term release rate of radionuclides. The surface area of glasses at the site would need to be measured to validate the estimated surface area.

(3) *Development of a model describing radionuclide releases from and chemical interactions in the chimney and cavity regions*. Modeling has been performed with a modified version of the GIMRT code which has some important limitations. Based on geochemical modeling, which shows no pure radionuclide (RN) solids to be at saturation, it is assumed that all radionuclides in the exchange volume (e.g., ^{137}Cs and ^{90}Sr) associated with solids are adsorbed on rock surfaces and that no radionuclides precipitate in mineral form. This assumption cannot be proven without examination of rock samples obtained from the exchange volume. In addition to being adsorbed, significant amounts of RNs are also likely to occur as trace species in solid solution within major secondary minerals.

(4) *Development of models to describe reactions involving radionuclides in the exchange volume and alluvium.* Assumptions regarding radionuclide adsorption and precipitation are unnecessarily conservative with regard to ^{155}Eu, ^{241}Am, and ^{239}Pu, and possibly ^{90}Sr. All of these nuclides will be strongly adsorbed and may also be incorporated in carbonate or other solid solutions. A solid solution model would need to be added to GIMRT to evaluate this possibility. The redox potential of the groundwater may decrease with depth in the alluvium. Measurements of redox potential with depth in alluvial wells are needed to evaluate this possibility. To determine the effect of an Eh reduction on radionuclide mobilities, a variable redox potential needs to be considered in the modeling.

(5) *Development of a groundwater flow and radionuclide transport model*. Concentration data for ^{60}Co, ^{36}Cl, ^{129}I, ^{85}Kr, ^{99}Tc, ^{106}Ru, and ^{125}Sb radioisotopes were available from wells RNM-1 and RNM-2S. Why were those data not used to validate radionuclide transport modeling or used in dose calculations?

(6) *Sensitivity analysis: the mineralogical models.* The reactive surface areas of the melt glass and of sorptive goethite, and the abundance and distribution of reactive minerals in the alluvium were all varied in sensitivity analyses to determine their effect on the predicted fate and transport of radionuclides as a function of time and distance. This approach is reasonable; however, little to no site data are available to validate assumed parameter values. Further, probable and possible reactions that could reduce the concentrations of ^{241}Am, ^{155}Eu, ^{239}Pu and ^{90}Sr have been neglected in the modeling. However, inclusion of radionuclides, whose source term is classified, such as ^{237}Np could increase radionuclide concentrations and doses. For such reasons there is no way to know whether the modeling results presented are conservative.

d) *Inconsistent Assumptions and Results of the LLNL and IT Studies*

The only rock type considered in the assessment of sorption properties in the LLNL study was alluvium, whereas the IT studies considered only volcanic tuffs. No discussion of the relationship between the K_d values assigned to these rock types is presented. Selection of important radionuclides for modeling transport and dose calculations and selection of their reaction chemistries (e.g., K_d values) is inconsistent between IT Volumes II and III and between these volumes and the LLNL CAMBRIC source term report. Thus, results of the LLNL study are not directly applicable to the IT studies, nor are the results of Volume II directly applicable to those of Volume III. The inconsistencies are detailed in Section 3.4.

CHAPTER 3

DETAILED COMMENTS ON MODEL COMPONENTS

This chapter describes the technical concerns which have been identified by the panel in reviewing the three IT volumes and the LLNL report. These detailed comments tend to focus on significant weaknesses and shortcomings in the modeling effort, as this is one of the primary purposes of this review. In general, the panel finds that the material in the four reports is effectively organized and presented, consistent with normal expectations for such technical reports. Included are suggestions for improvements which would make the presentation more effective. The detailed comments include some discussions of possible improvements in the technical approach, but the overall rationale for the recommended improvements is developed in Chapter 4, which contains a systematic discussion of these issues. The detailed review comments in this chapter are organized according to the three volumes of the IT report. The exception is Section 3.4 which discusses the LLNL report in detail, but also considers material on the source term and radionuclide sorption in the IT volumes.

3.1 Hydrostratigraphic Model (Volume I)

3.1.1 Overall Comments on Volume I

Volume I describes development of the three-dimensional hydrostratigraphic framework for Frenchman Flat, which relies entirely on available data. The panel deems the available geologic and hydrogeologic database inadequate for this purpose. We are especially concerned with the virtual absence of site-specific data in the geographic neighborhood of underground nuclear test areas, where the contamination originates, and migration is expected to take place. This situation is highly unusual for sites with existing or possible groundwater contamination, and throws into question the reliability of the entire modeling effort. We are concerned that smoothing and averaging of hydrostratigraphic data misrepresent the important effect that block faulting may have on vertical flow and contaminant migration from the AA to the LCA.

The conceptual structural model of Grauch and Hudson is considered to be plausible but inferential, and therefore nonunique. Neither it, nor available borehole data, support in detail the geologic and hydrostratigraphic cross-sections in Appendix A of Volume I. Therefore, we deem many of these details to be conjectural. Because some of them may have major impact on vertical movement from the AA into the LCA, we question whether adopting a single deterministic model of geology, structure, and hydrostratigraphy at the site is justified. The conceptual model of Grauch and Hudson indicates a sizeable area of direct lateral and vertical contact between the alluvial and carbonate aquifers in the eastern portion of the basin, which is not mediated by faults. This seems to be inconsistent with the CAU-scale groundwater flow model, in which these two aquifers are separated from each other laterally by an assumed fault of low permeability.

The panel is also concerned about the division of volcanic rocks into aquitards and aquifers. Some aquitards are at least locally "leaky," and there is significant uncertainty about the spatial distribution, thickness, and block faulting of confining units across the site. Thus, we question the validity of assigning uniformly low vertical leakance values. There is also the possibility that buried channels may act as preferential flow paths across the alluvium, which the model does not consider. In summary, because the geologic database for Frenchman Flat is extremely meager, any postulated hydrostratigraphic framework will be largely subjective.

3.1.2 Comments on Chapter 1: Introduction

Volume I describes the three-dimensional hydrostratigraphic framework for Frenchman Flat, which underlies the CAU-scale flow and transport models. The framework is based in part on a previously developed regional model for the NTS (IT,1996), but includes additional site-specific details.

The hydrostratigraphic model integrates topographic and geologic maps, surface gravity and magnetic survey data, borehole data concerning the areal distribution of geologic units and their thickness, as well as surmised hydraulic properties of identified or postulated rock units into 12 geologic, and 14 hydrostratigraphic, cross-sections. Digitized versions of the hydrostratigraphic sections form the basis for maps of the elevation of the top surfaces of eight hydrostratigraphic units (HSUs) into which the rocks and sediments in the basin have been classified for modeling purposes. Digitized versions of these maps are in turn used to distribute HSUs, and their hydraulic properties, among layers and grid blocks of the CAU-scale computational flow model. The final product is a smoothed version of site hydrostratigraphy in which boundaries between HSUs, and fault planes, are much less sharply defined than in the original hydrostratigraphic sections and maps. Similarly, HSU and fault hydraulic properties are also averaged across relatively large computational blocks of the flow model. We are concerned that this smoothing and averaging severely limits the ability of the model to resolve the potential effect that block faulting may have on vertical hydraulic communication, and contaminant migration, between the AA and LCA at Frenchman Flat.

Due to a paucity of drill hole data, and the lack of any geophysical subsurface imaging data, the hydrostratigraphic framework was based on a conceptual model of basin structure developed by Grauch and Hudson (1995). Yet Volume I devotes only one brief paragraph to this conceptual model in the Introduction, and another shorter paragraph in Section 4.0 on the Structural Geology of Frenchman Flat. We have reviewed the report of Grauch and Hudson and offer the following observations. Grauch and Hudson used surface gravity data to delineate the edges of the Frenchman Flat structural basin, and aeromagnetic data to identify volcanic rock units and associated faults in the subsurface. In the authors' view, their analysis delineates the location of some geologic contacts in plan view fairly well, but provides only a rough description of the configuration of more complicated or near-horizontal boundaries and lithologies at depth. They define the lateral limits of the structural basin on the basis of a map of horizontal gravity gradients, which is not included in their report. This omission makes it difficult for us to assess their interpretation of the gravity data, which implies that the lateral limits of the structural basin may vary with depth and differ significantly from those of the topographic basin.

The presence of volcanic rocks in the subsurface was determined by Grauch and Hudson primarily from aeromagnetic data, based on six surveys conducted at widely varying altitudes and line spacings. Resolution is laterally uneven and decreases with depth, requiring analytical continuation of the magnetic data downward. The authors define the lateral limits of volcanic rock units at depth, and faults associated with these units, on the basis of a map of horizontal magnetic gradients. It is difficult to assess their interpretation of the magnetic data, which implies (among other things) that the minimum depth to the top of probable volcanic rocks near the center of the basin is about 200 m, but may otherwise be as large as 700 m.

Based on these interpretations of surface geologic, gravity and aeromagnetic data, Grauch and Hudson develop a conceptual structural model for the basin. According to this model, Frenchman Flat is a Cenozoic extensional basin dominated by faults having both normal and left-lateral offsets. The basin forms an asymmetric half graben with west-to-northwest downthrow of normal faults and eastward tilt of fault blocks. This view is presented graphically in the form of a structural map. It shows the basin boundary and major faults within and around it, as well as a near east-to-west cross-section that depicts the block-faulted structure extending through the Tertiary volcanic and underlying Paleozoic rocks (reproduced as Figure 4-1 in Volume I).

The panel considers the conceptual structural model of Grauch and Hudson plausible but inferential and therefore nonunique. We note with concern that the report of Grauch and Hudson provides little direct support for the geologic and hydrostratigraphic cross-sections in Appendix A of Volume I. These cross-sections contain a much greater amount of geologic, structural, and hydrostratigraphic detail than is included in the Grauch and Hudson report. Very little of this detail is supported by borehole evidence. What, then, is the source of this detailed information? According to Section 4.0 of Volume I, faults are considered that were not part of the Grauch and Hudson model. These faults have displacements in excess of 61 m (200 ft) at the surface and were taken from surface geologic maps. Other faults were added in response to U.S. Geological Survey (USGS) recommendations that more faults be included for geometrical considerations. We have the impression that most of the added faults and detail are conjectural. If so, how many other possible ways are there to depict subsurface hydrostratigraphy, and structure, at the site? What implications does this have *vis-a-vis* groundwater flow and contaminant transport at Frenchman Flat? These questions may have important implications because possible vertical movement from the AA into the underlying LCA depends in a critical way on the (virtually unknown) hydrostratigraphy and structure of block-faulted units, and associated faults, that lie between them in (poorly delineated) portions of the basin where the two aquifers are not in direct contact. Adopting a single deterministic version of this hydrostratigraphy and structure does not seem to us valid in light of the scarcity of site data to support a unique model.

According to the conceptual model of Grauch and Hudson (see cross-section in Figure 4-1 of Volume I), there is a sizeable area where the AA and LCA are in direct lateral and vertical contact in the eastern portion of the basin. The contact between the two, apparently, is not mediated by faults. We are concerned about an inconsistency between this conceptual picture and the CAU-scale groundwater flow model in which these two aquifers are separated from each other laterally by the Rock Valley Fault system, which limits hydraulic communication between them.

The introduction to Volume I acknowledges that not all contributors agree with the current hydrostratigraphic and structural interpretation of the Frenchman Flat database. Clearly, other interpretations of this database are possible. However, there has been little effort in the present program to transform these detailed alternatives into digital data for input into the hydrologic model. The report argues that after the flow and transport models are developed, the relative effects of alternative hydrogeologic interpretations on the predicted contaminant boundary can be used as indicators of the validity of these interpretations. We doubt that the particular hydrostratigraphic framework adopted for Frenchman Flat, and associated groundwater flow and transport models, are flexible enough to provide for the exploration of meaningful alternatives.

Most importantly, the panel is of the opinion that a model is not a substitute for data but a tool to integrate and interpret data. No amount of interpretation and analysis can make up for the absence of key site information. As the available database for Frenchman Flat is meager, any hydrostratigraphic framework postulated on its basis will be subjective, so that its validity remains a matter of conjecture.

3.1.3 Comments on Chapter 2: Overview of Methodology

Few subsurface data points exist at the site, so the Grauch and Hudson concept of what the basin might look like was used to guide the construction of geologic and hydrostratigraphic cross-sections in Appendix A. Little detail is given on how the cross-sections were constructed (see also discussion of Section 6.0), except that they incorporate knowledge of (a) processes associated with volcanism as documented elsewhere in the NTS and its surroundings; (b) depositional and erosional processes associated with basin-and-range type faulting and valley filling; and (c) character of pre-Tertiary rocks exposed in the surroundings of Frenchman Flat. This seems like a reasonable way to proceed, given the sparseness of the available data. However, lacking appropriate detail, the panel could not develop an informed opinion about the validity, or even plausibility, of the cross-sections in Appendix A. Since these sections underlie the entire CAU-scale modeling effort and, in particular, the nature of possible vertical pathways from the alluvium to the underlying carbonate aquifer, our inability to assess them raises concerns regarding the validity and plausibility of the modeling results.

The cross-sections in Appendix A provide a useful visual image of the complex three-dimensional geologic and hydrostratigraphic setting, as postulated by the authors for Frenchman Flat. It would be difficult to gain a similarly vivid image of this setting from the text and stratigraphic tables alone. The graphical display could be further enhanced by considering the following minor issues: (a) The water table is indicated on geologic sections but only on some hydrostratigraphic sections. It would seem more logical to indicate it on the latter or on both sets of sections. (b) Some geologic sections show every member (*c.f.*, Section FCR4, Figure A1a) while others group members into thicker units (*c.f.*, Section FSD4, Figure A13a). Is there some reason for this inconsistent treatment? (c) Sections FMS2 and FSD4 are extensions of one another; taken together, they form a single extended section. However, FMS2 is a north-to-south section drawn from left to right, while FSD4 is a south-to-north section drawn in the same direction. The two sections are difficult to reconcile when viewed together.

3.1.4 Comments on Chapter 3: Stratigraphy of Frenchman Flat

This short section summarizes the stratigraphic setting of Frenchman Flat and the thicknesses of major geologic units across the site. We note that there are no isopach maps provided in the report for either geologic or hydrostratigraphic units. A set of such maps, one for each unit, would further facilitate the readers' comprehension of the proposed hydrostratigraphic framework. It is possible to gain some appreciation for the thicknesses of the various geologic and hydrostratigraphic units from a detailed examination of the cross-sections in Appendix A. However, it would be helpful to be able to assess this important information directly from isopach maps.

3.1.5 Comments on Chapter 4: Structural Geology of Frenchman Flat

This section briefly summarizes the tectonic history of the basin over the last 16 million years, and the Grauch and Hudson (1995) conceptual model of basin structure. The cross-sections in Appendix A are said to constitute an extreme simplification of actual faulting in the Frenchman Flat basin, mainly to illustrate the style of faulting.

The panel is concerned about the impression that may be conveyed by the detailed graphical information in the appendices of Volume I. All of this information -- 12 detailed geologic sections, 14 detailed hydrostratigraphic sections, and 8 corresponding elevation contour maps -- may cause readers to overlook the fact that the information was founded on an illustration of the style (but not actual detail) of faulting in the basin. Nowhere else in the report is it implied that these cross-sections, and maps, have been prepared primarily for illustration purposes. Instead, the overall impression conveyed to the reader is that the graphics quantitatively capture actual details of site geology, structure and hydrostratigraphy, based on the best available data and state-of-the-art interpretive ideas and techniques. We feel that this impression could be rectified with improvements in the graphical presentation as discussed in the review of Chapter 6.0 below.

3.1.6 Comments on Chapter 5: Hydrostratigraphic Framework

Volcanic rock units are categorized as confining units (aquitards) if they are altered by zeolitization, and as aquifers if they are unaltered. Because there is very little direct information about the degree of alteration at depth within the Frenchman Flat basin, the division of volcanic rocks into aquitards and aquifers is uncertain. Also some units designated as aquitards are acknowledged to be at least locally "leaky." Furthermore, there is significant uncertainty about their spatial distribution, thickness, and block faulting. Thus, we question the validity of ascribing to these units uniformly low vertical leakance values throughout the CAU-scale model.

In particular, the Volcaniclastic Confining Unit (VCCU) is believed to behave as an aquitard because of its tuffaceous character (tendency to become zeolitized below the water table) and abundance of fine-grained clastic rocks. However, it contains limestone and coarser clastic (including gravel-rich) beds that render it locally leaky.

The Tuff Confining Unit (TCU) is designated as an aquitard because it is believed to be comprised mainly of zeolitized, bedded tuff. Its transmissivity is considered to be very low, based on hydraulic tests within similar units in Yucca Flat. The TCU is said to be present in the northern two-thirds of Frenchman Flat, but absent over the structural highs south of the Rock

Valley Fault. Rock units corresponding to the TCU that presently lie above the regional water table, especially in northern Frenchman Flat, are believed to be unaltered and therefore to behave as a vitric-tuff aquifer.

Interestingly, the Wahmonie Volcanic Confining Unit (WVCU) is not considered to be an aquitard, but part of the Volcanic Aquifer (VA), in the regional model (Table 5-3). The WVCU appears to correspond to the Lava-Flow Aquifer of Winograd and Thordarson (1975) in Table 5-1. The rationale given for treating it as an aquitard in the CAU-scale model is that ash-fall tuff units, which are found within the WVCU in the eastern part of the basin, tend to become zeolitized where saturated. In the western third of Frenchman Flat, where lavas and flow breccias predominate, the rocks are locally argillized and therefore not hydraulically conductive. However, some of the lava flows may remain vitric to devitrified, which renders them transmissive. West of UE-5c, the WVCU is considered to be leaky. We wonder what site-specific data there are to support the treatment of the WVCU as a confining unit with low vertical leakance in the CAU-scale model, given that the same unit has been regarded as an aquifer on the regional scale.

The Upper Clastic Confining Unit (UCCU), which is listed among the eight HSUs in Table5-2, is not believed to be present under Frenchman Flat due to erosion. It is present northwest of Cane Spring Fault where it may contribute to elevated water levels in the CP Basin.

Based on limited data, Pawloski (1996) concluded that the alluvium is homogeneous on a basin-wide scale. Reference is made to Sully et al. (1993) to the effect that the alluvium is hydraulically isotropic. This latter conclusion seems inconsistent with Table 7-1 of Volume III which shows vertical-to-horizontal ratios of hydraulic conductivity for the alluvium, in the CAU-scale model, between 0.002 and 0.22. Since sediment deposition is largely in the form of alluvial fans (debris flow, sheet wash, braided streams) which coalesce to form discontinuous, gradational and poorly sorted deposits, we question whether it is appropriate to treat the alluvial aquifer as homogeneous, and laterally isotropic, in the CAU-scale model.

The panel is concerned about the possibility that buried braided channels may form continuous pathways of elevated permeability, which may allow rapid preferential flow to take place laterally from the alluvium toward the carbonate aquifer where the two units may be in direct contact, even under low horizontal hydraulic gradients west to east. Even if these pathways converge toward Frenchman Playa, they may still form an interconnected network across and beyond the playa, through which radionuclides may be transported preferentially from west to east, under gradients similar to those obtained from the calibrated CAU-scale flow model. We recommend that this possibility and its potential consequences be explored analytically and/or numerically as another plausible conceptual model.

