ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE: UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS

Division of Waste Management
Office of Nuclear Material
Safety & Safeguards
U.S. Nuclear Regulatory Commission

Revision 2
June 1999

Volume I

PART-1

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Change History of "Issue Resolution Status Report, Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions"

Revision	Section	Date	Modification
Rev. 2	3.1	8/99	Material imported from original IRSR on climate issues (NRC, 1997a)
Rev. 2	3.2	8/99	Material imported from original IRSR on climate issues (NRC, 1997a); added note that water-table rise could increase lengths of flowpaths in valley-fill aquifer
Rev. 2	Section 4	8/99	All previous color figures changed to black & white
Rev. 2	4.1	8/99	Material imported from original IRSR on climate issues (NRC, 1997a)
Rev. 2	4.1.1 & 5.1.2	8/99	Acceptance criteria streamlined and simplified
Rev. 2	4.2	8/99	Material imported from original IRSR on climate issues (NRC, 1997a)
Rev. 2	4.2.1 & 5.2.2	8/99	Acceptance criteria streamlined and simplified
Rev. 2	4.2.2.2	8/99	Added info from Nye Co. drilling program that shows depth to groundwater at two former paleospring deposits; also added discussion about Devils Hole
Rev. 2	4.2.2.2	8/98	Updated Table 2 to include Nye County well data
Rev. 2	4.3.1 & 5.3.2	8/99	Acceptance criteria streamlined and simplified
Rev. 2	4.3.2	8/99	New discussion and new Figure 2 added and subsequent figures were renumbered (revised map of estimated shallow infiltration at YM - supercedes Figure B-2 in attachment E)
Rev. 2	4.4.1 & 5.4.2	8/99	Acceptance criteria streamlined and simplified
Rev. 2	4.4.2.4	8/99	Added geochemical discussion and quotes from Paces et al. (1998b)
Rev. 2	4.4.2.5	8/99	Added discussion (under isotopes) about things that can influence groundwater isotopic interpretation
Rev. 2	4.4.2.5	8/99	Added discussion (under chloride mass balance) about influence of climate change and the drying of playa lakes

Rev. 2	4.4.2.7	8/99	Added climatic discussion and cited Tyler et al. (199[illegible] Phillips (1994)
Rev. 2	4.4.2.9	8/99	Added isotopic discussion, and noted that data from well WT-24 shows the so-called "large hydraulic gradient" to be less steep than previously thought
Rev. 2	4.5.1 & 5.5.2	8/99	Acceptance criteria streamlined and simplified
Rev. 2	4.5.2.6	8/99	Added discussion about aquifer anisotropy; minor revisions to discussion on water levels
Rev. 2	4.5.2.6	8/89	Under large hydraulic gradient, revision to discussion about well WT-24
Rev. 2	4.5.2.6	8/89	Under moderate hydraulic gradient, revised discussion about well SD-6 (now drilled), and recent penetration of Solitario Canyon Fault by east-west drift
Rev. 2	4.5.2.6	8/89	Revised discussion of vertical hydraulic gradients
Rev. 2	4.5.2.6	8/89	Former Figure 10 changed to Figure 11, and vice versa; Figure 11 now incorporates Nye County water-level data
Rev. 2	4.5.2.14	8/89	Added discussions about D'Agnese, et al. (1997a), Czarnecki, et al. (1997), and subsection titled "TSPA f[illegible] the VA approach to saturated zone flow and transpor
Rev. 2	4.5.2.15	8/89	Added and revised material to subsection on dispersion
Rev. 2	4.5.2.16	8/89	Added material from Nye County program and discussion about aquifer anisotropy; also added new subsection titled "heterogeneity and flow channelization"
Rev. 2	4.6.5	8/89	Added some material about matrix diffusion in valley fill
Rev. 2	5.1 to 5.6	8/99	Acceptance criteria have been streamlined and revised, and discussions updated and revised based on VA review and preliminary review of new Nye County well data
Rev. 2	5.7	8/99	Introduction to this section has been revised and now includes a table that summarizes subissue resolution
Rev. 2	Former Appendix E	8/99	Eliminated and spliced into main report
Rev. 2	Former Appendix F	8/99	Now appendix E