The report is inconsistent throughout with respect to its reference to the Nopah (NO) Formation. In some parts of the report, and in some of the tables and figures, the Lower Carbonate Aquifer is divided into two hydrostratigraphic units: the LCA and the NO. In other places the NO unit is included in the LCA. The NO appears as a separate unit on the cross-sections in Appendix A of Volume I, but is not treated as a *bona-fide* HSU in the text, appearing instead in a brief discussion at the bottom of page 5-5. We recommend revising all tables and text to reflect the existence of the NO, so as to render them consistent with one another, and with the cross-sections in Appendix A of Volume I.

3.1.7 Comments on Chapter 6: Construction of Cross Sections

This section makes it clear that the geologic, and hydrostratigraphic, cross-sections in Appendix A were constructed largely in a subjective manner. As already noted, we consider it essential that the text, the cross-sections, the structure contour maps based upon them in Appendix B, and the CAU-scale flow model built upon these clearly indicate the reliability of the data. For example, they should describe, in an unambiguous manner, which fault segments, offsets, and portions of hydrostratigraphic boundaries are based on actual site-data, and which are hypothesized. To accomplish this, drawings could display all hard data points, and to use solid, dashed and dotted (or variably colored) lines and curves to designate the level of confidence one should have in features and boundaries shown on the drawing.

3.1.8 Comments on Chapter 7: Nature and Significance of Geologic Uncertainties

This short section restates the belief that the VOIA has identified and evaluated sources of uncertainty in determining the regulatory contaminant boundary by means of the Frenchman Flat models. It lists aspects of site geology, structure, and hydrostratigraphy that the authors consider uncertain, and repeats their earlier assertion that the hydrologic significance of these uncertainties can be explored by varying model parameters in the current flow and transport models. We do not consider this treatment of geologic uncertainties adequate for its purpose.

3.1.9 Comments on Chapter 8: Alternative Geologic Interpretations

The only model of Frenchman Flat hydrostratigraphy, adopted and digitized for CAU flow and transport modeling, is that presented in Volume I. The claim is repeated that most alternative conceptualizations, and representations, of relevance can be addressed by varying the parameters of the current CAU-scale flow and transport models. The section, thus, contains recommendations as to what alternatives can and should be explored by varying these parameters. We have already commented on the inadequacy of this approach.

3.2 Groundwater Data (Volume II)

3.2.1 Overall Comments on Volume II

The database assembled in Volume II is a crucial element of the overall modeling effort. It forms the basis for both the hydrogeologic conceptualization of the flow system of Frenchman Flat, and the parameterization/calibration of the quantitative numerical model which was implemented. For these purposes, we regard the data to be severely limited in terms of spatial coverage and quality.

The water level data, which cover only a very limited portion of the basin, are ambiguous regarding the magnitude and direction of horizontal and vertical hydraulic gradients in the alluvium. Information on the inflow to the modeled region is indirect and uncertain. Recharge is inferred by an empirical method of doubtful accuracy and horizontal fluxes at boundaries are imposed from a regional model of unknown reliability. The hydraulic conductivity data are derived from single borehole hydraulic tests or inferred from grain size distributions, both of which may lead to inaccurate estimates. The hydraulic conductivity of the alluvium could plausibly be an order of magnitude or more higher than that adopted in the model.

Largely because of the limited spatial coverage horizontally and vertically, water chemistry and isotope data do not provide sufficient information to constrain the interpretation of the flow system. The carbon-14 (^{14}C) age dating which is based on inorganic carbon, at best, provides only relative information on the age of the water. The report acknowledges that vertical transverse dispersivities are very small (on the order of millimeters) in alluvial sediments, but the transport modeling adopts an unreasonably large vertical transverse dispersivity (5 m) to accommodate a limitation of the computer code. The use of large vertical transverse dispersivities will overestimate the amount of dilution calculated for nearly steady plumes.

Radionuclide sorption properties for the alluvium are derived from laboratory batch tests on tuffs at Yucca Mountain, but the transferability of such data to alluvium at Frenchman Flat is not adequately addressed. Regarding source data, there are concerns that restriction of the data to unclassified sources may limit the representativeness of the analyses, and that the radionuclides selected for analysis are not consistent among the different components of the study.

3.2.2 Comments on Chapter 1: Introduction

The stated objectives of the data assessment task which is documented in Volume II (p. 1-8) are:

a) To collect, compile, and qualify pertinent hydrologic data for the Frenchman Flat area,
b) To ensure that the data are of sufficient quality and quantity for use in the groundwater flow and contaminant transport model, including estimates of uncertainty and variability of the data,
c) To provide centralized documentation of the data to facilitate efficient technical review of the modeling process.

The scope (p. 1-7) indicates that the work also includes an assessment of relevant data derived from studies of subsurface environments or rock types similar to those of Frenchman Flat. Also included as an objective in the data documentation task was the development of an electronic database. However, that information was not made available to us for review. Generally we find that the collection and compilation of available (unclassified) existing data under objective (a) is largely accomplished, though there may be some question whether the data are adequately qualified as discussed in the following.

Regarding objective (b), little has been done to address the question of whether the data are sufficient for the specific modeling application developed in Volume III. In fact, almost all of the locations for which hydrologic data are available fall in a very narrow north-south zone in the center of the basin. None of the boreholes are deep enough to determine the properties of the volcanic confining units presumed to underlie the alluvium. Such a nonuniform spatial distribution of data will obviously impose major difficulties in trying to definitively calibrate a basin-wide model. Such difficulties are not discussed in Volume II. However, the report does cite (p. 1-4) the value-of information-analysis (VOIA) (IT Corporation, 1997b) as a basis for concluding that no additional data are needed. This VOIA report (Section 3.1) contains a thorough summary of the uncertainties in the data. It recognizes the problem of the spatial distribution of data, and concludes (pp. ES-1, 2) that the data are not sufficient to determine if contaminants could be transported from the alluvium down into the LCA. We agree with this conclusion. Volume II needs an updated discussion, probably in Chapter 2, which addresses the sufficiency of the data for the current modeling approach if objective (b) is to be addressed.

In the case of objective (c), we feel that the material assessing the quality of the data needs to be very carefully, thoroughly, and explicitly documented; a qualified reviewer should be able to independently assess the quality of the data without having to ferret out crucial information from other sources. In some cases such documentation of the data is more than adequate, while in others there is need for improvement. Detailed comments and concerns in this regard are developed in the discussion of the individual chapters in Volume II. This goal of thorough and explicit documentation is important for the project as it imposes a need for the staff to clearly identify the most important kinds of information and acknowledge subjective interpretations that are being made; this will also make the work more defensible in regulatory and public forums.

The report does little to address the important issue of whether data from other areas in the regional system can legitimately be transferred to the Frenchman Flat area. To simply presume, without discussion, that observed properties from a similar rock type in another area are an adequate representation of this site is not justified, particularly when there is so little direct information about the rocks that underlie the alluvium in Frenchman Flat. This transfer process involves large uncertainties that need to be discussed. Another overall concern is the lack of clear links between the data summarized in Volume II and the parameters actually incorporated in the modeling of Volume III. Specific examples are discussed in connection with the individual chapters.

3.2.3 Comments on Chapter 2: Modeling Approach and Data Requirements

One might expect that this chapter would explain how the specific data situation of Frenchman Flat affects the selection of a modeling approach. Instead, the discussion of model selection is focused on generic features of the computer code. There should be some discussion of the possibility of using a simpler model covering a much smaller area around the contaminated sites where data are available. The list of data needs for the flow model (p. 2-5) should include data needed for boundary conditions. It would be helpful to have a table that identifies the data for both the flow model and the transport model in terms of whether it is used as a calibration parameter or a calibration target, and whether such use is quantitative or qualitative.

The code SWIFT-98 is used to model groundwater flow and radionuclide transport in this study. The code can simulate solute movement, and can consider radionuclide decay, colloid transport, and adsorption as described by a K_d. However, it lacks the capability to consider more complex geochemical processes including solution speciation, adsorption by ion exchange or surface complexation, precipitation or dissolution of solids or reaction kinetics. Most of these processes and capabilities are included in the code GIMRT used by Tompson et al. (1999). The greater limitations of the SWIFT-98 code require that simplifying assumptions be made about the hydrologic source term and radionuclide transport, which probably leads to unrealistic results in some cases. The codes should be compared.

3.2.4 Comments on Chapter 3: Potentiometric Data

The detailed discussion in Section 3.5.3 of the 26 individual wells is very helpful. However, a number of questions arise when one tries to relate the information in this chapter to that used in the model calibration as discussed in Volume III. The water level values presented in Table 2-3 of Volume III for several of the wells differ significantly (as much as 1 m for WW-C) from the means reported in Table 3-2 of Volume II as being representative of predevelopment water levels. What are the reasons for these differences? These should be discussed in Section 3.5.3 for each well and the estimated predevelopment levels should be included in the hydrographs in Appendix B, Volume II. Table 2-3 should include a column that shows the period of record and a remarks column noting any special features of the well and/or the data.

The treatment of the quantification of the uncertainty in the water level is unsatisfactory particularly as it relates to the head calibration data (see Table 7-3 of Volume III). What is the WFAC in that table and how is it determined from the water level statistics presented in Chapter 3 of Volume II? The rationale for calculation of the weighted residual in Table 7-3 needs to be thoroughly explained and justified. How is the land surface accuracy in Table 2-3 of Volume III determined and used? How is the water level standard deviation in Table 3-2 of Volume II being used in the calculation? The statement on the top of p.3-12 that, “The uncertainty in the mean value is the two standard deviation range of the available measurements” is statistically indefensible. The variance in the estimate of the mean using n independent samples is the population variance divided by the number of samples, so that this should be twice the standard deviation divided by the square root of n.

There is no discussion of the magnitude and direction of the hydraulic gradients that are reflected by the water level measurements. It seems to us that nothing very definitive can be said about the direction of the horizontal gradient or the implied flow direction. Also, a definitive picture regarding vertical hydraulic gradients and possible vertical flow is lacking. This ambiguity regarding flow direction is significant and should be discussed, as it indicates that the water level information is of little use in sorting out whether a model can predict the magnitude and direction of groundwater flow. The three wells near the Radioactive Waste Management Site (UE-5PW-1, UE-5PW-2, UE-5PW-3) have been installed relatively recently. Apparently, these wells are regarded as yielding particularly reliable water levels. Of particular interest is one well (UE-5PW-2) showing a continually increasing water level trend since 1993. The direction of flow indicated by the three wells has changed by about 45 degrees (from north to northeast) over a period of 4 years. Are these changes indicative of changing hydrologic conditions (recharge or pumpage) or is this behavior the result of a malfunctioning well?

3.2.5 Comments on Chapter 4: Recharge and Discharge

There is very little that can be done to accurately quantify recharge over extensive areas in arid and semiarid settings where recharge amounts may be only a small fraction of precipitation. Recharge predictions based on empirical methods such as the Maxey-Eakin formula used in this study are subject to large uncertainties because such methods are based on state-wide data and do not take account of local variables such as soil, vegetation, channel infiltration capacity, and the like. It is probably fair to say that recharge to the Frenchman Flat area is not knowable within an order of magnitude. Therefore, it is inappropriate to report recharge amounts, as quoted on page 4-2, to six significant figures. The elevations of the mountains surrounding Frenchman Flat are in the range of 5,000 to 7,000 ft, this being similar to elevations at Yucca Mountain where very detailed studies of the vadose zone are indicating recharge on the order of 10 millimeter per year (mm/yr) (Civilian Radioactive Waste Management System Management and Operating Contractor, 1997). The map of Figure 4-1, although not very clear, seems to indicate that, in the highest portion of the basin to the northwest, the recharge could exceed 58 m^3/day/km^2 (21 m/yr) indicating that the predicted recharge is in a plausible range.

Lateral inflow through the model boundaries is also an important source of water to the Frenchman Flat system. These contributions will be similarly uncertain because neither gradients nor conductivities are known at the boundaries. The spatial distribution of recharge also plays a role in the flow modeling through the assignment of recharge locations associated with major washes (Figure 4-4, Volume III). The channel recharge sites in the northern part of Frenchman Flat were eliminated as a calibration expedient. The same effect could be accomplished by increasing hydraulic conductivities in that area. This would be more conservative in that transport velocities would then be larger.

3.2.6 Comments on Chapter 5: Hydraulic Parameters

Here, our discussions focus on the hydraulic conductivity data as this information will be critical in any prediction of contaminant migration. The site-specific material relating to hydraulic conductivity is inadequate because it does not permit the reader to independently assess the likely reliability of the estimates of this crucial parameter. Although the report is not quite clear about this point, it seems that all of the hydraulic conductivity data are based on single borehole hydraulic testing or grain size data. Apparently no standard aquifer tests (with a pumping well and multiple observation wells) have been done in the Frenchman Flat area. These tests are generally accepted as being reliable at intermediate scales (10^2 m). Single borehole hydraulic tests are notoriously troublesome in that the results can be strongly affected by conditions immediately adjacent to the borehole. Typically, given the bias in such tests, estimated hydraulic conductivities would be expected to be on the low side. Grain-size-based conductivity determinations are similarly unreliable. The table in Appendix D-1 is not helpful in clarifying the quality of data. In several cases the type of test and/or method of analysis are not specified, and one cannot even determine the original source of the data from the table. For the new wells near the Radioactive Waste Management Site (UE-5 PW-1, 2, 3) neither the type of test nor method of analysis are specified, yet these values are assigned a medium (M) quality evaluation.

In the alluvium there are only eight or nine different hydraulic test locations or intervals presented in Table D-1; the multiple entries apparently represent different interpretations or possibly repeated tests of the same location/interval. In view of the critical importance of the hydraulic conductivity of the alluvium in determining the extent of contaminant migration, it certainly would be appropriate to include, in Chapter 5, detailed discussions of the interpretations of these hydraulic tests with supporting graphics, and including reanalyses by up-to-date methods as appropriate. There are likely to be many more complications and ambiguities in the interpretation of these hydraulic tests than there were in the case of the water level data, yet those data were graphed and discussed in detail individually in Chapter 3. Unless a clear-cut, specific case can be made for the low hydraulic conductivity adopted for the alluvium, it must be considered that the conductivity there could be higher by an order of magnitude or more.

The summary statistics presented in Table 5-1 are misleading if they are intended to portray spatial variability as is contended on p. 5-10 or for that matter the uncertainty in the hydraulic parameter. The problem is that the statistics are apparently derived from the data tabulated in Table D-2. This table includes data from different locations/intervals as well as data representing repeated interpretations and possibly repeated tests at a given location/interval. For example, in the case of the TMA, there is only one sampling location so that the standard deviation calculated for the four repeated samples actually represents a measure of measurement error, and says nothing about spatial variability. When one has several different sampling locations with repeated samples at a given location, all of these values can no longer be viewed as independent samples. A more consistent way to characterize spatial variability would be to calculate the variance of the mean values calculated for each of the different locations and add to that, the average of the variance of the measurement errors at each of the different locations. It is not clear how the statistics in Table 5-1 have been used in the uncertainty analysis of Chapter 11 in Volume III, as Table 11-3 there contains only a nebulous reference to Volume II, among other sources, for the range of values assigned. The link between the data and the variability assigned in the uncertainty analysis needs to be clarified if the uncertainty analysis is to be regarded as quantitatively meaningful.

Chapter 5 says nothing about the data support for hydraulic conductivity values assigned to the volcanic confining units beneath the alluvium. Apparently there is a presumption that information from other parts of the regional system can be transferred to Frenchman Flat. Similarly, no site-specific justification is provided for using the hydraulic conductivity depth decay coefficient (Table 5-2) from the regional system. From Figure 1 (from K. Rehfeldt's presentation of CAU modeling results to the peer review committee on 5/20/99), we can see that the values being assigned in the model (Table 7-1, Layers 4 –7, Volume III) fall many orders of magnitude below the range of the observations. The whole question of the validity of transferring hydraulic properties based on broad geologic classifications needs to be addressed thoroughly. In addition, the large uncertainty involved in such transfers should be acknowledged.

The hydraulic conductivity data interpretations for the CAMBRIC RNM test area are shown in Figure 2 (based on Tompson et al., 1999, Figure 10) along with the depth decay relation using the AA parameters assigned in the model (Table 7-1, Layer 8, Zone 5, Volume III). From this

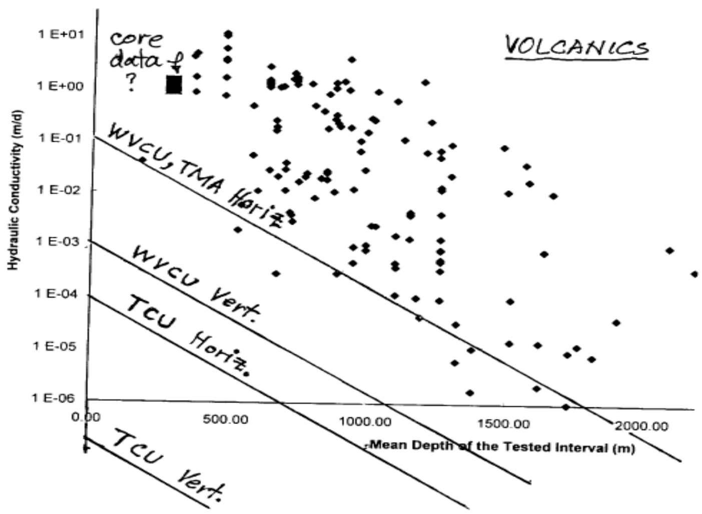

Figure 1
Depth Decay of Hydraulic Conductivity Used in the Flow Model (solid lines) Compared With Volcanics Data

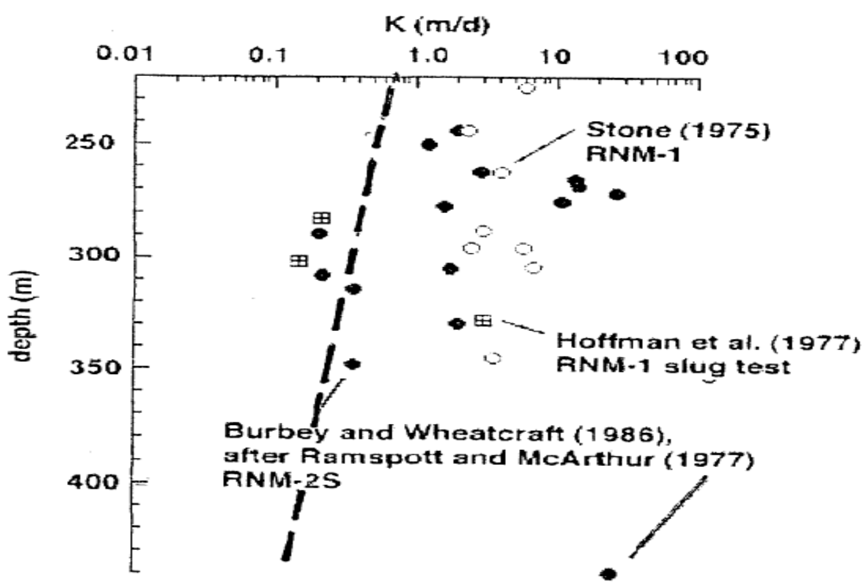

Figure 2
Hydraulic Conductivity Data at CAMBRIC; Dashed Line is the Conductivity Used in the Alluvium (after LLNL report, Figure10)

comparison it is evident that the conductivities used in the model fall at the lower end of the observed range. Over most of the vertical section the CAMBRIC/RNM models developed by LLNL and by Burbey and Wheatcraft (1986) (see Figure 38, Tompson et al., 1999) used values of hydraulic conductivity that are an order of magnitude larger than those used in Volume III. These discrepancies at the CAMBRIC site, which is quite near the playa where lower conductivities would be expected, are naturally a concern. The discrepancy could be substantially larger nearer the mountain front where more coarse material occurs. A kludge in the grain-size based permeability calculations (see Burbey and Wheatcraft, 1986, p. 24) adds a "hypothetical sieve" with a size one-tenth the size of the smallest sieve actually used. This approach will decrease the calculated permeability particularly in cases where a significant portion of the sample passed through the finest sieve.

We have received a number of preliminary documents, often undated and/or untitled, relating to the Desert Research Institute (DRI) work on spatial variability. Generally, it is not clear how this material fits into the overall project, as this work is not discussed in the modeling volumes. This material is not suitable for formal review at this stage, but these documents do not provide specific justification, in terms of hydraulic conductivity data, for the required geostatistical inputs (means, variances, and correlation scales) which have been adopted for the simulations. In a DRI report dealing with Frenchman Flat (Shirley et al., 1997) we find in Table 5, for the alluvial aquifer, the following statistics of $\log_{10}$ of hydraulic conductivity in m/day:
mean = 0.674, standard deviation = 0.662, horizontal correlation scale = 100 m, vertical correlation scale = 60 m. The 60 m vertical scale seems quite unreasonable for such sediments; values on the order of a meter are what have been observed (Gelhar, 1993; Table 6.1). Even larger vertical correlation scales have been assumed in the other HSUs. In several cases statistical isotropy has been presumed with vertical scales up to 350 m. The mean hydraulic conductivity is an order of magnitude larger than that reported in Table 5-1 of Volume II (-0.356) and the standard deviation is about twice that of Table 5-1 (0.39). If these spatial variability simulations are to be an important part of the modeling effort, thorough and defensible documentation of the basis for the geostatistical parameters is needed. These input parameters will largely dictate the nature of the simulation results.

3.2.7 Comments on Chapter 6: Groundwater Chemistry
The stated goals of the groundwater chemistry effort for the Frenchman Flat CAU include:

a) To assemble a comprehensive groundwater chemistry data set;
b) Using the data set, to characterize the groundwater chemistry of the major hydrostratigraphic units; and
c) Based on the geochemical characterization, support the evaluation of groundwater flow paths and travel times.

The data set has been assembled. However, because sampled wells included only five from the LCA, five from volcanic rocks, and eight from the AA, the data set is hardly comprehensive. The available chemical and isotopic data show that alluvial and volcanic rock groundwaters are both usually of the Na-K-HCO_3 type, presumably because the alluvium is chiefly comprised of weathered volcanic rock. As expected, groundwater from the LCA is chiefly of the Ca-Mg-Na-HCO_3 type.

Geochemical modeling indicates that with only two exceptions, groundwaters in all three rock types are saturated or supersaturated with respect to calcite, which is present as a secondary mineral in the alluvium and volcanic rocks. Saturation with respect to calcite supports the argument that coprecipitation of radionuclides with calcite should be considered in transport modeling. All the waters are also saturated or supersaturated with respect to Ca and Mg montmorillonite clays. Alluvial and volcanic groundwaters are generally saturated or supersaturated with respect to one or more zeolite minerals which are weathering/alteration products of the volcanic rocks. The mineral saturation results are consistent with the selection of the saturated minerals as sorbing phases by Tompson et al. (1999).

Stable isotope data for the well waters (δD, $\delta^{18}O$, and $\delta^{13}C$) show logical differences in $\delta^{13}C$ values between waters in the LCA and in the combined alluvial and volcanic aquifers. However, examination of the δD and $\delta^{18}O$ data leads to ambiguous conclusions regarding the origin and history of groundwaters in the alluvial aquifer. This problem may in part reflect the paucity of such data, and also the fact that the well waters have been sampled from different depths in the alluvium. In short, the available chemical and stable isotopic data for groundwater are inadequate to fulfill the third goal of the study, which was to support the evaluation of groundwater flow paths and travel times.

Groundwater can be age dated using the ^{14}C approach with dissolved inorganic carbon (DIC) or carbonate species in the water, or by analyzing the ^{14}C content of dissolved organic carbon (DOC). DIC ^{14}C ages must be corrected for the presence of dissolved carbonate derived from carbonate minerals that may contain ‘dead’ (^{14}C-free) carbon, and for mixing between younger local and older regional groundwaters at the NTS. Davisson et al. (1999) argues that meaningful correction for these combined effects may be impossible in southern Nevada groundwaters. The DOC ^{14}C method gives results that may require fewer and less contentious corrections. For the Ash Meadows springs, Thomas (1996) (see also Thomas et al., 1996) obtained maximum (uncorrected) DOC ^{14}C ages of a few thousand years, whereas corrected DIC ^{14}C ages (which are generally younger than the uncorrected ages) were typically 10,000 yrs or greater. It seems probable that the DOC ^{14}C ages were the more reliable. The uncorrected DIC ^{14}C ages of groundwaters obtained from four alluvial wells at Frenchman Flat, range from 9,000 to 28,600 yrs. The oldest is of groundwater from relatively deep Well WW-5c, which is screened to 366 m below ground surface. In general it has been shown that groundwaters in the LCA are older than waters in the alluvium. The shallow alluvial well waters are thus likely to be younger than the few thousand years age of the Ash Meadow springs. It would be instructive to sample wells at different depths and locations in the alluvium to determine their DOC ^{14}C ages. These DOC ^{14}C ages might be usefully compared to ages based on hydrologic modeling.

3.2.8 Comments on Chapter 7: Transport Parameters

The stated purpose of this chapter is to assemble porosity, dispersivity, matrix diffusion, and distribution coefficient data that are representative of rocks on the NTS and Frenchman Flat.

The tables of porosity values for the different HSUs on the NTS (Appendices F-1 and F-2) are very extensive. It would be useful to compare the statistics of the values for the Frenchman Flat area with those for the remainder of the NTS to see if significant differences are evident. The mean fracture porosity of nine percent reported in Table 7-2 for the LCA seems unusually high. Is there any explanation for the three seemingly anomalous values?

Regarding dispersivity data, it is not clear what the rationale is for viewing the simulation results of Table 7-8 as data. The results obviously depend on what input variance and correlation scales are presumed in generating the conductivity field; that information is not provided here. The conclusion on p. 7-28 regarding the agreement with the Gelhar et al. (1992) results would better be conveyed by showing the NTS data superimposed on the plot. It may not be adequate to simply increase transverse dispersivities in proportion to the increase of longitudinal dispersivity as suggested on p.7-28. A very long narrow plume has been observed in the Condie sand and gravel aquifer near Regina, Canada (Van der Kamp et al., 1994); at a distance 5.5 km the horizontal transverse dispersivity was 0.1 m and the vertical transverse dispersivity was only 0.4 mm. The contaminant transport simulations in Volume III (Chapter 9) actually use an unreasonably large vertical transverse dispersivity of 5 m, because of a numerical limitation of the code used in the simulations. This exaggerated dispersivity value will cause the simulations to overestimate the amount of dilution.

Regarding matrix diffusion field experiments, it is surprising that the Moench (1995) analysis of the Bethune fractured chalk tracer test (Table F-4) is not included in the matrix diffusion table, as it seems to be by far the most definitive test showing matrix diffusion effects in the field. There is no information on the magnitude of the matrix diffusion effects under field conditions in the volcanic or carbonate rocks at Frenchman Flat.

As to distribution coefficient values, there is naturally the question of how well one can expect the Yucca Mountain tuff data to transfer directly to the alluvium of Frenchman Flat as proposed on p. 7-41. There is also the question of the distribution of reactive minerals in relation to permeability as explored in the LLNL simulations for the source term (Tompson et al., 1999). It would seem that such effects have not really been considered in the Yucca Mountain experiments and that the distribution of reactive minerals relative to permeability could be quite different in the alluvium and in the volcanic tuffs. A more detailed discussion of radionuclide sorption issues is found in Section 3.4.

3.2.9 Comments on Chapter 8: Source Term

A detailed discussion of the data relating to the source description is found in Section 3.4. Here we note only two overall concerns: First, that the need to limit the source term information to unclassified data may compromise the representativeness of the current transport calculations. Second, that there are several potentially important differences in the radionuclides selected to be of concern among the three different documents, Volume II, Volume III, and the LLNL report.

3.3 Groundwater Flow and Contaminant Transport Model (Volume III)

3.3.1 Overall Comments on Volume III

Volume III describes the model studies undertaken to evaluate the Frenchman Flat CAU. It moves from a discussion of the overall modeling strategy, through a description of models for the regional and Frenchman Flat CAU scales, a calibrated base-case model and finally sensitivity and uncertainty analyses.

Overall, the panel has serious concerns about many aspects of the modeling. In terms of the modeling process, there is a disproportionate emphasis on the regional scale, as opposed to the sub-CAU scale on which potential plumes are developed. This emphasis is explained in part by the cumbersome processes of running both the regional and Frenchman Flat CAU models in tandem. In our view, this approach does not improve the accuracy of the CAU-scale model, and severely limits the scope of the sensitivity and Monte Carlo analyses. The combination of the modeling scale, the design of the SWIFT-98 model, and the overall complexity of the hydrogeologic setting have restricted the range of conceptual hydrogeologic frameworks models that were explored in the analysis. The database is not sufficient to exclude other reasonable conceptualizations of the geologic settings and pathways for contaminant migration to the LCA. In addition, the gridding scheme that is implemented does not capture the essential behavior of faults and displacements across faults in sufficient detail.

The calibrated Frenchman Flat flow and mass-transport models are nonunique and there are concerns related to the gridding and parameter selection. Hydraulic data are neither sufficient to exclude alternative hydrogeologic conceptualizations, nor to constrain the choice of particular flow parameters. There are critical assumptions made that strongly impact model predictions, and are probably contrary to actual conditions. For example, the present model assumes a decrease in hydraulic conductivity with depth in the AA, which is contradicted by existing data. Because the size of the source and extent of spreading are small relative to the size of grid blocks, concentrations are underestimated. Also contributing to errors in predicted concentrations is an inappropriate choice of dispersivity values that exaggerates dispersive mixing. The mass transport modeling is illustrative and not quantitative, given the total absence of parameters describing the loading and transport, and limited ability to calibrate or verify.

The uncertainty analysis, represented by sensitivity and Monte Carlo runs, is incomplete. The scope of the analysis is limited to scenarios that can be created by simple changes to model parameters. Additional studies are required to examine uncertainties in the geologic setting related to faulting and the arrangement of HSUs. In addition, other key parameters need to be evaluated as well. The lack of data also impacts the uncertainty analyses in the choice of probability distributions for the parameters and statistics characterizing the variability.

3.3.2 Comments on Chapter 1: Introduction

Volume III describes the CAU-scale groundwater flow and contaminant transport models for Frenchman Flat. The transport model is based on unclassified source term data and, as such, is not considered final. Rather, the transport results in this report are meant to demonstrate the process that will ultimately be followed when data derived from the classified source term is included in the analysis. We consider features of radionuclide transport (most notably contaminant release rates from the source, and retardation rates due to sorption and diffusion) to be strongly dependent on detailed information about the actual source. We are therefore not convinced that reviewing the current model allows us to assess the adequacy of the modeling process that will ultimately be used to predict the spatial and temporal extent of the regulatory contaminant boundary at Frenchman Flat.

The modeling process consists of model selection; model development including data assessment; model verification; and contaminant boundary prediction. It is our opinion that there are not enough quality data to verify either the flow or the transport models. Indeed, the modeling effort to date (as described in Volume III) has not included verification of any kind.

Whereas the hydrostratigraphic model documented in Volume I, and the hydrologic data compilation and evaluation documented in Volume II, have been completed, the modeling activities described in Volume III are said to be ongoing. The value-of-information-analysis (VOIA, IT Corporation, 1997b) is cited as a basis for the decision that no additional data were needed to achieve the objectives of the Frenchman Flat CAI. Hence, there are no plans to collect additional data for purposes of model development (including verification). Yet, the text of Volume III, as well as the decision diagram in Figure 1-2, indicate that new data may be collected if, during the CAI decision process, it is determined that a need exists. A summary report for the data assessment and modeling activities is currently planned for Fiscal Year 2000. We have already made clear (see Sections 2.1 and 3.2.1) our concern with the decision, apparently based on the VOIA, that no additional data are required. The issue of the need for additional data to be collected in support of the Frenchman Flat modeling effort needs to be addressed much more thoroughly prior to preparation of the final report.

The deepest aquifers, the fractured clastic and carbonate NO and LCA (the NO is sometimes included in the LCA; see Table 1-1), extend beyond the physical boundaries of the basin. They provide a conduit for groundwater movement over large portions of southern Nevada. Therefore, it is important to know whether the predicted contaminant boundary reaches these regional aquifers within the 1,000-year regulatory period. The CAU-scale flow and transport models are predicated on the assumption that the LCA is separated from the shallow AA by an effective barrier to downward groundwater flow and contaminant migration. This barrier consists of four confining units UCCU, VCCU, TCU, and WVCU which, together, form a thick low-permeability aquitard across which significant migration from the AA down to the LCA is largely precluded, under existing hydraulic gradients, except possibly through faults. We have noted in the discussion of Volume I (Section 3.1) that there is considerable uncertainty regarding the horizontal extent, cumulative thickness, and permeability of these presumed hydraulic barriers, and that the grid structure, and method of assigning parameter values to grid blocks, in the existing CAU-scale models are not suitable for a credible assessment of such local increases in leakance and their impact on vertical radionuclide migration. This suggests the need for a more flexible numerical approach which allows tailoring the computational grid and parameters with relative ease to various arrangements of discrete block-faulted rock volumes, associated faults, and their hydraulic properties.

It is stated in the Introduction that the AA is more likely to discharge into the LCA horizontally where the latter is stratigraphically high, than vertically by leakage across the intervening aquitard. We do not think that the available data, and the existing CAU-scale hydrologic model, are adequate to allow reaching this or the opposite conclusion.

Flow across the lateral boundaries of the Frenchman Flat model area is computed by means of the regional hydrologic model. It is our view that large uncertainties accompany this boundary flux calculation, due to inadequate data to calibrate either the regional or the Frenchman Flat hydrologic models reliably. Large uncertainties also accompany the assignment of recharge distributions and values to the CAU-scale model. Hence the utility of the entire, cumbersome process of jointly calibrating the regional and CAU-scale models, for both hydraulic parameters and Frenchman Flat boundary fluxes, is in question. The process results in a CAU-scale model that is driven by lateral boundary flux and vertical recharge values which include potentially large systematic and random errors. Because boundary fluxes and recharge are important factors affecting the prediction of contaminant transport in the basin, the resulting predictions are necessarily uncertain. We do not think that this uncertainty is adequately acknowledged and accounted for in the report.

3.3.3 Comments on Chapter 2: Conceptual Model of Groundwater Flow

Volume III emphasizes that defining the conceptual model is the most important task in the modeling process. If the conceptual model is incorrect, then it is likely that model predictions will be incorrect as well. Although three conceptual models of groundwater flow in Frenchman Flat are discussed, much of Chapter 2 is devoted to justifying the one concept selected as a basis for the numerical model. In our review of Volume I, we have already commented on the inadequate range of conceptual hydrogeologic frameworks considered in the report, and on the inability of the selected modelling tools to explore a wider range of conceptual options, which we think is warranted in light of the meager database established for the site. The same comments apply to Volume III.

Three conceptual models of groundwater flow are discussed in Volume III. All three are compatible with the geologic, structural, and hydrostratigraphic framework adopted in Volume I. The models differ from each other only in the interpretation of groundwater flow in the alluvium, and corresponding radionuclide migration from test cavities. One conceptual model postulates flow in the alluvial aquifer to be from north to south, another from west to east, and one views the alluvium as a bathtub.

The main difficulty in choosing among these models is a lack of properly distributed hydraulic-head data. Boreholes are located with a considerably greater density near underground test areas than elsewhere in the basin (Fig. 2-1). Predevelopment water levels (Fig. 2-3) in the center of the study area, west and north of Frenchman Playa, are remarkably similar and suggest very small lateral hydraulic gradients. These gradients are difficult to discern because of uncertainty in the cited water level data. The report acknowledges that it is; therefore, easy to construct potentiometric surface contours which show either a southerly or an easterly direction of flow in this portion of the alluvial aquifer. The same data can also be interpreted to imply no lateral flow at all. Interestingly, the north-to-south conceptual model agrees with the original regional groundwater flow model (U.S. Department of Energy, Nevada Operations Office, 1997). However, both it and the Bathtub model are rejected in favor of the west-to-east concept. We consider the arguments for the selection of the west-to-east model to be weak or inconclusive. As flow model development rests on the west-to-east concept, and model calibration is done with west to east flow as a target, we deem it important to examine some of these arguments.

The nearly flat hydraulic head field in the alluvium neither supports nor refutes any of the three conceptual flow models. The report cites water levels in the LCA, north of Frenchman Flat, and in wells outside the basin to its north-west and west, as a basis for refuting the north-south flow idea. We question the relevance of these LCA and other data, outside the basin proper, to the issue of which way groundwater flows in the alluvium. In our view, the only way to definitively resolve this issue is to rely on direct measurements of water levels and hydraulic properties within the alluvium. The available data are evidently insufficient to resolve this issue.

The report cites water-level data from existing wells as evidence against downward vertical flow in the alluvium. The authors take this as lack of clear evidence in support of the Bathtub model. We consider the available water level data inadequate to say anything of significance about vertical hydraulic gradients in the alluvium anywhere within the basin.

Another argument raised in the report in favor of lateral, as opposed to vertical, flow in the alluvium is that its hydraulic conductivity is expected to decrease with depth, due to an increase in overburden pressure. The report cites U.S. Department of Energy, Nevada Operations Office (1997) to support its assertion that hydraulic conductivity decreases with depth as a general rule. We question the relevance of the information from the cited report to conditions in the alluvium at Frenchman Flat. Figure 3.11 of U.S. Department of Energy, Nevada Operations Office (1994) would reveal that saturated hydraulic conductivity in the alluvium, at wells UE5PW-1, 2, and 3, fluctuates over two orders of magnitude about a more-or-less constant mean value down to a sampling depth of 250 m. Figures 3.8 - 3.10 show that a similar lack of vertical trend is exhibited by porosity data. In the absence of comparable data from greater depths, we consider the available site data as hard evidence, which contradicts the assertion of a decrease in hydraulic conductivity with depth in the alluvium at Frenchman Flat. Such a decrease is built into the computational groundwater flow model and, in our view, could significantly affect its output.

The limited available water chemistry data were examined and found to neither support nor refute any of the three conceptual flow models.

The way in which faults impact the flow system is unknown. The favored conceptual flow model considers the Cane Springs Fault to be leaky, and postulates large displacement along the Rock Valley Fault system which acts as a leaky barrier to lateral flow from the AA to the LCA to the east. In Section 3.1 it was noted that there is neither geologic nor geophysical evidence for a fault-mediated contact between these two aquifers in the eastern portion of the basin. Instead, the structural conceptual model of Grauch and Hudson (1995), on which the CAU-scale model is said to rely, shows the AA and LCA to be in direct lateral and vertical contacts in the east, without any intervening fault (Fig. 4-1, Volume I). To postulate a barrier between them, in contradiction to the structural conceptual model, seems nonconservative, and adds to our unease with the selected conceptual model of groundwater flow.