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LIST OF ACRONYMS AND ABBREVIATIONS

>	Greater Than
%	Percent
~	Approximately
$\delta^{13}C$	Delta Carbon 13
$\delta^{18}O$	Delta Oxygen 18
δD	Delta Deuterium
σ	"Satiated" Matrix Saturation
^{14}C	Carbon 14
^{18}O	Oxygen 18
1D	One Dimensional
2D	Two Dimensional
^{36}Cl	Chlorine 36
3D	Three Dimensional
^{3}H	Tritium
$^{87}Sr/^{86}Sr$	Strontium 87 and Strontium 86 Ratio
ACNW	Advisory Committee on Nuclear Waste
acre-ft/yr	Acre-Feet Per Year
acre-ft	Acre-Feet
AEC	Atomic Energy Commission
ALTS	Apache Leap Test Site
AULG	Affected Units of Local Government
BRF	Bow Ridge Fault
Ca^{+2}	Calcium Ion
CFu	Crater Flat undifferentiated
CHn	Calico Hills non-welded
CH_{nv}	Calico Hills non-welded vitric
Cl^{-}	Chloride Ion
CNWRA	Center For Nuclear Waste Regulatory Analysis
DCAGW	Dose Conversion Analysis for Groundwater
DHW	Drill Hole Wash
DKM	Dual-Permeability Model
DLS	Detailed Line Survey
DOE	U.S. Department of Energy
DVGFS	Death Valley Groundwater Flow System
ECM	Equivalent Continuum Model
FEHMN	Finite Element Heat Mass Nuclear
ft	Feet
ft sq Per day	Feet Squared Per Day
ft/day	Feet Per Day
$ft^3/d/m$	Cubic Feet Per Day Per Meter
FWP	Field Work Package
FY	Fiscal Year
gal	Gallon(s)
GDF	Ghost Dance Fault
GFM	Geologic Framework Model
GMWL	Global Meteoric Water Line
gpm	Gallons Per Minute
GWSI	Ground Water Site Inventory

HCO_3^-	Bicarbonate Ion
HLW	High Level Waste
hr	Hour(s)
IRSR	Issue Resolution Status Report
K^+	Potassium Ion
KESA	Key Elements of the Subsystem Abstraction
km	Kilometer(s)
K_{sat}	Saturated Hydraulic Conductivity
KTI	Key Technical Issue
ky	Thousand Years
kya	Thousand Years Ago
LBNL	Lawrence Berkeley National Laboratory
m/m	Meter(s) Per Meter(s)
m	Meter(s)
m/d	Meter(s) Per Day
m/s	Meter(s) Per Second
M&O	Management and Operator
m^2	Square Meter(s)
m^2/d	Square Meter(s) Per Day
m^2/s	Square Meter(s) Per Second
m^3/yr	Cubic Meter(s) Per Year
m^3	Cubic Meter(s)
Ma	Million Years Ago
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
mg/L	Milligrams Per Liter
Mg^{+2}	Magnesium Ion
mm/yr	Millimeter(s) Per year
nrem/yr	Millirem Per Year
msl	Mean Sea Level
Na^+	Sodium Ion
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
NV	Nevada
NWIS	National Water Information System
NWTRB	Nuclear Waste Technical Review Board
PTn	Paintbrush Tuff non-welded
QA	Quality Assurance
RT	Radionuclide Transport
RTTF	Residence-Time Transfer Function
SCA	Site Characterization Analysis
SCF	Solitario Canyon Fault
SDS	Structural Deformation and Seismicity
SiO_2	Silicon Dioxide
SMOW	Standard Mean Ocean Water
SNL	Sandia National Laboratory
SP	Study Plan(s)
SRP	Standard Review Plan(s)
SZFT	Saturated Zone Flow and Transport
Tac	Calico Hills Formation
Tacbt	Bedded Tuff of Calico Hills Formation