There is little justification for selecting a single conceptual model of either the hydrogeology or the groundwater flow for Frenchman Flat. As a single model does not provide the flexibility to treat a wide range of alternative options that are considered potentially consequential and equally likely, we regard the model output as highly uncertain.

3.3.4 Comments on Chapter 3: Modeling Approach

This chapter describes key aspects of the modeling approach. We have already commented on many of these. Here we add that the manner of accounting for faults does not, in our view, capture their potential impact on flow and transport. This is because faults are not included as discrete features in the model, but are accounted for indirectly by modifying the hydraulic properties of relatively large box-shaped computational grid blocks. The block hydraulic properties are weighted averages based on assumed thicknesses and hydraulic properties of the faults (and surrounding rock units). This approach does not represent with adequate resolution or accuracy the local effects that faults, and block-faulted structures, may have on flow and transport across aquitards at Frenchman Flat. The SWIFT-98 finite difference code is not suitable for the incorporation of realistic and potentially important hydrogeologic features in the Frenchman Flat model. We think that other more versatile codes (e.g., finite element) could be better suited for this task than SWIFT-98.

The panel does not consider a sensitivity analysis conducted with the regional model to be indicative of how CAU-scale model parameters affect flow and transport in Frenchman Flat. In our view, such analyses should have been performed with the CAU-scale flow and transport models, as well as with smaller-scale models that focus on areas closer to the two clusters of test sites. The choice of parameters included in the regional and site-scale sensitivity analyses, and the ranges within which they are varied, are too narrow to reflect the full range of parameters and values that we think are supported by the available knowledge base. Of particular concern to us is the narrow range of values assigned to the reference (surface) hydraulic conductivity K_o, the exponent λ that controls the assumed decrease in hydraulic conductivity with depth, and the ratio of vertical to horizontal hydraulic conductivity.

To assess the effect of parameter uncertainty on model predictions, a number of scenarios are considered in the regional groundwater flow model. These scenarios concern the spatial distribution and rates of recharge, fault properties, effective porosity, and vertical anisotropy. Monte Carlo simulations of contaminant travel distances are then conducted with the CAU-scale model between presumed end points of these scenarios. We do not think that the listed scenarios, and their assumed end points, do justice to the much wider range of circumstances, which we believe are credible in light of the available knowledge base for the site.

3.3.5 Comments on Chapter 4: Regional Groundwater Flow Model

The report describes the regional model in much greater detail than it does the CAU-scale flow model. We consider this emphasis on the regional model in Volume III to be misplaced.

Although the regional model is of value as a way to integrate available data into a coherent and plausible holistic picture of regional hydrogeology and groundwater flow, we see no reason to trust this relatively crude model, with its sparse data support, as capable of providing reliable quantitative inputs into the much finer Frenchman Flat model, or descriptions of flow and transport on the CAU-scale. The modeling emphasis should be shifted away from the regional scale, toward Frenchman Flat and the still smaller scales of the two nuclear test areas within the CAU, which are much more relevant to contaminant migration from nuclear test cavities at the site than is the surrounding region.

The primary reason for recalibrating the regional flow model, after it had been modified for purposes of the Frenchman Flat CAI, was to replicate the west to east flow system proposed in the favored conceptual model. Because we consider this conceptual model to be nonunique, here is yet another reason to consider the recalibrated regional model as being nonunique.

The panel finds that the presentation in Volume III is insufficient for an independent assessment of the adequacy of the modified recharge distribution and increased rates imposed on the Frenchman Flat portion of the regional model (Figs. 4-3, 4-10; Table 4-10). This input is based on the Maxey-Eakin approximation and subjective professional judgement of the modelers. We expect it to be approximate and nonunique. It is possible that recharge to the west and north-west of Frenchman Flat, and to the alluvium, may have considerable impact on radionuclide transport from underground test cavities. It may be more appropriate to treat it as an unknown parameter field to be evaluated by model calibration, rather than prescribing it in a largely subjective manner.

The report lists, and depicts, weighted rather than actual water level residuals obtained from calibration of the regional flow model. We find these weighted residuals uninformative, as neither the corresponding weights nor the rationale behind them are given in Volume III. Although the latter information can apparently be found in IT Corporation (1997a), we would consider it much more revealing if actual residuals were included in the report. The panel would also like to see actual water level data points and values depicted on the contour maps in Figures 4-6 and 4-7.

3.3.6 Comments on Chapter 5: Frenchman Flat CAU Flow Model

This chapter provides details about the Frenchman Flat numerical flow model. We have already commented on many of these details. The only new aspect is that each layer in the model is treated as confined, including layers that contain a water table. This approximation was adopted to limit the computational burden. We doubt that this approximation will introduce significant errors in the steady flow simulations, but advise that, at a minimum, the accuracy of the present approach be examined in more detail. This approximation may not be adequate for future transient simulations, due to major differences in storativity between confined and unconfined aquifers. If SWIFT-98 is unable to handle transient water table situations efficiently, this may be another reason to consider a different code.

3.3.7 Comments on Chapter 6: Frenchman Flat CAU Model Calibration

The purpose of this brief chapter is to explain the calibration process for the flow model for Frenchman Flat. It describes the treatment of faults in the alluvium to provide appropriate model adjustments, and highlights several issues (e.g., localized mounding, p. 6-2) that could not be resolved with the present database.

The approach in model calibration involves trial and error calculations where repeated adjustments in the model are made to achieve some fit with the observed data. Most of the emphasis in the calibration was on reproducing the low hydraulic gradient evident in the northern part of the basin (p. 6-1). In particular, the discussion explains how fault characteristics were adjusted to reduce eastward flow in the alluvium towards the LCA.

The panel is critical of this calibration exercise for two reasons. First, given the overall complexity of the hydrogeologic setting and the very limited data, one should expect the calibration to be nonunique. In other words, a model based on a different geological conceptualization and/or a different parameter set could reproduce the available head measurements equally well. In a data-poor environment like the Frenchman Flat CAU, many different flow models could be constructed. This issue requires significant elaboration in this chapter and leads naturally to a second concern, namely that the modeling strategy has not come to grips with the data problem.

When a flow model is well constrained by data, calibration helps to provide reasonable estimates for parameters that may be poorly defined. If the model cannot be reliably constrained by data, calibration will not define the base-case parameters for the system in a unique manner. The discussion in this section concentrates on the alluvium because the bulk of the head data are for parts of this unit. Besides the LCA, there is essentially no data to calibrate parameters/fluxes in the other units at Frenchman Flats. Ultimately, the sophistication of the modeling effort cannot replace the fundamental need for data in a modeling study.

3.3.8 Comments on Chapter 7: CAU Flow Modeling Results

This chapter discusses the results of the CAU Flow Modeling. It briefly summarizes the hydraulic conductivity values for each HSU, presents plots of the steady-state hydraulic head values for layers 3 and 12, and discusses differences between observed and simulated hydraulic head values.

Table 7-1 (p. 7-2) warrants a more detailed examination. One small problem is the labeling scheme for Column 1. The term “model layer” is also used to describe the slices through the model (e.g., Appendix C), but the numbering sequence is reversed. We would suggest that a consistent terminology be adopted throughout the volumes. A more serious problem concerns the origin of values for the key parameters in Table 7-1. There are no actual data presented in either Volumes II, or III concerning the vertical anisotropy ratio (K_V/K_H) and depth decay coefficients in Frenchman Flat. In the absence of actual data, presenting the results in Table 7-1 implies that these parameters have been backed out of the model via calibration. Given that there are few data on vertical permeabilities or head gradients at Frenchman Flat, it is surprising that the anisotropy ratios and depth decay parameters are presented with such precision. The data of Burbey and Wheatcraft (1986) for the alluvium do not indicate significant depth decay within the alluvium. Based on the known data for Frenchman Flat, we expect the data on vertical anisotropy ratio and the depth decay parameter to be highly uncertain. In addition, hydraulic parameters for the confining beds are also poorly constrained.

There are a few hydraulic conductivity estimates for the alluvium and the LCA. However, it is noteworthy that the modeled values for the LCA are larger than the measured range for the LCA in three of four instances (p. 7-1). This discrepancy is explained as a feature related to fracturing rather than simply an inappropriate choice of model parameters. Although the differences in the interpretations remain to be resolved, aspects of Table 7-2 reinforce our view that the calibration is highly uncertain.

Illustrative hydraulic head data are presented in Figures 7-1, and 7-2 for model layers 3 and 12 respectively. Interpretation of results would be facilitated by presenting the observed heads according to the model layers. For example, Figure 7.2 has heads from the AA plotted with the model results for the LCA. This presentation gives the mistaken impression that the model calculations do not fit the observed data. There is a need within the report, as well, to provide some selected vertical-cross-sectional plots of hydraulic head-contours produced by the CAU models. Examples could be provided in Chapter 7 with additional results in Appendix C of Volume III. These plots would be the cross-sectional equivalents of Figures C-43 to C-54. They could be used by the reader to visualize flow directions and potential transport paths. However, it would not be appropriate to put flow lines or flow arrows on these plots because they in general will not be parallel to the flow directions.

The predicted hydraulic head contours in layer 3 (Figure 7-1) fit the observed data reasonably well. This goodness-of-fit; however, does not argue persuasively for the validity of the conceptual model. The measured data are limited in number and spatial coverage within the simulation domain.

Section 7.2.2 explains how the residuals are distributed spatially, and discusses the likely cause of some of the larger residual values. Modifications to the model are suggested that could locally improve the calibration. However, without actually doing confirmatory simulations, it is not exactly clear what these discussions add. In our opinion, if the calibration could have been improved then it should have been done. Figure 3 is a plot of observed versus predicted hydraulic heads, based on the data in Table 7-3. It shows more explicitly what the report states, namely that water levels are underpredicted in the southern part of the region. Overall, there is a bias toward underprediction of hydraulic heads. The explanation provided for this result is reasonable. Again; however, if the cause is known why not fix the calibration?

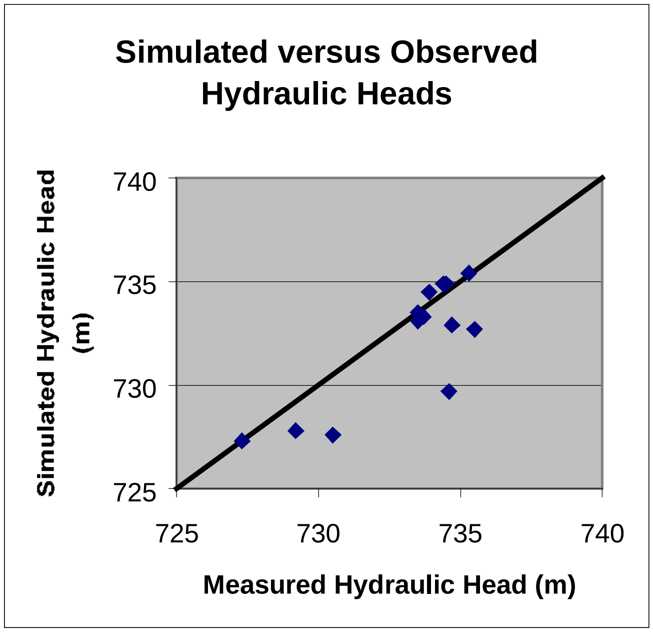

Figure 3
Simulated and Observed Heads for the Frenchman Flat CAU Model

3.3.9 Comments on Chapter 8: Flow Model Sensitivity Analyses

Chapter 8 begins to explore the dependencies between model-input data and sensitivities in model output. By identifying key variables, one can begin to understand how uncertainties in these parameters influence flow and transport. First, the sensitivities in the regional ground-water flow model were examined to provide a more limited set of parameters to test with the Frenchman Flat model. The analysis involved adjusting some 76 hydraulic conductivity values and 76 depth decay parameters. The magnitudes of the adjustments were very small – a factor of 2 times higher and lower in hydraulic conductivity and a range of 10 percent for the decay parameters.

Of the four sensitivity measures used, the advective travel distance in the alluvium is most relevant to transport from sources at Frenchman Flat. This analysis found that changing five of 76 hydraulic conductivity values increased the 1,000-year particle transport distance by more than 10 percent. These particular sensitivities were tested in more detail with the Frenchman Flat model. However, the number of runs with the Frenchman Flat model was limited. Besides a somewhat longer execution time, running the Frenchman Flat model was complicated by the need to run the regional model in tandem. This requirement is cumbersome and reduces the scope and flexibility of the sensitivity analysis. There are opportunities for improving the sensitivity (and Monte Carlo) analyses by finding a reasonable way to decouple the two models. There are other, much more significant, uncertainties in the Frenchman Flat model than the boundary fluxes. The rigor gained by coupling the two models together does not outweigh the benefits of conducting a more thorough sensitivity analysis.

One important problem with the present sensitivity and uncertainty analyses is that it is structured around a few variables that are easy to adjust in the model. Hydraulic conductivity values, which are examined here in Chapter 8, and recharge rates in Chapter 11 are examples. Interestingly, not all of the logical parameters are considered in the sensitivity analysis. For example, changes in anisotropy ratios (K_V/K_H) or depth decay parameters were not evaluated. Both of these parameters would control the extent to which lateral flow develops in relation to vertical flow, and are important to the overall analysis.

Other sensitivities that are more difficult to model were also not considered here or in Chapter 11. The hydrostratigraphic framework is an example. Key uncertainties in the study relate to the possibility that faulting provides simple connections between alluvial or tuff aquifers and the regional carbonate aquifer (i.e., hydraulic "short circuits"). Volume I characterizes the present conceptualization of faulting as "…an extreme simplification of the actual degree of faulting." The faults represented in the cross-sections are illustrative in character, and are designed to represent the kind of faulting that might be expected in the basin. It is generally acknowledged that many more, smaller faults are likely present. Volume I suggests that an increased number of faults would locally increase the hydraulic conductivity of the aquifers and confining beds. However, the uncertainty/sensitivity analyses conducted so far have not examined this issue in detail.

Another important geologically related uncertainty is the thickness and extent of the confining units. For example, in moving west to east across Frenchman Flat, the TCU appears to pinch out. However, the lateral extent of this unit is poorly defined. Similarly, there are uncertainties concerning the distribution of the UCCU. The interpretation is that this unit is not present under Frenchman Flat. The presence or absence of these potential confining units is important because there are concerns that the VCCU, which remains as the key-confining unit in parts of the basin, is locally permeable because of the presence of very transmissive clastic rocks. In addition to uncertainties in the broad distribution of hydrostratigraphic units, the hydraulic properties assigned to these units are likewise poorly constrained.

In summary, the sensitivity analysis is limited in its scope. It focuses on just a few parameters and ignores key dependencies in the model. The present modeling scheme that requires iteration between the regional flow model and Frenchman Flat model is cumbersome and not suitable for analyzing different conceptualizations of the geologic setting. The panel is concerned that the uncertainties in the geologic setting are the most important and yet are not analyzed. Suggestions are provided in Chapter 4 for a more flexible modeling approach that is more amenable to sensitivity/uncertainty analyses.

3.3.10 Comments on Chapter 9: Frenchman Flat Transport Model

Chapter 9 describes the transport model that is part of the modeling strategy to define the 4-mrem/yr enclave of contamination. The calculations involve the SWIFT-98 package, which is a finite-difference code that can handle key mass transport processes. While the code appears adequate for the modeling effort, it is limited in its ability to represent small, irregularly-shaped features (e.g., faults). It also apparently lacks tools like a flexible mesh generator or parameter estimation procedures that could make the modeling effort more efficient.

This chapter explains how the source term is constructed using the model approach described in Tompson et al. (1999). We recognize that the present report provides an illustrative calculation of contaminant migration and that the actual loading will be addressed in a confidential analysis. Insufficient detail is provided in the report to examine how well the source term model is implemented in the modeling approach. There are also cases where the information provided with respect to the source term is inconsistent with the LLNL report. As mentioned elsewhere, there are concerns about how well the source term model represents actual tests.

The panel has serious concerns about the accuracy of the overall concentration calculations, starting at the source. The report on page 9-2 indicates that the grid blocks representing the sources could be up to 10 times larger than one cavity volume. Thus, calculated source concentrations will underestimate actual values. Similarly, dispersivity values (p. 9-5) are much, much larger than reasonably could be expected for a plume of this size in alluvium, especially in the vertical direction. This unrealistically large transverse dispersivity would again lead to the underestimation of radionuclide concentrations at points down-gradient from the source.

Of the other potential processes contributing to contaminant attenuation, sorption is the most uncertain. The conceptualization of sorption as a one parameter sorption process has always been problematical, as is the total lack of K_d data for Frenchman Flat.

No mention is made in the report about the calibration of the mass transport model. Obviously, the lack of concentration data precludes any attempt to calibrate this model. This having been said, the report needs to talk about the value of model predictions in the absence of data for calibration and verification. The inability to calibrate the source-term and mass-transport models, the scaling-related errors, and uncertainties in parameter values, make the application of a mass transport model for prediction infeasible. Realistically, predicted concentrations could be many orders-of-magnitude away from actual concentrations.

3.3.11 Comments on Chapter 10: Transport Simulation Results

Chapter 10 illustrates what the mass transport predictions might look like once the classified source inventory is included. Results are expressed as a dose to an adult individual who drinks 700 liters of water per year. The dose conversion is straightforward; however, no perspective is provided as to how this information is applied in a regulatory sense.

The results of the simulations (Figures 10-1 to 10-15) suggest very limited migration away from the source. The transport is limited to a few grid blocks in the vicinity of each of the potential sources. When plumes are represented by just a few grid blocks, the calculated concentrations have some error associated with them. However, it is not clear exactly how important these errors are. To eliminate these errors, the likely extent of spreading has to be represented with an appropriate number of grid blocks.

Figures 10-16 to 10-20 present the simulation results as the number of occurrences of the 4-mrem/yr boundary in a given cell. We have some concern that this form of presentation of the results is not very clear and can create confusion. Other ways of presenting the results more effectively and understandably should be explored.

3.3.12 Comments on Chapter 11: Uncertainty Analysis

The most common application of ground-water models is for predictive analysis. In practical terms, given some knowledge of basic principles of contaminant migration and the physical and chemical conditions at a site, it should be possible to predict the pattern of contaminant migration in the future. Unfortunately, the reality is that all model predictions are uncertain because of the imperfect ability to represent key transport processes in a model and to describe hydrogeologic conditions. Thus, the extent to which models meet their goals as analytical and predictive tools depends upon whether the inherent uncertainty in model results is evaluated and accounted for in the interpreted model results.

There are two major sources of uncertainty in modeling – model uncertainty and data uncertainty. At its heart, a mathematical model is an attempt to abstract natural processes by mathematical equations. Uncertainty comes into the formulation and development of models because relevant processes may not be included, the mathematical representation of the processes might be oversimplified, or the dimensionality of the model may be mismatched with the problem at hand. The present report does not consider model uncertainty. It implicitly assumes that other sources of uncertainty are more important. Model uncertainty will likely become important when there is significant flow and transport through fractured rocks.

Much of the emphasis in the sensitivity and Monte Carlo analyses is on uncertainties associated with estimates of hydraulic conductivity. While this uncertainty is real, it may not be the most important in the context of the overall Frenchman Flat analysis. The issue of uncertainties in the geologic and structural settings is of greater concern to us. Besides uncertainties in mean values of parameters, there was some emphasis in the Frenchman Flat studies on the impact of spatial variability in hydraulic conductivity (see Subsection 3.2.6). This geostatistical work, undertaken by DRI, did not appear in the Frenchman Flat reports but was presented at the introductory meeting as a component of the overall uncertainty investigation. The panel does not expect such spatial variability effects to be a very important contributor to the overall uncertainty, and regards that these analyses to be speculative and unrealistic given the overall lack of data at Frenchman Flat. Given the expected greater importance other sources of uncertainty, we would place a low priority on further spatial variability studies of this type at Frenchman Flat.

A sensitivity analysis is performed on the calibrated regional model to determine which among its parameters are most important for the assessment of radionuclide migration at Frenchman Flat. These parameters are then varied randomly, within preassigned ranges, and fed into the CAU-scale models (in lieu of the calibrated parameters) for a Monte Carlo analysis of uncertainty in predicted contaminant travel distances. The use of combinations of parameters that do not produce a calibrated model honoring the head data seems inconsistent and may be influencing the uncertainty results.

3.4 Hydrologic Source Term and Radionuclide Sorption Issues

3.4.1 Scope of the Review

In this section the panel discusses issues related to defining and characterizing the hydrologic source term for the CAMBRIC test site and modeling groundwater flow and radionuclide transport from the site as presented by Tompson et al. (1999). We also examine related efforts at groundwater flow and RN transport modeling in the Frenchman Flat CAU that includes the CAMBRIC test site, as described in Volumes II and III prepared by IT Corporation. A summary discussion of major issues considered in detail here is presented in Section 2.5.

3.4.2 Disclaimer with Respect to Classified Radionuclide Source Term Data

It is emphasized repeatedly in the LLNL report (Thompson et al., 1999) that the complete RN source term inventory at the CAMBRIC test site and at other test locations is classified. It is further stated that the list of radionuclides currently included in the transport calculations "cannot be finalized" at this time and "may be modified" in the future. For the LLNL CAMBRIC source term study and IT's Frenchman Flat CAU studies the DOE directive was thus to select radionuclides whose source term was "unclassified and available" for transport calculations.

There is no discussion in any of the reports about the possible impact on the transport calculations of using the classified source term data. The panel is asked to set aside this issue, and comment on the appropriateness of the methodology, independent of the results presented. This assignment is difficult, as much of our thinking about the Frenchman Flat situation is colored by the limited contamination predicted by the modeling exercise. We feel the need to put on record a disclaimer, noting that we are not privy to the classified information, and recognizing that it is possible that the representativeness of the current transport calculations may be compromised by the need to limit the source term to unclassified data.

As a side remark, it is not clear what rationale there is for limiting the period of regulatory concern to 1,000 years, considering that some source radionuclides and/or their daughter products at the NTS (e.g., ^{237}Np) have far longer half-lives.

3.4.3 Hydrologic Assumptions Related to the CAMBRIC Test Source Term and Transport Modeling

A questionable aspect of the hydraulic-conductivity field in the LLNL model is the use of lower values of the hydraulic conductivity (K) in the chimney and cavity volumes than in the surrounding alluvium. Burbey and Wheatcraft (1986, p. 45), included analyses of sensitivity to cavity-K values, but all the K values they considered for the cavity were lower than those in the surrounding media. However, it would seem more defensible to assign higher permeabilities to these highly-disturbed zones. This is an important point because in the case of a lower-K local groundwater flow tubes will be diverted around the source area, thus minimizing the contact of the source area with the flowing groundwater, whereas in the higher-K case the flow tubes will be drawn into the source area, thus maximizing contact. At the very least, the relative K-values between the source-area and near-field should be considered uncertain, and the effect of alternative K ratios should be addressed in the sensitivity studies. If the LLNL modelers are convinced that the cavity-K value is lower than that of the surrounding media, a better case must be made in the report.

The overall modeling approach, using heterogeneous physical and chemical properties with reactive transport solutions developed along individual streamlines, is conceptually attractive and seems to produce some interesting results. However, the method has limitations both in terms of fundamental realism and practical predictive capabilities. Fundamentally, the model neglects any transverse dispersion or diffusion between the individual streamlines , and also assumes that there is no local dispersion or diffusion along the streamlines (see (10) on p. 99). By these assumptions the model eliminates any mechanism for actual mixing within the aquifer. Only at a point of withdrawal (a well) or at some fictitious outflow boundary where fluxes are aggregated across all of the streamlines will there be any "mixing." The neglect of mixing is a concern because there may be important controls on chemical reactions within the aquifer which are misrepresented when concentration changes due to internal mixing in the aquifer are completely eliminated. Over the past several years the issue of what controls actual mixing in a heterogeneous aquifer has been researched extensively, notably in the work of Kapoor, and others. This work has shown that mixing within the aquifer is controlled by the interplay between local dispersion/diffusion and very small-scale fluctuations in the hydraulic conductivity (much smaller than the correlation scale), and that such mixing ultimately has an important influence in multi-species reactive transport. These findings regarding mixing are based on theoretical developments that are confirmed by numerical simulations and laboratory experiments (see Kapoor and Gelhar, 1994a,b; Kapoor and Kitanidis, 1996, 1997, 1998; Kapoor and Anmala,1999; Kapoor et al., 1997; Lyn et al., 1998; Kapoor et al., 1998).

The LLNL report does not seem to recognize the important distinction between solute spreading (which can be adequately represented by considering only advective velocity differences associated with variations in hydraulic conductivity, either through numerical simulations or via stochastic theory), and mixing or dilution (which requires treatment of local dispersion/diffusion and fine-scale velocity variations in order to be adequately quantified). One of the reasons that the model predicted unreasonably high pH in some of the sensitivity runs may be the elimination of all internal mixing in the model. The recommendations (p. 163 second to the last bullet) state that the effects of cross-stream diffusion should be evaluated, indicating that it "…may promote a small degree of additional physical mixing." The words "small" and "additional" are inappropriate here as there is no mixing in the current model. It is easy to say that cross-stream diffusion should be included, but is this really feasible within the streamline formulation when all of the streamlines become coupled? It seems that one may be better off with a fully three-dimensional transport model. Regardless of how this might be done, a grid much finer than the 2 m would be required if the internal mixing is to be realistically simulated, because the fine-scale velocity variations will have a controlling influence. Though this term apparently was not used in the simulations, the longitudinal dispersion term of (42) in Appendix 6 is incorrect in a curvilinear streamline coordinate; the cross-sectional area of the stream tube must appear inside the derivative with the porosity and the entire term is divided by the area (see Gelhar and Collins, 1971).

The practical predictive capability of the model is limited because of the large number of geometry, flow, transport and reaction parameters which have been assigned more or less arbitrarily. Generally, there are little or no data to support the parameter selections; often parameter values were simply adopted from earlier studies without critically assessing the validity of such information. In particular, the hydraulic properties and layering were taken directly from Burbey and Wheatcraft (1986) without any acknowledgement or discussion of the rather severe limitations of that model. Burbey and Wheatcraft (1986) used a very coarse grid and one of the key parameters, the longitudinal dispersivity, was fixed in the calibration process. The characterization of the heterogeneity of hydraulic conductivity (p. 96) seems to be largely arbitrary; certainly Gelhar (1993), Table 6.1, p. 291, does not provide justification for selecting a vertical correlation scale of 6 m, as the largest value in the table is 3 m and many values are below a meter. It seems that this choice represents a numerical expedient rather than physical reality.

Generally the report does not justify the selection of parameter values. Under these circumstances it is difficult to regard the quantitative results to be defensible. The report emphasizes the ambiguity of the results in the statement in italics at the end of Conclusion 7 (p.159), but, in view of the many arbitrarily assigned parameter which were not varied in the sensitivity studies, we doubt that "…Models 11 and 10a represent upper and lower bounds of mobilities of the radionuclides considered." The results of the LLNL model should be viewed with caution. Users might be so impressed with the apparent sophistication of the process representations and the dramatic color graphics used to portray the results, that they lose sight of the uncertain nature of the inputs to the model and may begin to believe that the predicted results reflect reality.

Overall, one needs to be concerned about whether the current deficiencies in input data for the LLNL model are rectifiable through a feasible and practical program of field and laboratory data collection. The report, in principle, addresses this issue in Section 15.4, Recommendations for Future Work, but, in our view, falls short of what is needed in this regard. What we find there is the usual general shopping list of data needs; modelers always want more data. What is needed, in order to get a better idea whether we are looking at something that could be practical in the NTS context, is a prioritized list of data collection activities which specifically defines the kinds of samples (archived sediments, new boreholes, undisturbed cores), the types of tests to be done (mineralogical analyses, batch test, *in situ* or lab permeability), the number and spatial distribution of sampling locations, and how the new data will be used to better determine the pertinent model parameters. Presumably the priorities in this list would reflect the results of the sensitivity studies, possibly supplemented by additional sensitivity work on other parameters of likely importance, such as the permeabilities of different zones of the shot-affected volume. The degree to which reactive minerals are associated with lower hydraulic conductivity zones seems to be the most important factor affecting the flux of sorbing nuclides. Presumably any testing program would need to focus on determining the relationship between mineralogy and hydraulic conductivity, but the Recommendations do not emphasize this need or what kinds of data will be needed to address this issue.

3.4.4 Utilization of the CAMBRIC Test Source Term in Frenchman Flat CAU-Scale Transport Modeling

Insertion of the LLNL-produced source term into the CAU-scale model seems appropriate in principle, although questions arise. It is claimed that the insertion is conservative because the output from the LLNL model that is used as input to the CAU model is for a case with no retardation and no decay in the source zone. However, this conservatism is offset (at least with respect to concentrations) because the source term is inserted as a mass rate of contaminant into a single grid cell, and there is a resulting dilution in source concentration (although the total mass is conserved). The implications of this approach deserve more discussion on page 9-4 of Vol. III.

The question of "prompt injection" of RNs to considerable distances away from the detonation point does not receive sufficient attention in the LLNL report. To the uninitiated, an explosion that has sufficient strength to melt and vaporize rock, create temperatures of several million degrees celsius, produce pressures close to one megabar, and set up intense shock waves, would seem to have the potential to drive RNs much further into the subsurface geological environment than is claimed. Burbey and Wheatcraft (1986, pp. 17 & 58), discuss a "tritium exchange radius" that is larger than the cavity radius, but it is admittedly not significantly larger.

For detonations above the water table, the availability of vapor phase transport in the unsaturated zone would appear to offer some early-time migration routes that are not fully addressed in the report. It is noted that there are some volatile radioisotopes (^{3}H, ^{36}Cl, ^{129}I), and some radioisotopes (^{90}Sr, ^{137}Cs) with noble-gas precursors (^{39}Ar, and an unidentified Kr radioisotope). It is not clear that these RNs could not be transported out of the cavity/chimney into the alluvium in the gas phase. In addition, it is noted that CO_2 and $^{3}H_2O$ could act as carrier gases to move fission products away from the explosion point. Could these mechanisms not lead to spreading of the source radionuclides out into the alluvium in the near-field, perhaps to considerable distances?

It is claimed that the treatment of the source term in the CAU-scale model is conservative because it is inserted at the water table, thus taking no credit for possible attenuation in the unsaturated zone that lies between the test cavity and the water table. There are several bases on which this supposed conservatism can be questioned. Of the 10 underground nuclear tests performed at Frenchman Flat, the CAMBRIC test was below the water table, and the nine other tests were conducted within 100 m of the water table, with at least five of those tests having cavities that "…may extend to the water table." There is insufficient evidence presented to confirm that test cavities from the remaining four tests do not also extend to the water table. It is possible that zones of greater conductivity might develop beneath some test locations resulting in source zones that extend well below the water table, not just to the water-table surface. Finally, as suggested earlier, prompt-injection and/or unsaturated-flow mechanisms might spread the source over a greater area than is currently assumed.

It would appear that the CAMBRIC-based source-term model has been used for all the test sites in Frenchman Flat. It was developed for an alluvial environment, and may not be appropriate for the PIN STRIPE test which was detonated in tuff, or the DERRINGER test which was detonated near the alluvium/rock contact. The results of the regional groundwater model suggest that contaminant migration in fractured rock is significantly greater than in alluvium. Do the results for the Frenchman Flat CAU shown in Figures 10-1 through 10-20, 11-1, 11-2, 11-5, and 11-7 through 11-11, reflect the fractured-rock conditions at PIN STRIPE and just below DERRINGER? If not, could the contaminant plumes from these two test locations perhaps be significantly larger than indicated?

3.4.5 The CAMBRIC Test Source Term Study

A basic purpose of the LLNL CAMBRIC test source term study has been to determine and model the specific reactions that control RN concentrations released from the glass and exchange volume in the test cavity, and attenuated by interactions with minerals in the alluvium during transport. Tompson et al. (1999) have model-predicted concentrations of RNs taking into account reactions that include solution speciation, the rate of dissolution of melt glass, RN desorption from the exchange volume, and RN precipitation and adsorption by minerals in the alluvium. A fundamental understanding of these various reactions must be developed and modeled if model predictions of RN source term concentrations for the next 1,000 years are to have credibility. Providing this understanding is the justification for the fundamental approach taken by the LLNL study.

A major goal of the LLNL study is to provide RN concentration input values for the larger scale transport calculations for the Frenchman Flat CAU performed by IT Corporation. Because of the complexity and large number of the various reactions; however, they cannot be incorporated directly in transport codes such as SWIFT-98 which can only consider radioactive decay and RN adsorption as described by distribution coefficients (K_d's). To make their study results practically useful and to conform to the input requirements of SWIFT-98, the LLNL group has converted their predicted concentrations into apparent RN retardation coefficients ($R_d$values) from which corresponding K_d's may be computed for use in SWIFT-98 transport modeling. In principle this approach seems logical and quite reasonable.

Unfortunately, there are serious inconsistencies between the approaches taken to define the important radionuclides and their transport parameters in the LLNL CAMBRIC study and in IT's CAU 98 Frenchman Flat Volumes II and III. Inconsistencies include: (1) the selection of a different set of RNs of concern in each of the three documents; and (2) the selection of vastly different K_d values and reactivities for some of the same RNs among the three documents. These inconsistencies mean that the conclusions of the three reports are only qualitatively useful for assessing the future risk of RN releases and groundwater transport at Frenchman Flat. Specific issues and observations related to the hydrologic source term are discussed below in terms of the same items (a) through (f) identified in the Executive Summary of the LLNL report:

a) *Selection of radionuclides for analysis.*
   The selection has been made from among RNs with unclassified source term data only. Among these, the list was further shortened for a variety of reasons to exclude the following RNs ^{238}U, ^{85}Kr, ^{99}Tc ^{36}Cl, ^{106}Ru, ^{125}Sb, and ^{129}I. It is not shown what the elimination of these species from consideration does to the predicted radiologic dose in groundwater. A radioisotope of Kr (apparently not ^{85}Kr) is the parent RN for ^{90}Sr. There is evidence that this gaseous Kr isotope and ^{137}Xe gas may migrate upwards into unsaturated portions of the chimney (pp. 25, 93). This would place their daughter

products ^{90}Sr and ^{137}Cs in such locations, perhaps at some distance from the shot cavity in fractured rock. Neglecting the Kr parent of ^{90}Sr may lead to an underestimation of the ^{90}Sr source term from the exchange volume. Separately, ^{85}Kr was found in waters pumped from well RMN-2S, 90m south of the CAMBRIC test. A host of RNs not considered in the modeling were measured and found in waters pumped from wells RMN-2S and/or RNM-1 adjacent to the CAMBRIC test. Are the data for these RNs classified? As noted in Tompson et al. (1999, p. 177), ^{237}Np is the immediate daughter of ^{241}Am. Because it is not mentioned among RNs whose source terms are unclassified, the source term for ^{237}Np is evidently classified. Neptunium-237 has a half-life of 2.1 my and is likely to be highly mobile in alluvial groundwaters relative to its immobile parent ^{241}Am. The RN of most concern in Yucca Mountain groundwaters after about 10^4 yrs is ^{237}Np. We are given no evidence that RNs with classified source term information, such as ^{237}Np, are not important to radioactive dose at the NTS. For this reason we cannot be confident that predicted doses in groundwater migrating from the Frenchman Flat CAU are either meaningful or conservative.

b) *Determination of total inventory of RNs and their partition among glass and rubble zones.* More detailed justification should be given for the assumed partitioning of RNs, which depends on many variables that include the half-lives of precursor RNs, relative RN volatilities after the test, and the movement of RNs within and away from the test cavity. RN partitioning apparently depends on the size of the test and the surrounding geology. Does it also depend on the depth to groundwater? It is estimated that between 700 and 1,300 metric tons of glass result from each kiloton of test yield (p. 6). The LLNL report notes that the size of the exchange volume can often be estimated from correlations that have been developed from drillback hole data (p. 93). The LLNL report states that the final size of the cavity is dependent on the yield of the explosion, the overburden stresses, and the strength of the surrounding rock, which will obviously vary substantially among alluvium and the different volcanic rocks. Is there a predictable difference in the amount of glass produced from tests performed in alluvium versus in volcanic rocks?

c) *Development of a model describing radionuclide release from the melt glass.* The kinetic model for glass dissolution overall seems reasonable. Persuasive evidence is offered supporting the choice of a glass dissolution rate constant for 25°C. The largest acknowledged uncertainty (orders of magnitude) in the glass dissolution rate is due to uncertainty in the reactive glass surface area (A_s). Considerable effort is made to estimate a reasonable A_s value (p. 42). However, no direct measurements of A_s for the *in situ* glass have been made. For most dissolving silicates the reactive surface area would increase with time. However, incongruent dissolution of the glass results in precipitation of hydrated secondary minerals including clays and zeolites. Their molar volume exceeds that of the glass so that their formation on the surfaces of internal cracks apparently limits access of groundwater to these internal glass surfaces. These secondary clays and zeolites are likely sorbents for RNs released from the glass.