TBD	To Be Determined
TBM	Tunnel Boring Machine
TCw	Tiva Canyon welded
TEDE	Total Effective Dose Equivalents
TOP	Technical Operations Plan
TPA	Total System Performance Assessment
TSPA-VA	Total System Performance Assessment - Viability Assessment
TSw	Topopah Spring welded
USFIC	Unsaturated And Saturated Flow Under Isothermal Conditions
USGS	United States Geological Survey
UZ	Unsaturated Zone
UZFLOW	Unsaturated Zone Flow
UZFT	Unsaturated Zone Flow and Transport
V/Z	Vitric/Zeolitic Transition
VA	Viability Assessment
WP	Waste Package
YM	Yucca Mountain
yr(s)	Year(s)
°C	Degree(s) Centigrade
°F	Degree(s) Fahrenheit
μm	Micrometer(s)

ACKNOWLEDGMENTS

This report has been prepared jointly by staff from the U.S. Nuclear Regulatory Commission and the Center for Nuclear Waste Regulatory Analyses (CNWRA). Primary authors of the report are, in alphabetical order, Amit Armstrong, Jeff Ciocco, Neil Coleman, David Farrell, Randall Fedors, Latif Hamdan, Debra Hughson, Stuart Stothoff, David Turner, James Winterle, and Gordon Wittmeyer. The authors offer special thanks to David Brooks, Budhi Sagar, and English Pearcy for their excellent reviews.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: NRC and CNWRA-generated original data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance (QA) Manual. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: The TPA Version 3.1.1 code was developed using the procedures described in CNWRA Technical Operating Procedure, TOP-018, which implements the QA guidance contained in the CNWRA QA Manual. The code was used to perform the sensitivity studies described in Section 3.

INTERNET WEBSITES

The reader can find informative discussions about the Yucca Mountain Project by visiting internet web sites and associated links. A partial list is provided below. The U.S. Nuclear Regulatory Commission (NRC) web site provides general information about agency programs and nuclear wastes. The U.S. Nuclear Waste Technical Review Board (NWTRB) website in particular provides many additional important links.

U.S. Nuclear Regulatory Commission	http://www.nrc.gov http://www.nrc.gov/ACRSACNW/
U.S. Department of Energy (DOE)	http://www.ymp.gov [and] http://www.rw.doe.gov
U.S. Nuclear Waste Technical Review Board	http://www.nwtrb.gov/
Nevada Nuclear Waste Project Office	http://www.state.nv.us/nucwaste/
Nye County, Nevada	http://www.nyecounty.com/
Los Alamos National Laboratory	http://ees13.lanl.gov/!ees-13y.htm
Lawrence Livermore National Laboratory	http://energy.llnl.gov/Yucca.html
Earnest Orlando Lawrence Berkeley National Laboratory	http://www-esd.lbl.gov/NW/yuccamtn.html
Sandia National Laboratories	http://ntp.nwer.sandia.gov/nwmp/ymp.htm
U.S. Environmental Protection Agency	http://epa.gov/rpdweb00/yucca.index.html
U.S. Geological Survey	http://nevada.usgs.gov/doe_nv/index.htm

'.0 INTRODUCTION

Figure 1 (DOE, 1997a, p. 10) shows the location of the Yucca Mountain (YM) site, about 100 miles northwest of Las Vegas, NV. The site is currently being studied as a possible location for the permanent disposal of high-level nuclear waste (HLW). One of the primary objectives of NRC's refocused prelicensing program is to focus activities on resolving the 10 key technical issues (KTIs) it considers to be most important to repository performance. Repository performance refers to the ability of a proposed site to isolate HLW for long periods of time, and to slow the release of radionuclides to the environment. The staff's approach is summarized in Chapter 1 of the staff's periodic progress reports (e.g., NUREG/CR-6513, Center for Nuclear Waste Regulatory Analyses, CNWRA, 1996).