The glass dissolution rate model may be conservative and yield a maximum dissolution rate for reasons that include: (1) the dissolution rate constant for glass, based on the dissolution experiments of Mazer (1987), is a maximum value because of Mazer's experimental design; and (2) the solubility of the glass is taken equal to that of amorphous silica, which may exceed that of the glass by roughly 40 milligram per liter (mg/L) (about 50 percent). However, the model may be unconservative for at least three reasons: (1) temperature is assumed constant at 25 ^{o}C instead of starting near 100 ^{o}C and decreasing with time. The authors have shown that after 10^5 yrs, at 25^{o}C about 6 percent of the glass will have dissolved, whereas at 50 ^{o}C, about 64 percent of the glass will have been solubilized (p. 52); (2) A_s is assumed constant instead of increasing with time as expected; and (3) the choice of A_s = 118 square meter per cubic meter (m^2/m^3) for the glass, which is equivalent to 4.7×10^{-5} square meter per gram (m^2/g) is extremely small. As noted in the LLNL report (p.43), measurements using a gas adsorption (BET) method produced a surface area of 0.05 m^2/g for glass from the SHOAL test. This is about 1,000 times greater than used in the LLNL model. Both of these values are extremely low compared to the surface areas of natural materials which generally exceed 0.1 to 10 m^2/g (Langmuir, 1997). To confirm the assumed values it is highly desirable that measurements be made of the surface area of characterized, weathered glasses obtained from the CAMBRIC test site. In recognition of the uncertainty in A_s, the authors have examined the effect of increasing its value by 10, 100, and 1,000 times in sensitivity analysis on the rate of RN releases from the glass and on RN transport.

d) *Development of a model describing RN release from and chemical interactions in the chimney and cavity regions.*

The reactive transport modeling code GIMRT has a great many limitations that required special modifications and adjustments to make the code more applicable. Is it the best choice for a code to be used here? Would it not be simpler to use a more versatile geochemical model without as many limitations? For example, were codes such as HYDROGEOCHEM 2 and CHMTRNS considered? Some limitations of GIMRT include:

- Cannot use surface complexation models. Have to remodel published adsorption data assuming a single nonelectrostatic adsorption site and binding constant. (Authors acknowledge that a two-site electrostatic double layer model should be implemented in GIMRT (p. 184)).
- Must assume a single adsorption site in ion exchange
- Cannot model competitive ion exchange except among ions of the same charge
- Does not differentiate among isotopes of a given element (p. 60)
- Does not consider radioactive decay and the fate of daughter products
- Solid solution of RNs cannot be considered (p. 71)

Tompson et al. (1999) have modified the original GIMRT code and its output to account for radioactive decay. Further code modifications, some of which have been proposed, could address other limitations given above. A serious limitation of any modeling effort of RN releases from the chimney and cavity regions (the exchange volume) is the lack of knowledge of the form of occurrence of the RNs in the exchange volume (p. 57). The assumption is made simply that RNs in the exchange volume are held only on adsorption or exchange sites. This would make them readily available to circulating groundwaters without significant kinetic hindrance, although desorption of Pu, Am and Eu in particular, is likely to be very slow and incomplete.

e) *Development of models for the aqueous complexation, surface complexation, ion exchange, precipitation and dissolution reactions that control chemical interactions among the glass exchange volume and alluvium*.

The assumptions regarding aqueous complexation and ion exchange appear reasonable. Assumptions regarding RN adsorption and precipitation are considered unnecessarily over- conservative with regard to Eu, Am, Pu, and possibly Sr. Eu and Am have been assumed unreactive and as having the behavior of inert tracers. It was stated that surface complexation (SC) modeling adsorption data for Eu and Am was not available. It seems likely that the results of Degueldre et al. (1994) for sorption of Am by hematite, corrected for sorbent surface area, could be used to develop a simple double layer model for Am sorption by goethite. Adsorption parameters for Eu(III) could be reasonably assumed equal to those for Am(III). In Yucca Mountain tuffs, Triay et al. (1997, p. III.3-11) found that Eu and Am were strongly adsorbed from waters saturated with respect to calcite, which the groundwaters of Frenchman Flat apparently are (IT Corporation, 1999a, p. 6-11) and will be more so at elevated temperatures. Eu and Am were also strongly adsorbed on rocks that contained a few percent clay. The assumed mineralogy of the alluvium includes not only 1% goethite, but also potential Eu and Am sorbents calcite (1%), clinoptilolite (5%), and the clays smectite (5%), and illite/muscovite (1%).

Measurable concentrations of reactive species ^{60}Co, ^{90}Sr, ^{137}Cs, and ^{239}Pu were reported in wells RNM-1 and RNM-2S (pp. 21, 24, 135). Why were not the concentrations used to estimate apparent K_ds or adsorption constants for these RNs to compare with such values being assumed in the modeling for ^{90}Sr, ^{137}Cs and ^{239}Pu? Comparison of model predicted and measured concentrations of ^{239}Pu in water from well RNM-1 shows that measured concentrations are roughly 2,500 less than predicted (p. 150). As noted by the authors, this indicates that Pu mobility is considerably less than predicted, and is not adequately accounted for in the modeling. The authors suggest that disagreement in the Pu results could be due to the lack of an electrostatic model for sorption (by goethite) in GIMRT.

Only precipitation and dissolution of pure RN phases were considered in the modeling. However, at the trace concentrations they are present in groundwaters, most RNs are likely to be precipitated in solid solutions of major secondary minerals rather than as pure phases. RN concentrations might then be controlled at considerably lower values than at saturation with pure RN phases (Langmuir, 1997). In Frenchman Flat alluvial groundwaters, the formation of RN solid solutions with calcite seems likely. Curti 1999) presents partition coefficients for RNs (Am, Eu, Pu) in calcite that could be added to the modeling effort. Strontium is known to form a solid solution within aragonite ($CaCO_3$) (Glynn, 1990), and to a less extent within calcite ($CaCO_3$) (Pingitore and Eastman, 1986; Tesoriero and Pankow, 1996). Possible Sr incorporation in a calcite solid solution should be considered to ascertain if it might be a significant sink for Sr. Such control might define much lower maximum aqueous Sr concentrations than expected at saturation with respect to strontianite ($SrCO_3$).

Recent measurements from wells near Yucca Mountain suggest that redox potentials of 100 mv or less are possible in volcanic groundwaters at the NTS. If such potentials also occur in the alluvium, plutonium will be present as Pu(IV), which is highly insoluble and immobile. It is assumed in the modeling that atmospheric oxygen is present with $0_2(g) = 0.2$ bars. However, to simplify transport modeling, ferromagnesian minerals (biotite and hornblende) have been neglected. The ferrous iron in these minerals could deplete oxygen in the groundwater and reduce mobile Pu(V) and Pu(VI) species to immobile Pu(IV). The possibility of lower redox potentials, particularly in deeper alluvial groundwaters, needs to be considered in the transport modeling. Have Eh and/or dissolved oxygen measurements been made of well waters in the alluvium at the NTS?

f) *Development of a groundwater flow and radionuclide transport model*
Tritium recovery in well RNM-2S observed in a 16 yr test (Burbey and Wheatcraft, 1986) has been used to calibrate the transport component of the LLNL source model. The 16-yr pump test led to detection of ^{3}H, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{106}Ru, ^{125}Sb, and ^{129}I in waters from wells RNM-1 and RNM-2S, with ^{60}Co, ^{90}Sr, ^{137}Cs and ^{239}Pu also detected in RNM-1 waters. These RNs include relatively unreactive (inert) and reactive species. Why were not these analyses used to validate RN transport modeling predictions for RNs other than tritium? Why were ^{60}Co, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{106}Ru, ^{125}Sb, and ^{129}I, for which data are available in one or the other of these wells, not considered in modeling or dose calculations?

The authors acknowledge that they have not considered the fate of radioactive daughter products of RN decay, and that ^{241}Pu, for example, which decays to ^{241}Am with a half-life of 14.4 yrs should be included in the modeling. Even more important would be consideration of ^{237}Np, the highly mobile and long-lived daughter of ^{241}Am. Also important might be consideration of gaseous ^{85}Kr which has an unknown daughter product and a half-life of 10.76 yr.

g) *Assess model sensitivity to melt glass and reactive mineral surface area, as well as the spatial abundance and distribution of the reactive minerals in the alluvium: the mineralogic models.*
A GIMRT-model sensitivity analysis has been performed with interesting results. It uses a range of possible values for the surface areas of melt glass and sorbing goethite, as well as a varied abundance and distribution of reactive minerals in the alluvium. Individual sensitivity analyses are detailed in numbered "mineralogical models." However, site-specific data are lacking to establish if the values chosen for modeling are realistic so as to

properly frame or bound the modeling results. As a result it cannot be stated with any confidence that any of the mineralogic models are conservative or nonconservative.

Information on the distribution of reactive minerals in the alluvium is not available (p.135). For this reason, the spatial distribution and occurrence of reactive minerals in the alluvium were varied in modeling RN releases, reactions and transport (p. 135). Goethite surface areas of 50 and 600 m^2/g were considered in sensitivity analysis modeling of Pu and Sr adsorption, as was the effect of increases on the surface area of the melt glass of 10, 100, and 1,000 times on the rates of release of Pu, Am, Eu, Cs, and Sr from glass dissolution (p. 133).

Peaks in RN fluxes at early times (at about 50 yrs) reflect releases from the exchange volume. Later RN releases (generally at lower flux rates) are from the glass and reflect the kinetics of glass dissolution. The results have been corrected by the authors for radioactive decay. The authors do not select a single model as most likely given the lack of data on the distribution and reactivity of minerals in the alluvium.

The modeling results are highly sensitive to the abundance and distribution of reactive minerals in the alluvium, and to the assumed surface areas of adsorbent goethite and of dissolving melt glass. Field data are lacking to allow determination of reasonable values for these unknowns. Evidence that retardation of Pu and Am has occurred at the site supports the assumption of some retardation of these species. The known existence of sorbents such as ferric oxides, clays, and zeolites in the alluvium makes some adsorption of RNs certain and model 11 unrealistically conservative. The lack of knowledge of the distribution and occurrence of sorbent minerals makes it impossible to confidently select from among models 10, 12, or 13 or their variants. Model 13a may be the most realistic of the models presented. It assumes a goethite surface area of 50 m^2/g which is more likely than 600 m^2/g. The larger area would normally apply to freshly precipitated Fe oxides rather than to goethite which is more crystalline. The probability that sorptive minerals are more abundant in fine-grained, lower permeability alluvium is also assumed in this model. However, data are lacking to confirm the assumed distribution of hydraulic conductivities.

Probable and possible reactions that could reduce the concentrations of Am, Eu, Pu, and Sr in the groundwater have not been considered in the modeling effort. Inclusion of such reactions in the modeling may substantially reduce the concentrations and fluxes of these RNs as a function of time. However, inclusion of RNs whose source term is classified, such as ^{237}Np, in the modeling will almost certainly increase RN doses in the groundwater.

3.4.6 UGTA Project CAU-98 Frenchman Flat Volume II

Tompson et al. (1999) considered ^{3}H, ^{90}Sr, ^{137}Cs, ^{155}Eu, ^{239}Pu, and ^{241}Am as the important RNs in their CAMBRIC source term study, although tritium was only considered in the analysis of the pumping experiment of well RNM-2S. Tompson et al. used example RN behavior (e.g., the RN is inert, or adsorbed by ion exchange or by surface complexation) and available thermodynamic data as their chief criteria for selecting the RNs to be used in source term analysis and modeling.

In contrast, in Volume II of the IT study the selection criteria was to consider the most significant RNs, whose source term is unclassified, for predicting the contaminant boundary and RN doses that might move from the Frenchman Flat CAU for 1,000 years. Based upon this criteria the important RNs selected were ^{3}H, ^{14}C, ^{129}I, $^{239/240}$Pu, ^{137}Cs, ^{90}Sr and ^{238}U. Tritium, ^{14}C, ^{129}I, and ^{238}U were ignored in the LLNL study. ^{241}Am and ^{155}Eu were not considered in the IT study. Presumably, the results of the CAMBRIC source term study should be consistent with and directly applicable to the larger-scale Frenchman Flat CAU study. Examination of the LLNL and IT documents suggests that the authors of these studies have worked almost independently with little coordination of their efforts.

The LLNL source term model (GIMRT) assumes Pu and Sr adsorption by goethite using a simplified surface complexation approach. Cs and additional Sr adsorption is modeled assuming ion exchange behavior, with Sr adsorbed by clinoptilolite and smectite, and Cs adsorbed by muscovite/illite. Adsorption of Am and Eu is ignored. In Appendix 9 of their report, Thomson et al. (1999) discuss the possibility of simplifying their relatively complex approach to RN adsorption of Pu, Sr, and Cs, employing retardation coefficients (R_d values) for application to larger scale simulations such as the Frenchman Flat CAU. From their GIMRT modeling output, they compute apparent R_d values as a function of time and flow distance along different flow paths. They indicate that constancy of R_d values (and thus of K_d values) can be reasonably expected and assumed along streamlines within mineralogically and hydrologically homogeneous geologic units (i.e., the alluvium), but not, for example, when groundwater flow moves from the glass and exchange volume into the alluvium.

The only rock-type considered in adsorption modeling by Tompson et al. (1999) was alluvium. All of the rock-types considered by IT in adsorption modeling were volcanic tuffs. Both groups also assessed adsorption by iron(III) oxides.

In the SWIFT-98 modeling effort, it is assumed that adsorption can be addressed assuming a simple K_d approach, with K_d values grouped into categories based on four rock types which include devitrified tuff, vitric tuff, zeolitic tuff and iron oxides (p. 7-37). The K_d values for these rock types were obtained from batch laboratory studies of Yucca Mountain tuffs described by Meijer (1990) and Triay et al. (1997).

Typical R_d values in the alluvium estimated by Tompson et al. (1999) are 3,000-3,500 for ^{137}Cs, roughly 1500 for ^{90}Sr, and 500 or less for ^{239}Pu. These values approximately correspond to K_d values of 300-900 for ^{137}Cs, 150-400 for ^{90}Sr, and 125 or less for ^{239}Pu. In fair agreement, these estimates may be compared to K_d values for the three tuff rocks adapted by IT that range from 100 to 5,000 for ^{137}Cs, 50 to 50,000 for ^{90}Sr, and equal 300 for ^{239}Pu. The IT report acknowledges that K_d values commonly range over several orders of magnitude (p. 7-41).

3.4.7 UGTA Project CAU-98 Frenchman Flat Volume III

In Volume III, IT Corporation inexplicably reduces its list of RNs important to dose from ^{3}H, ^{14}C, ^{129}I, $^{239/240}$Pu, ^{137}Cs, ^{90}Sr and ^{238}U, which were emphasized in Volume II, to ^{3}H, ^{90}Sr, ^{239}Pu and ^{241}Am. No reason is given for eliminating ^{14}C, ^{129}I and ^{238}U from the list. As shown in Table 1, this list also differs from the selection of Tompson et al. (1999).

Table 1
Cross-Comparison of Radionuclides of Concern
Among the Various Study Reports

Source	Radionuclides of Concern
Tompson et al. (1999)	Am-241*, Cs-137, Eu-155, Pu-239, Sr-90, (H-3)
IT Volume II	Cs-137, Pu-239, Sr-90, H-3, C-14, I-129, U-238
IT Volume III	Am-241, Pu-239, Sr-90, H-3

*Underlined RNs have been assumed unrealistically to be unretarded (K_d = 0).

In IT Volume II retardation of RNs in the Frenchman Flat Transport Model is assumed fully accounted for by assigned K_d values based on experimental measurements involving tuffaceous rocks (p. 9-3). In Volume III, IT assigns single K_d values of 0, 0, 50 and 100 L/kg to ^{3}H, ^{90}Sr, ^{239}Pu and ^{241}Am, indicating that ^{90}Sr moves in the groundwater as an inert tracer. These K_d values appear arbitrary and are inconsistent with the values discussed and selected by Tompson et al. or in Volume II. Table 2 contrasts the K_d values for Cs-137, Sr-90 and Pu-239 selected in the three documents.

Table 2
Cross-Comparison of K_d Values Among the Various Study Reports

Radionuclide	K_d Range Estimated from R_d of Tompson et al. (1999)	K_d Range Selected by IT Corp. Vol. II	K_d Range Selected by IT Corp. Vol. III
Cs-137	300-900	100-5,000	RN ignored
Sr-90	150-400	50-50,000	0
Pu-239	~125	300	50

Tritium, ^{90}Sr, ^{239}Pu, and ^{241}Am are among the RNs modeled by Tompson et al. (1999) who in addition considered ^{137}Cs and ^{155}Eu transport. As a further difference, the LLNL group assumed that ^{90}Sr mobility is limited by adsorption and ion exchange. The IT report assigns a K_d value of 100 L/kg (10^5 ml/g) to ^{241}Am, whereas Tompson et al. assume its K_d = 0. In other words the hydrologic source term parameters for RNs used in Volume III of the IT study bear little relationship to those proposed in Volume II, or developed and used in the LLNL study. The only species for which there is agreement is tritium, which both studies assume to be unretarded ($K_d = 0$). Thus, except where tritium dominates RN dose, results of the IT modeling effort can only be considered illustrative of RN behavior and not an indication of actual or potential future total dose in groundwater.

RN concentrations are converted to RN doses in mrem/yr, using the equation on p. 10-1, which assumes that the average individual consumes groundwater at a rate of 700 L/yr. Of particular interest from a human health standpoint is the projected location of the 4 mrem/yr dose boundary. IT modeling results in Volume III suggest that after 100 yrs, in order of decreasing dose, the most to least important RNs are ^{90}Sr, ^{239}Pu, ^{241}Am, and ^{3}H. Given that adsorption of ^{90}Sr has been ignored, these results are of questionable value.

As noted by IT, a detailed uncertainty analysis did not consider the effect on dose of varying values of K_d for individual RNs. The range of values chosen should be consistent with the wide range of apparent retardation coefficients for Pu, Cs, and Sr estimated by Tompson et al. (1999), and should take into account the K_d values for RNs presented in Volume II. Presumably, future revisions in the adsorption/precipitation reaction chemistry of Am, Eu, Sr, Pu, and other RNs by the LLNL group should be taken into account in the IT transport modeling and its uncertainty analysis.

Because of the low groundwater flow rates predicted by the Frenchman Flat model, the IT report projects a maximum advective groundwater flow of about 530 m in 1,000 yrs. The modeling suggests that RNs from the tests and the 4-mrem/yr boundary in particular will move only short distances from the test sites. Given their short half-lives ($t_{1/2}$ values) and the low groundwater flow rate, ^{3}H ($t_{1/2} = 12.3$ yr) and ^{90}Sr ($t_{1/2} = 28.8$ yr) will have largely decayed within 100 yrs. Although they have much longer half-lives, strong adsorption of ^{241}Am and ^{239}Pu also limits their movement to short distances from the test sites. Assigning a non-zero K_d value to ^{90}Sr adsorption which is more correct than the IT assumption that $K_d = 0$, will further limit ^{90}Sr transport. However, not considered in dose calculations is the probable persistence and high mobility of ^{237}Np, the daughter of ^{241}Am, and other radionuclides whose source term data are classified.

CHAPTER 4

RECOMMENDED ACTIONS

As described in the first three chapters of this report, the panel has concluded that the current model results and uncertainty analyses leave many of the key issues unresolved. Under these circumstances, it seems appropriate for us to suggest some alternative approaches that might lead to a more defensible prediction of the possible migration distances of the 4-mrem/year contaminant boundary from the Frenchman Flat source areas within the 1,000-year time frame. Our recommendations fall into two categories, those that involve the collection of additional data through field work and laboratory analysis, and those that involve alternative modeling strategies. Each category is treated in a separate subsection below.

Some preliminary discussion is perhaps in order. First, it is our opinion that neither category of recommended action will be sufficient by itself. What is required is a phased, integrated program of modeling and field-data collection, in which decisions on data collection are contingent upon the latest modeling results, and vice-versa. We recognize that there may be a preference for modeling strategies over field-data collection, but we must reiterate our belief that a model can never be viewed as a substitute for data. At a contaminated site no amount of additional modeling or uncertainty analysis can make up for the absence of key site information.

Having said this, it would be irresponsible for the panel to recommend a costly field-measurement program without a well-supported basis for its value. The benefits of the collected data should outweigh the costs. The question of whether this is so, or not, depends to a large degree on the performance criteria that are defined, and the costs associated with a failure to meet these criteria, both direct remedial costs and indirect social costs. Unfortunately, we find information on these topics lacking in the documents under review. Without such information in hand, we have tried to put together a rationale for data enhancement, and a phased set of recommended actions that would allow for an assessment of the worth of additional data at each step of the Frenchman Flat program.

The panel is not opposed in principle to the attempt to apply modeling in a data-sparse environment, using the limited available "hard" data, together with interpretive "soft" data, to produce an initial prediction of the extent of migration of the contaminant boundary, and an estimate of the uncertainty associated with that prediction. We view this initial modeling as a "prior" Bayesian prediction, against which a value-of-information analysis can be carried out. It is our opinion that such a VOIA analysis, if it were to include all the appropriate uncertainties, especially those associated with all feasible failure scenarios, and if it included full recognition of the total social costs associated with a "failure," would indicate the need for additional data in the Frenchman Flat CAU. It is usual at large, politically-sensitive, contaminated sites to anticipate at least one, and often several, iterations of the model/data-collection loop. A single, premodeling VOIA that suggests that no further data collection is necessary, as is the case for the current work in Frenchman Flat, is most unusual. The panel considers the model/data iteration process at Frenchman Flat to be incomplete.

4.1 Rationale for Data Enhancement

There are two aspects to the rationale that we have developed to support the need for additional field and/or laboratory measurements in the Frenchman Flat CAU. The first recognizes the need for scientific legitimacy in the modeling process. The second recognizes the need to place the modeling effort in a decision-support framework. We see four elements to the scientific legitimacy rationale: (1) the need for improved problem identification, (2) the need to test assumptions used in the modeling strategy, (3) the need to calibrate and validate model predictions, and (4) the need to build confidence in target audiences. We see two additional elements associated with the decision-analysis viewpoint: (5) the need to place the collection of additional data into a cost/benefit framework, and (6) the need to place the value of additional data at the Frenchman Flat CAU into a comparative context with the potential value of data at other apparently-higher-priority CAUs in the NTS.

In our opinion the current level of problem identification in the Frenchman Flat CAU is not acceptable. Additional field data are needed simply to see whether problems exist or not. Given the current level of information, it is not possible to unequivocally determine the direction of groundwater flow, let alone whether any contaminant plumes have developed in the flow systems at the site. Current model predictions suggest that no such problems exist, but there is almost no field evidence to back up these claims. We know of no precedent where a no-further-action recommendation has been reached at a potentially-contaminated site without a much better understanding of the hydrogeological environment and some field confirmation of the model-generated predictions of contaminant distribution. In the initial phases of field study, we do not recommend a full "plume-chasing" exercise, simply some attempt at ballpark confirmation of the presence of contamination in the groundwater, or the lack thereof.

The current modeling approach is replete with assumptions. Examples include decreasing values of hydraulic conductivity with depth in the alluvium, complete aquitard continuity beneath the alluvium in the vicinity of the test areas, lower hydraulic conductivity in the cavity/chimney volume than in the surrounding alluvium, preferential distribution of retarding minerals in low-permeability deposits in the source area, and others. Field and laboratory measurements are needed to assess the validity of these assumptions. Current model predictions reflect these assumptions, and to the degree that they are not confirmed, confidence in the model predictions will suffer.

Given the current sparseness of the database, it has only been possible to carry out a relatively loose calibration of the flow model, and it has not been validated in any sense. More critically, the transport model has not been either calibrated *or* validated. Under the circumstances, we recognize that a full validation of the models is not possible. At best, we anticipate a limited verification of some of the more fundamental aspects of flow and transport. A minimal level of acceptable modeling practice requires at least some ballpark validation of predicted flow rates, flow directions, contaminant concentrations, and contaminant migration rates.

A partially-calibrated, unvalidated model prediction is unlikely to gain the confidence of the requisite target audiences. It is our opinion that collection of additional field data for the purposes of problem identification, assumption testing, and model validation, as outlined above, is necessary in order to build confidence in the DOE program within the technical community, regulatory agencies, and the public at large.

While the panel feels strongly about the need for scientific legitimacy, we also recognize the need to place decisions about additional data into a cost-benefit framework. To some extent, this has been done in the VOIA analysis that was carried out prior to the CAU-modeling step. However, it is the opinion of the panel that the VOIA was flawed on at least four counts. First, the uncertainty ranges used in the parameter-uncertainty analysis were too narrow. Second, the uncertainty analysis did not consider a full enough suite of alternative geological conceptualizations, especially those that might represent potential failure modes. Third, and perhaps most important, the VOIA did not carry its analysis through to consider the impact of uncertainty reduction on the costs of remedial action and/or long-term monitoring. And fourth, the VOIA did not provide any comparative context with other CAUs in the NTS.

The panel believes that the modeling effort should be carried out as a part of a larger integrated remedial-design framework that assesses the value of additional data collection activities in terms of the reduction of uncertainty that can be achieved, and the impact of such reductions on remedial design. There should be closer coordination of the modeling step and the VOIA step, with the latter based on a clearer definition of performance criteria, and defensible estimates of the costs of data-collection activities, remedial actions, long-term monitoring, and contingency actions in the event that performance criteria are not met.

4.2 Additional Data Needs

Building confidence in the evaluation of the Frenchman Flat CAU will require the collection of additional field and laboratory data. As outlined in Section 4.1, these data will help in defining the scope of the contamination problem, in testing assumptions about the hydrogeologic setting, and in model validation. The present database for Frenchman Flat is inadequate to answer the questions posed about the likely pattern of contaminant migration.

There are compelling needs for data to document the historical pattern of ground-water contamination in the vicinity of a few detonation sites. The Frenchman Flat (and possibly other CAUs) are somewhat unique in comparison to many other contamination sites. Beyond some awareness that sources exist, there is no information on local patterns of contaminant migration. Initially, some data are required to understand how radionuclides are spreading in the ground-water system. Ultimately, this information is needed to validate the source-modeling approaches developed by LLNL and to provide an indication that the IT flow and mass transport models have some connection to reality.

There is also a significant data deficiency relating to vertical and horizontal gradients and hydraulic conductivity values, particularly for the alluvium. These data are important in assessing horizontal and vertical fluxes (including recharge) and advective velocities. They also will help to verify or refute the present assumption of a decrease in hydraulic conductivity with depth in the alluvium. This assumption biases the model away from vertical flow.

The panel recognizes that the size of the CAU, the number of detonation sites, and the very deep and permeable LCA provide a unique challenge because of prohibitive costs that might be incurred in a deep-drilling and sampling program. Accordingly, we suggest a phased field approach with an initial (Phase I) program that involves the existing wells, available data, a few new test holes and a seismic survey. A considerable emphasis in Phase I would be in establishing the physical hydrogeologic framework, which would include hydraulic properties and flow patterns. Later phases involving more test holes would be predicated on the findings of improved modeling based on the new data and a defensible VOIA at the end of each phase. If the results from Phase I are consistent with the present conceptualization, additional fieldwork might not be necessary. If the new data were inconsistent with the present conceptualization, then, additional drilling might be required in a Phase II program to characterize the distribution of contaminants.

A Phase I program might include the following elements.

- *Two multilevel wells located in the north and south clusters of detonations at Frenchman Flats.* Each of these wells should be completed below the water table in the vicinity of a selected detonation site. Emphasis would be placed on drilling to depths of 350 m or shallower. The test holes would be located so as to test the present conceptualization of the hydrogeologic setting, and to answer questions about likely pathways of contaminant migration. Using multilevel sampling devices, it would be possible to estimate vertical gradients and local-scale hydraulic conductivity values. Significant vertical gradients and downward contaminant migration would suggest vertical leakage possibly caused by flow along faults, thinning of the confining beds, or localized zones of higher permeability in the confining beds. Evidence of eastward flow might suggest a pathway to the LCA east of the Rock Valley Fault.

  These new boreholes should be geophysically logged and, to the extent practical, fluid and solids samples should be collected for laboratory measurements. Water samples would be obtained for analysis of radionuclides, ^{14}C (in the organic fraction), tritium, stable isotopes, colloids and major ions. The solid samples would be collected to determine the mineralogy and to measure distribution coefficients for the key radionuclides and the relationship of these properties to the hydraulic conductivity.

- *Aquifer testing in the alluvium.* We recommend that aquifer testing in the alluvium be considered in each of the north and central test areas. To the extent possible, existing wells should be utilized, supplemented by the multilevel wells as observation points. These tests would be important in assessing bulk hydraulic properties and vertical to horizontal anisotropy ratios for the alluvium. Testing should be accompanied by groundwater sampling for chemical and isotopic analysis as described above, with samples obtained as a function of sampling depth.

- *A campaign involving Frenchman Flat and adjacent areas of the NTS to resample existing wells.* The panel suggests that all existing wells be sampled in order to provide waters for environmental isotope, ^{14}C (in the organic fraction) and major species analyses. Such data have been underutilized in the Frenchman Flat investigation and could be useful in verifying the Frenchman Flat hydrologic model.

- *Collect near-surface samples of rock and alluvium to determine mineralogical and surface properties*. The present understanding of the mineralogical and sorptive properties of alluvium and shallow bedrock is very limited. First, archived samples of the alluvium obtained from drillholes should be sought. Samples of unweathered fresh materials could be collected relatively inexpensively for laboratory study and analyses with a shallow drilling/sampling program. Data relating these properties to the hydraulic conductivity are needed, as the LLNL report argues that this relationship is important.

- *Sample and study the melt glass and the rock in the exchange volume.* Among the largest uncertainties in defining the hydrologic source term are the assumed surface area of the melt glass and the form of occurrence of radionuclides in the exchange volume, neither of which has been measured at the site. Glass surface area has been assumed from other studies. It is assumed that radionuclides in the exchange volume are only adsorbed. Melt glass and rock from the exchange volume should be sampled and subject to laboratory study to obtain site-specific information for source term modeling.

- *Reflection seismic surveying.* There is a need to determine geologic conditions in the subsurface in greater detail. At the present time, there is no basis for analyzing the possibility of hydraulic short circuits providing local connections between deep and shallow aquifers, and the presence or absence of various geologic units. Reflection seismic techniques would offer the best opportunity in this respect. Initially, we would propose a modest two-dimensional pilot study along three or four separate lines.

- *Outcrop studies and literature reviews of fault zones.* Studies are required to improve understanding as to the nature of fault zones. The fieldwork might look at the relative spacing of fault zones, the width of individual fault zones, and fault displacements. Similar data likely exists in relation to the Yucca Mountain Project that might be applied here.

It would be premature to specify what Phase II and subsequent investigative phases would look like. It is clear, however, that borehole investigations would be a significant component, given the relatively modest drilling in Phase I. The trigger for subsequent phases would be surprises that have relevance as far as possible radionuclide transport was concerned. These issues would be identified in a VOIA analysis that logically followed Phase I.

4.3 Alternative Modeling Strategies

It is clear from our earlier discussions that an appropriate modeling strategy must include the ability to assess uncertainties associated with all potential failure scenarios. The question of what constitutes a “failure” does not seem to have been carefully examined in the context of the

Frenchman Flat situation. If we conservatively assume that significant contaminant migration to the LCA represents a "failure", then the pertinent failure scenarios include horizontal contaminant migration through the alluvium toward the east where there are potential stratigraphic connections between the AA and the LCA, and vertical contaminant migration through the confining layer that separates the AA from the LCA beneath the source zones. Vertical migration routes might arise via faults, fracture zones, more-permeable sections in the confining layer, or zones of aquitard thinning in areas of block offsets. Current uncertainty analyses address the horizontal migration routes (albeit with parameter ranges that are thought by the panel to be too narrow), but not the vertical migration routes, which are considered by the panel to be of equal or greater importance.

Furthermore, it appears that the current CAU-modeling strategy is not well-suited to an assessment of the fault issue. It is true that in the current analysis a few alternative geologic models are assessed, but what is really required is a more systematic assessment of how the uncertainties associated with predictions of contaminant-migration distance are affected by such issues as fault spacing, and the hydraulic properties of faults and block-faulted confining units. The current finite-difference CAU-model does not allow adequate flexibility in the representation of fault locations. The grid spacing is too large, the averaging process too crude, and the process for setting up the grids for alternative fault densities too cumbersome.

It might be argued that if further uncertainty analyses are required, the preference would be to carry out the additional work with the existing CAU-scale model, perhaps using larger uncertainty ranges as suggested by the panel, and invoking a few more alternative geologic models. While this approach might improve the uncertainty analysis associated with the alluvium, it is not likely to suitably address the more important issue of potential vertical leakage through the confining layer. In addition, the present modeling approach cannot likely be modified to rectify errors related to source dilution and excess dispersion. Monte Carlo analyses will remain cumbersome within the present framework.

One step that could be taken for the CAU-scale modeling would involve abandoning the finite-difference approach, with its rectilinear grid, in favor of a finite-element (or finite-volume) approach that includes a flexible, unstructured grid that would allow a more realistic representation of discrete geologic features. Some finite-element codes also permit planar elements that are particularly well-suited to faults and fracture zones. The use of an automatic grid generator would ease the demands of setting up many alternative fault-spacing scenarios. We recognize that this option would represent a major undertaking at the Frenchman Flat CAU, but it might possibly be warranted, given the desire within the program for some degree of transferability from CAU to CAU.

Another option, which might seem more expeditious, would involve the conduct of a separate, smaller-scale, uncertainty-modeling analysis. This option would require the development and application of a local-scale model at one or both of the two Frenchman Flat test areas (northern and southern), for the purpose of carrying out sensitivity and Monte Carlo analyses to assess key uncertainties. Of particular interest would be an analysis of the potential relationships between fault-controlled failure scenarios and contaminant-boundary uncertainty. These uncertainty calculations could be based on flow-and-particle-tracking calculations, possibly carried out in two-dimensional vertical cross-sections, with numerical solutions that use a flexible-gridding approach. They would encompass a region of flow several hundred meters to a couple of kilometers in lateral extent, with depth extending from the AA to at least the base of the confining layer at the top of the LCA. They would allow more complete assessment of direct fault conduits, short-circuit paths created by fault offsets, and potential pathways through high-permeability facies of the confined aquifer. Simulations would be constrained by the need to honor the observed head drop between the AA and the LCA. Unlike the larger-scale models, the local-scale models would be of sufficient simplicity to facilitate a variety of uncertainty analyses. The model strategy should be designed to produce output that better clarifies the uncertainty associated with the geologic setting.

The panel finds the LLNL source modeling approach to be attractive in its ability to represent many of the fundamental physical and chemical processes involved in release of radionuclides from a detonation site. However, there are concerns about the fundamental limitations imposed by approximations in the chemical modeling codes (see Subsection 3.4.5 c, d and e) and the neglect of internal mixing in the aquifer (see Subsection 3.4.3). The importance of these limitations needs to be thoroughly evaluated by appropriate comparisons with other codes and approaches. If the LLNL source modeling approach is to become a practical predictive tool, additional data will be required to determine the model parameters. The possibility of using concentrations of additional reactive species measured during the CAMBRIC radionuclide migration test to evaluate the predictions of the LLNL model should be explored (see Subsection 3.4.5 e).

Lastly, the results of these alternative modeling strategies would provide input to a more defensible VOIA, along the lines laid out at the end of Section 4.1, above.

4.4 Summary of Recommendations

(a) The panel believes that it will be necessary to collect additional data for the Frenchman Flat CAU through field work and/or laboratory analysis, and to further assess site uncertainties through alternative modeling strategies. We envisage an integrated, iterative, phased, model/data-collection strategy, that reaches closure through a value-of-information analysis carried out at the end of each step of the phased field program. The VOIA must be based on clearly-defined performance criteria, and an uncertainty analysis that clearly relates uncertainty in the prediction of the contaminant boundary to the uncertainty associated with all feasible failure scenarios.

(b) There are two aspects to the rationale used to support the need for additional field and/or laboratory measurements in the Frenchman Flat CAU. The first recognizes the need for scientific legitimacy in the modeling process. The second recognizes the need to place the modeling effort in a decision-support framework. There are four elements to the scientific legitimacy rationale: (1) the need for improved problem identification, (2) the need to test assumptions used in the modeling strategy, (3) the need to partially validate model predictions, and (4) the need to build confidence in the DOE program in the technical community, the regulatory agencies, and the public at large. There are two additional elements associated with the decision-analysis viewpoint: (5) the need to place the collection of additional data into a cost/benefit framework, and (6) the need to place the value of additional data at the Frenchman Flat CAU into a comparative context with the potential value of data at other apparently-higher-priority CAUs in the NTS. With respect to item (4), it is the opinion of the panel that a politically-acceptable level of confidence is unlikely to be reached without some degree of field validation of model predictions at Frenchman Flat.

(c) The panel recommends consideration of the following data-collection activities as part of the first phase of the field program:

- *Two multilevel wells located in the north and south clusters of detonations at Frenchman Flats*
- A*quifer testing in the alluvium*
- *A campaign at Frenchman Flat and adjacent areas of the NTS to resample existing wells*
- *Near-surface samples of rock and alluvium to determine sorptive and reactive properties*
- *Sample and study the melt glass and the rock in the exchange volume.*
- *Reflection seismic surveying*
- *Outcrop studies and literature reviews of fault zones*

(d) The panel recommends the development and application of a local-scale uncertainty-modeling exercise at one or both of the northern and southern Frenchman Flat test areas. These uncertainty calculations could be based on flow-and-particle-tracking calculations, possibly carried out in two-dimensional vertical cross-sections, with numerical solutions that use a flexible gridding approach. They would be of sufficient simplicity to facilitate a variety of uncertainty analyses designed to produce a more complete assessment of potential vertical contaminant-migration routes across the block-faulted confining layer that separates the AA from the LCA beneath the test areas.

(e) There is unanimity among panel members for an immediate start on the collection of the less-expensive field data. However, there is a spectrum of views with respect to the subsequent ordering of events. Some panel members feel that the full Phase-I data collection program outlined in Section 4.2 is an absolute minimum requirement, and that it should precede the alternative modeling activities proposed in Section 4.3 (including a revised VOIA). Some feel that the two activities should proceed simultaneously. And some feel that the more-expensive data-collection activities should await the results of an improved VOIA. The latter position holds that a more defensible VOIA might lead to a field-data-collection program in the Frenchman Flat CAU that is either more extensive or more limited than the full Phase-I program outlined in Section 4.2.

CHAPTER 5

TRANSFERABILITY

In this chapter, we address the potential for transferability of the modeling strategy used in the Frenchman Flat CAU to other CAUs on the Nevada Test Site. We note that in the discussion of the transferability issue at the meeting on May 21, reference was made to the appropriateness of transfer from both a "technical" perspective and from a "regulatory" perspective. The following comments refer only to the technical perspective.

5.1 The Transferability Issue

The "modeling strategy" under discussion in this section is the one described in the three-volume model-documentation package for the Frenchman Flat CAU. It consists of the following steps carried out at CAU-scale: (1) assessment and interpretation of the available geologic, hydrogeologic, and geochemical data for the CAU, (2) development of a hydrostratigraphic model that delineates the three-dimensional distribution of hydrostratigraphic units and structural features in the CAU, (3) discretization of the conceptual hydrostratigraphic model into a horizontally-layered, three-dimensional grid of orthogonal nodal blocks, (4) establishment of a modeling framework that includes a steady-state, finite-difference, numerical flow model that solves the groundwater flow equation, and a transient, finite-difference, numerical transport model that solves the advection-dispersion-retardation-decay equation, (5) assignment of representative hydraulic and transport parameters to the nodal blocks, (6) assignment of boundary conditions along the lateral boundaries of the CAU-scale flow model on the basis of output from the regional-scale flow model, (7) trial-and-error calibration of the CAU-scale flow model, using available hydraulic-head data as the calibration targets, with hydrogeologic parameters, recharge distribution, and alternative hydrostratigraphic configurations as calibration parameters, and keeping boundary-condition consistency through iterative CAU-scale/regional-scale simulations, (8) performance of a sensitivity analyses with the flow model to changes in hydraulic parameters, and to alternative hydrostratigraphic configurations, (9) assignment of a hydrologic source term at the locations of underground nuclear tests, based on unclassified radiologic source data, and the output from the uncalibrated LLNL source-term model, (10)prediction of radionuclide-concentration-distributions and plume-dimensions for selected radioisotopes as a function of time, using the uncalibrated transport model, in particular, the location of a specified contaminant boundary of regulatory importance, (11) carrying out uncertainty analyses, using a Monte-Carlo-simulation approach, to assess the uncertainty that results in the plume dimensions in response to uncertainties in hydraulic and transport parameters, and due to alternative hydrostratigraphic configurations, (12) using the results of the uncertainty analysis, to predict the maximum extent of the regulatory contaminant boundary after a specified time at a specified level of confidence, and (13) carrying out a value-of-information analysis to determine whether the collection of additional data would lead to a cost-effective and beneficial reduction in uncertainty.