Consistent with 10 CFR Part 60 requirements and a 1992 agreement with the U.S. Department of Energy (DOE), staff-level issue resolution can be achieved during the prelicensing consultation period; however, such resolution at the staff level would not preclude the issue being raised and considered during the licensing proceedings. Issue resolution at the staff level during prelicensing is achieved when the staff has no further questions or comments (i.e., open items) at a point in time, regarding how DOE's program is addressing an issue. There may be some cases where resolution at the staff level may be limited to documenting a common understanding regarding differences in NRC and DOE points of view. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staff's approach to issue resolution is to provide DOE with feedback regarding issue resolution, before the Viability Assessment. Issue Resolution Status Reports (IRSRs) are the primary mechanism that the staff will use to provide DOE feedback on the subissues making up the KTIs. IRSRs comprise: (1) acceptance criteria that will be used by the staff to review DOE's license application and prelicensing submittals, as well as indicating the basis for resolution of the subissues; and (2) the tatus of resolution, including where the staff currently has no comments or questions, as well as where it does. Feedback is also contained in the staff's periodic progress report, which summarizes the significant technical work toward resolution of all KTIs during the preceding fiscal year (FY). Finally, open meetings and technical exchanges with DOE provide opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

In addition to providing feedback, the IRSRs will be guidance for the staff's review of information in DOE's Viability Assessment. The staff also plans to use the IRSRs in the future to develop the Standard Review Plan (SRP) for the repository license application.

Each IRSR contains six sections, including this "Introduction" in Section 1.0. Section 2.0 defines the KTI, all the related subissues, and the scope of the particular subissue that is the subject of the IRSR. Section 3.0 discusses the importance of the subissue to repository performance, including: 1) qualitative descriptions, 2) reference to a total system performance flowdown diagram, 3) results of available sensitivity analyses, and 4) relationship to DOE's Repository Safety Strategy (RSS): DOE's Strategy to Protect Public Health and Safety After Closure of a Yucca Mountain Repository, Revision 1, January 1998 (YMP/96-01) (i.e., the approach to its safety case). Section 4.0 provides the staff's review methods and acceptance criteria that will be used to evaluate DOE's prelicensing and licensing submittals. These

Site Layout

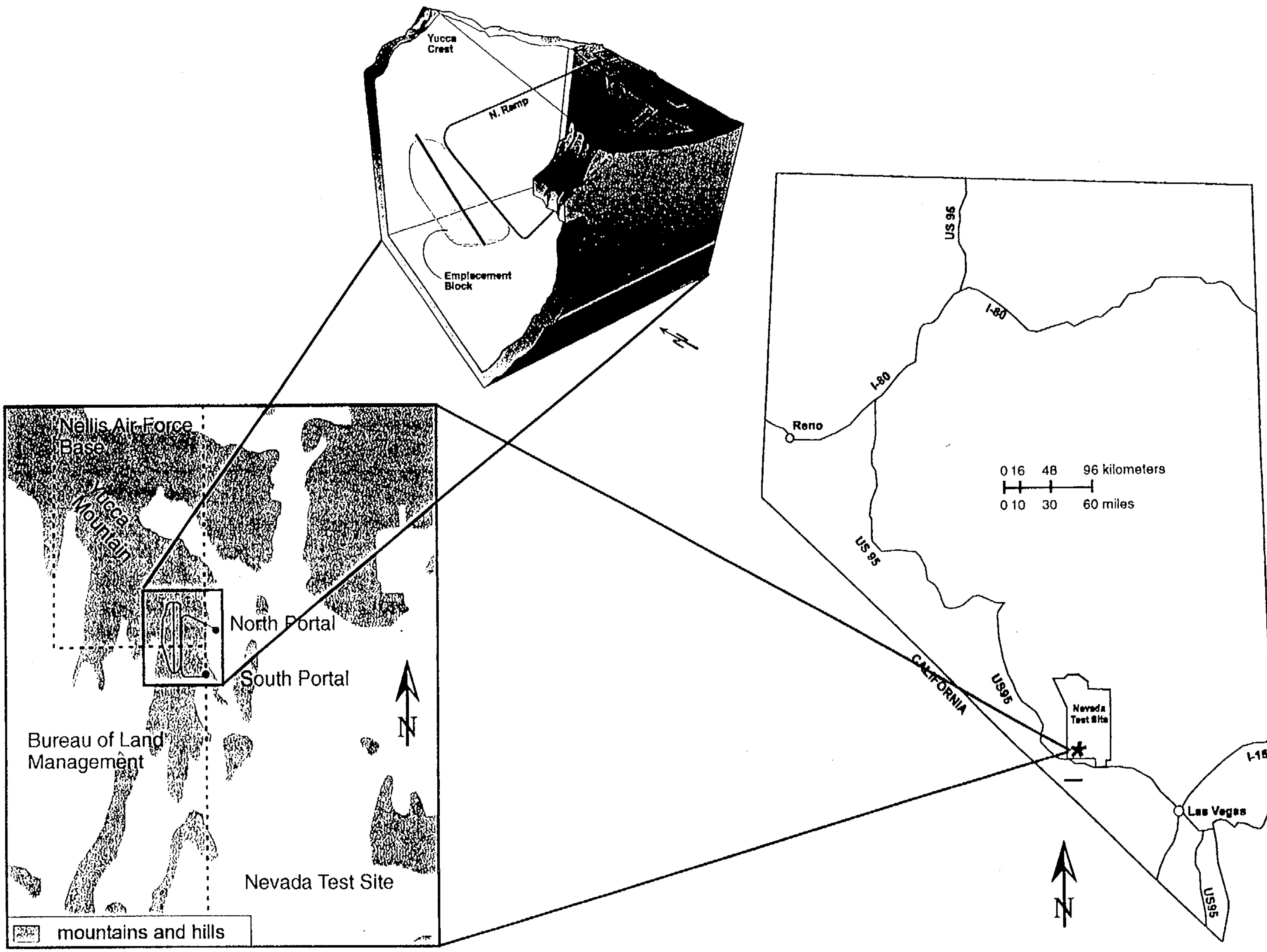

Figure 1. Location of the Yucca Mountain
e.

acceptance criteria provide guidance for the staff and indirectly for DOE as well. The staff's technical basis for its acceptance criteria will also be included to further document the rationale for the staff's decisions. Section 5.0 concludes the report with recommendations by the NRC staff and the status of resolution indicating those items resolved at the staff level or those items remaining open. The open items will be tracked by the staff and resolution will be documented in future IRSRs. Section 6.0 contains the references cited in the report.

2.0 ISSUE/SUBISSUE STATEMENT

The primary objective of this KTI is to assess all aspects of the ambient hydrogeologic regime at YM that have the potential to compromise the performance of the proposed repository. The secondary objective of this KTI is to develop review procedures and to conduct technical investigations to assess the adequacy of DOE's characterization of key site- and regional-scale hydrogeologic processes and features that may adversely affect performance. Subissues deemed important to the resolution of this KTI have been identified, and are framed in the questions shown below. Note that, since the release of the previous revision of this report, a new subissue has been added regarding matrix diffusion and that dilution mechanisms are now specifically mentioned under the saturated zone subissue.

(i) Climate change: What is the likely range of future climates at YM?

(ii) Hydrologic effects of climate change: What are the likely hydrologic effects of climate change?

(iii) Shallow infiltration: What is the estimated amount and spatial distribution of present-day shallow infiltration?