We assume that the term "transferability" implies that the codes and modeling strategy developed for Frenchman Flat could be used directly in the other CAUs, changing only the geologic model, the parameter values, the boundary conditions, and the source-term parameters, but not the underlying mechanisms of radionuclide reaction chemistry, flow and transport, or the methodologies used for discretization, calibration, simulation, sensitivity analysis, or uncertainty analysis.

It is perhaps appropriate to first ask the question whether the panel knows enough about the other CAUs to even assess this issue. It must be emphasized that we have not been provided with sufficient material to assess the appropriateness of the full UGTA program, nor have we been asked to do so. Our charge is limited to a review of the modeling efforts at Frenchman Flat. We have not been asked to review any other aspects of the corrective-action program at Frenchman Flat, nor have we been asked to review conditions at any of the other CAUs. We have been provided with detailed descriptions of the Frenchman Flat CAU, but not of any of the other CAUs. Having said this, it is only fair to recognize that most of the panel members have some knowledge of the other CAUs from their reading of the regional-flow-and-transport-modeling report, from past involvement on the NTS, or from involvement on the Yucca Mountain Project. However, it must be recognized that this knowledge is of a general nature, and our comments on transferability must therefore also be of a general nature. There may be details associated with the other CAUs that are not known to us, which could impact the transferability issue.

There are several questions that need to be answered within the context of the transferability issue. First, what are the types of differences that might exist between the Frenchman Flat CAU and the other CAUs? Second, given these differences, is it reasonable to expect that a single modeling strategy might be appropriate for all the CAUs at the NTS? Third, is the modeling strategy that has been used for the Frenchman Flat CAU the appropriate one for Frenchman Flat itself, and if it is not, what changes would make it more appropriate? Fourth, given the answers to the first three questions, what can we say about the transferability of the modeling strategy from the Frenchman Flat CAU to the other CAUs, either in its Frenchman Flat form, or in some similar but more appropriate form? The following sections address these questions.

5.2 Differences between Frenchman Flat CAU and Other CAUs on the NTS

Possible differences between the Frenchman Flat CAU and the other CAUs on the NTS lie in (1) the host geology, (2) the anticipated mechanisms of transport, (3) the number of tests in a CAU, (4) the yields of the tests, and their radionuclide inventories, (5) their depth of burial, and relation to the water table, (6) the nature of the hydrologic source term, (7) expected radionuclide attenuation reactions in surrounding rocks, and (8) the location of the tests relative to potential receptors.

Many of the other test sites on the NTS are located in fractured rock, rather than alluvium as was the case in Frenchman Flat. The only other tests at the NTS that were performed in alluvium took place in the Yucca Flats CAU. Four of the other five CAUs are in volcanic rocks and one (Climax) is in granite. On Pahute Mesa, where we understand the next CAU-scale modeling is planned, the host geology will involve fractured volcanic rocks. The impact of a nuclear detonation in fractured rock could be entirely different than that in alluvium. Without having studied the question in detail, we suspect that a much different cavity/chimney complex may develop in fractured rock than in alluvium, given the same test strength. When one factors in the presence of existing fractures in the surrounding rock, and new fractures introduced to greater distance by the detonation, we envisage a much larger "exchange volume" at the source in fractured rock than in alluvium. Without further explanation, we are unsure if the "stress-cage" effect mentioned at the May 21 meeting has significant potential to mitigate these conditions.

The relative importance of the mechanisms of contaminant transport in groundwater is different in fractured rocks than in alluvium. It is our opinion that the potential for pressure-driven "prompt injection" of radionuclides to considerable distances is much greater in fractured rock than in alluvium. In addition, the presence of well-developed fractures or fracture-zones can create high-permeability preferential pathways that strongly influence the rates and directions of advective flow. Porous-media assumptions may not be appropriate, especially near the source zone. The underlying causes of dispersion may be different. Matrix diffusion may take on greater importance.

Colloid transport in fractures may be of particular importance, especially for Pu, Eu, and Am. No colloid transport model was developed for the Frenchman Flat assessment. It was presumably assumed that colloids would be filtered by the alluvium. Effective filtration is unlikely at the volcanic-rock sites. For example, observed Pu migration 1.3 km from the BENHAM site is thought to be a result of colloidal transport (Kersting et al., 1999). A colloid transport model may have to be developed to allow prediction of radionuclide transport from the other CAUs.

Geochemical interactions are also likely to be different in fractured rocks than in alluvium. For example, the impact of dissolution or precipitation of minerals on flow and transport may be greater in fractured rocks. These differences may require different modeling approaches. It is unlikely that they can be handled by simply changing the parameter values in a model developed for an alluvial site.

The Frenchman Flat CAU hosted the least number of tests, and the tests that were carried out there were among the lowest yield tests in the NTS. There is thus greater potential for larger and more-disturbed cavity/chimney zones around many of the tests in other CAUs, and also a greater potential for possible interactions between more-closely-spaced test sites, than was the case in Frenchman Flat. Different depths of burial can affect subsidence, and consequently chimney and exchange volumes. The fraction of tests detonated above or below the water table can influence the saturated- and unsaturated-zone partitioning of the source term.

When it comes to the source term itself, we are in agreement with the LLNL scientists, who state that transferability of the source-term modeling to other CAUs "may not be possible because of different classification issues, different radionuclide inventories, dissimilar flow environments, and the fact that many key chemical and flow processes are mathematically nonlinear and do not scale with inventory." In particular, it is unlikely that the radiologic and hydrologic source terms are directly scalable. There is evidence that these source terms are not simply proportional among different tests.

The rate of glass dissolution, which controls releases of most of the radionuclides to the groundwater, is proportional to temperature. After the detonation in small tests such as CAMBRIC, glass and cavity temperatures rapidly return to near ambient (~25 ^{o}C), making reasonable the assumption of 25 ^{o}C for modeling purposes. However, after larger tests glass temperatures may remain elevated for long periods, increasing glass solubility and increasing the rate of dissolution of the glass and of other minerals into the groundwater. This will increase early time radiologic doses in the groundwater. It would be useful to estimate the possible importance of elevated temperatures on the hydrologic source term at CAMBRIC so as to at least roughly estimate the possible importance of temperature effects for larger tests at the other CAUs.

Lastly, with respect to the source term, we note again the limited availability of laboratory or field data with which to validate source-term model predictions, and the further limitations introduced by the classified nature of much of the inventory data. These limitations, even taken on their own merits without reference to all the other issues raised above, make the model predictions and methods at CAMBRIC of questionable value for other CAUs.

5.3 Assessment of Transferability

Given these differences in the strength of the tests, the source-term inventories, the host geology, and the mechanisms of transport, the panel is of the opinion that it is unlikely that a single modeling approach will be appropriate for all the CAUs on the NTS. This is particularly true for the hydrologic source term, where the greatest impact of the differences in source strength and host geology is felt. We concur with the opinions expressed in the LLNL report that the differing radionuclide inventories between tests, coupled with the presence of strongly non-linear transport processes, preclude the direct transferability of the source-term and near-field components of the modeling framework. In the far-field, it is somewhat more likely that a modeling framework such as that established for Frenchman Flat could be used directly elsewhere, with the differences handled solely as changes in parameter values. Even here, however, the huge differences in migration distances indicated by the regional model (cf.Figure7-25 and Table 7-11 of the regional-flow-and-transport report, where some Pahute Mesa sources are predicted to migrate almost 1,000 times farther than those in Frenchman Flat) may reflect different mechanisms of transport, that require a different modeling approach.

On a more philosophical note, the experience of the panel members over many years has led them to realize that every site is different. It is seldom the case that a “standard” approach can be applied directly. There is almost always some aspect of the site geology, source geochemistry, regulatory environment, or whatever, that makes the site unique, and leads to the need for special treatment in some aspect of the modeling endeavor. Proof of the unique nature of individual sites can be seen in the Frenchman Flat application itself. We suspect that the modeling framework developed for Frenchman Flat was actually developed with an eye to the need for later applications of greater complexity elsewhere. If one accepts the geological model apparently accepted by the Frenchman Flat modelers (with flow and transport from the test sites limited to the alluvium due to an extremely low horizontal gradient, an assumed decrease in K with depth in the alluvium, small vertical-to-horizontal hydraulic conductivity ratios, and the presence of a continuous low-permeability layer separating the Alluvial Aquifer from the Lower Carbonate Aquifer), then there was really no need to invoke the complex numerical model. They could easily have shown with simple analytical scoping calculations that the maximum extent of the contaminant boundary would lie within a few hundred meters of the sources, even under conditions of considerable uncertainty in parameter values. At this site, the key unresolved issue is whether there might be some geological configuration that could produce a conduit between the AA and the LCA, and this type of uncertainty could also probably have been addressed without the full modeling effort. In other words, the unique setting at Frenchman Flat would itself have led to a different modeling framework, had it been the only CAU-scale site in view. In fact, the framework put in place at Frenchman Flat may well be more suitable for some of the other CAUs than it was for the Frenchman Flat CAU. However, it will always be subject to the need for adaptation to the special conditions of each individual CAU, perhaps for one of the reasons mentioned in the preceding paragraphs, or perhaps for some reason not yet recognized.

As a bottom line, then, the panel sees the modeling strategy as being transferable from CAU to CAU only in the broadest terms. Certainly, the process will always involve the development of a geologic model and its interpretation for use in flow and transport calculations. There will always be the need for conceptual-model development, code selection or development, some form of discretization, calibration, simulation, verification, sensitivity analysis, and uncertainty analysis. However, different CAUs might require different emphasis when it comes to the relative importance of hydrostratigraphic layers vis-a-vis structural features such as faults and fracture zones, and this emphasis can exert considerable influence in selecting the most appropriate modeling framework. Porous-media assumptions may not be appropriate in all cases; in some cases dual-continuum and/or preferential-pathway calculations may be needed. Some sites may require numerical modeling; others may be more suited to analytical modeling. If numerical modeling is warranted, some sites might benefit from finite-element rather than finite-difference formulations. The relative importance of the various mechanisms of transport may vary significantly from site to site, with implications for modeling methodology. The nature and importance of the geochemical processes may differ from site to site, with further implications. The nature of the uncertainties can control the type of uncertainty analysis that is most appropriate. In some cases, a hypothesis-testing approach may have more value than a traditional geostatistical approach.

In summary, the panel can buy into the transferability of the scientific and engineering thinking that underlies groundwater modeling efforts to date, but not into a direct transfer of the codes and modeling strategy used at the Frenchman Flat CAU.

CHAPTER 6

APPENDICES

6.1 List of References

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6.2 Biographical Sketches of Panel Members

Dr. R Allan Freeze is President of R. Allan Freeze Engineering Inc. based in White Rock, BC, Canada. He consults widely for private-sector clients and government agencies on projects involving groundwater supply, groundwater contamination, geotechnical seepage and nuclear waste disposal. Prior to establishing his consulting practice, Allan Freeze worked for Environment Canada in Calgary, AB, the IBM Thomas J. Watson Research Center in Yorktown Heights, NY, and the University of British Columbia in Vancouver, BC. During his 18-year career at U.B.C., he was Director of the Geological Engineering Program for six years and Associate Dean of Graduate Studies for three years. During his academic career Allan Freeze published over 100 research papers. He has received the Horton and Macelwane Awards from the American Geophysical Union, the Meinzer Award from the Geological Society of America, the Hubbert Award from the National Groundwater Association, and the Theis Award from the American Institute of Hydrology. He is a Fellow of the Royal Society of Canada. He is a former Editor of the journal Water Resources Research, and a former President of the Hydrology Section of the American Geophysical Union. He is co-author, with John Cherry, of the widely used textbook "Groundwater."

Dr. Lynn W. Gelhar is Professor of Civil and Environmental Engineering at the Massachusetts Institute of Technology; he previously taught at New Mexico Institute of Mining and Technology where he headed the graduate program in hydrology. Prior to that he taught at MIT and the University of Wisconsin where he received a doctorate in 1964. His recent research activities have focused on stochastic approaches to understanding the effects of subsurface heterogeneity for unsaturated flow, fractured media, chemically heterogeneous media, variable viscosity fluids, in situ biodegradation, and multiphase flow, using stochastic theories, controlled field experiments, and high-resolution computer simulations. He is recognized as a leading authority on the use of stochastic methods in subsurface hydrology. In 1982, he received the American Geophysical Union's Horton Award in recognition of his pioneering work in stochastic subsurface hydrology, and in 1983 was elected a Fellow in the American Geophysical Union, cited particularly for work in stochastic methods. In 1987, he was the recipient of the O. E. Meinzer Award by the Geological Society of America for three papers dealing with stochastic methods. He is the author of the advanced textbook entitled *Stochastic Subsurface Hydrology*, published in 1993 by Prentice-Hall, and has authored over 140 research publications. He has extensive consulting experience with government and industry on aspects of groundwater hydrology, dealing particularly with problems of hazardous and radioactive waste disposal. He has over two decades of experience on aspects of subsurface hydrology relating to problems of radioactive waste disposal in the U. S. and abroad. He has served on several multidisciplinary review teams, including groups reviewing environmental aspects of the Hanford site in Washington, the WIPP radioactive waste disposal site in New Mexico, and the Nevada Test Site and the Yucca Mountain site in Nevada.

Dr. Donald Langmuir is President of Hydrochem Systems Corporation in Golden, CO, received his BA (with honors), and his MA and PhD degrees from Harvard University. He served as a geochemist with the Ground Water Branch of the U.S. Geological Survey's Water Resources Division, and taught and conducted research at the Pennsylvania State University where he was appointed full professor in 1976. He has also held temporary teaching or research positions at Rutgers University, the Desert Research Institute, and the University of Sidney, Australia. Since 1978, Dr. Langmuir has been professor at the Colorado School of Mines, performing research in environmental geochemistry, and teaching graduate level courses in introductory geochemistry and environmental chemistry, and advanced aqueous geochemistry. Dr. Langmuir has authored more than 150 papers, abstracts and books, including the advanced textbook 'Aqueous Environmental Geochemistry', published in 1997 by Prentice Hall. He has been elected a fellow of the American Association for the Advancement of Science, and of the Mineralogical Society of America. He was associate editor of *Geochimica et Cosmochimica Acta*, the journal of the Geochemical Society, and chaired the Environmental Committee of the Society. Dr. Langmuir has served on or chaired about twenty expert panels assisting organizations including the Environmental Protection Agency, the Nuclear Regulatory Commission, and the Department of Energy and its national laboratories. In 1989, Dr. Langmuir was nominated by the National Academy of Sciences and appointed by President Reagan to serve on the U.S. Nuclear Waste Technical Review Board. He was reappointed to that position by President Bush in 1992, and served until 1997. Currently, Dr. Langmuir is a senior advisory scientist at Los Alamos National Laboratory, and a member of the Radiation Advisory Committee of the Environmental Protection Agency's Science Advisory Board. As a consultant, Dr. Langmuir has worked on about 80 projects for clients in 24 states, and in Canada, Sweden, France, Australia, Japan, and the People's Republic of China. He has extensive experience solving problems related to surface and groundwater pollution caused by disposal of municipal, industrial and nuclear wastes, and by mining, including mine tailings disposal, tailings ponds, mine pit lakes, and acid mine drainage. Dr. Langmuir has served as an expert witness in numerous court cases.

Dr. Shlomo P. Neuman is Regents Professor of Hydrology and Water Resources at the University of Arizona in Tucson. Dr. Neuman's research group presently conducts field, theoretical, and computational investigations of flow and transport through unsaturated fractured tuffs at the Apache Leap Research Site near Superior, Arizona. 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 soil and rock properties vary randomly in space, and with the scale of observation; development of computational algorithms and computer programs to predict subsurface flow, and solute concentrations, under uncertainty, and to assess the associated prediction errors; estimation of flow and transport model parameters under uncertainty; and use of such computational models to help assess subsurface contamination, identify contaminant sources, design groundwater monitoring networks, and aid the design of remedial operations. Professor Neuman has summarized his scientific contributions in over 225 professional papers, books and reports. His varied professional activities include service on the Scientific Review Group of the Canadian high-level nuclear waste program. For his professional contributions and service, Professor Neuman has received the R.E. Horton Award from the American Geophysical Union, the O.E. Meinzer Award from the Geological Society of America, the M.K. Hubbert

Award from the Association of Groundwater Scientists and Engineers, the C.V. Theis Award from the American Institute of Hydrology, and a certificate of appreciation by the U.S. Department of Agriculture; has been elected member of the National Academy of Engineering, Fellow of the American Geophysical Union, and Fellow of the Geological Society of America; and has been named honorary professor of Nanjing University in China, Birdsall Distinguished Lecturer by the Geological Society of America, and fourth Langbein Lecturer in Hydrology by the American Geophysical Union.

Dr. Frank W. Schwartz joined the Ohio State University in 1988 as the Ohio Eminent Scholar in Hydrogeology. He was formerly a Professor of Geology at the University of Alberta. Frank is the author of more than 120 publications and is known internationally for his work on field and theoretical aspects of mass transport, contaminant hydrogeology, and ground-water geochemistry. He is co-author of the textbook *Physical and Chemical Hydrogeology* (1990, 1998). In recognition of his contributions to hydrogeology, he was named as a co-recipient of the prestigious O.E. Meinzer Award in 1984, a co-recipient of the Excellence in Science and Engineering Award in 1991, and the King Hubbert Science Award in 1997. He was elected as a Fellow of the American Geophysical Union in 1992. Frank is an Editor and Chief of the *Journal of Contaminant Hydrology*. In addition to teaching and research, Frank acts as a consultant to government and industry, and in various advisory capacities. He has worked extensively on problems of nuclear-waste disposal in the WIPP and Yucca Mountain Programs, the Martinsville site evaluation in Illinois, the AECL Program, and the Stripa International Project. He has served on a variety of expert panels of the National Research Council and chaired a committee charged with reviewing the applicability of contaminant transport models to contemporary problems in hydrogeology.

Dr. Dennis Weber received his Ph.D. in physics from the University of Idaho, after which he taught physics and solar energy at the University of Nevada. Since 1984, he has performed research at the Harry Reid Center for Environmental Studies on the application of geophysics, geostatistics, groundwater modeling, and vapor transport modeling to various environmental problems. He has spent the last four years investigating environmental contamination with regards to evaluating risk to human health and, specifically, developing cost-effective methods to characterize radiological surface soil contamination at the Nevada Test Site. His most recent research concerns probabilistic risk assessment of groundwater contamination at the Nevada Test Site.