(iv) Deep percolation: What is the estimated amount and spatial distribution of percolation through the proposed repository horizon (present-day, and through the period of repository performance)?

(v) Saturated zone: What are the ambient flow conditions in the saturated zone and what are the likely dilution mechanisms?

(vi) Matrix diffusion: To what degree does matrix diffusion occur in the unsaturated and saturated zones?

Subissues (i), (ii), and (iii) have already been addressed in IRSRs dated June 30, 1997 (NRC, 1997a), and November 7, 1997 (Attachment E: NRC, 1997b). This revision of the IRSR is an update of Revision 1 (NRC, 1998e).

3.0 IMPORTANCE TO REPOSITORY PERFORMANCE

The staff is developing a strategy for reviewing the performance of a proposed HLW repository at YM, Nevada. As currently envisioned, the elements of this strategy necessary to determine acceptability of repository performance are defined as key elements of the subsystem abstractions (KESA). The KESA are illustrated in the figures of Attachment A. Acceptance criteria for the key elements of the DOE TSPA are under development. As noted in the following sections of this report, this KTI on Unsaturated and Saturated Flow Under Isothermal Conditions (USFIC) is considered to be an important factor in repository performance.

3.1 CLIMATE CHANGE AND
3.2 HYDROLOGIC EFFECTS OF CLIMATE CHANGE

The importance to performance of this subissue was originally provided in the pilot IRSR (NRC, 1997a, pp. 2-4). The Earth's climate could change significantly during the time that nuclear wastes will remain hazardous. Climate controls the range of precipitation, which, in part, controls the rates of infiltration, deep percolation, and groundwater flux through a geologic repository located in an unsaturated environment. Changes in groundwater recharge will likely induce other changes, such as regional fluctuations in the elevation of the water table. Water-table rise would reduce the thickness of the unsaturated zone barrier, but it could also increase the lengths of flowpaths in the saturated valley-fill aquifer. Therefore, future changes in climate could significantly influence the ability of a repository to isolate waste.

The importance of groundwater flux as the key parameter for repository performance in an unsaturated zone is well known, and has been further emphasized in a DOE report (DOE, 1995) on total system performance assessment (TSPA). On page ES-30 of that report it is stated that "...in the overall TSPA analyses, an over-arching theme comes back again and again as being the driving factor impacting the predicted results. Simply stated, it is the amount of water present in the natural and engineered systems and the magnitude of aqueous flux through these systems that controls the overall predicted performance.... Therefore, information on...[this topic]...remains the key need to enhance the representativeness of future iterations of TSPA." Sensitivity studies clearly showed the predominance of percolation flux in estimating cumulative radionuclide releases and peak radiation doses over a 10-kyr (1 kyr=1000 years) period (see DOE, 1995, pp. 10-6 and 10-7).

DOE's "Waste Containment and Isolation Strategy" (DOE, 1996, p. 5) likewise stated that "performance assessments have shown that seepage into the emplacement drifts is the most important determinant of the ability of the site to contain and isolate waste." This conclusion was reiterated in DOE's recently published Repository Safety Strategy (DOE, 1998c). The importance of infiltration as a hydrologic parameter was recognized by the staff in its Iterative Performance Assessment Phase 2. NRC (1995, p. 10-4) states that "Although the flux of liquid water through the repository depends on...infiltration, hydraulic conductivity, and porosity, performance correlates most strongly to infiltration."

Water flow through a geologic repository and its environs depends on both surface processes (precipitation, evapotranspiration, overland flow, and infiltration) and subsurface processes (deep percolation, moisture recirculation, and lateral flow). To evaluate the significance of climate change to repository performance, bounds can be determined for either: (i) climate change (and by inference the importance of surface processes), or (ii) the subsurface processes such as shallow infiltration and deep percolation based on geohydrologic parameters, or (iii) both. Obtaining bounds of water flow from both the climate change and from geohydrologic parameters will most likely provide reasonable assurance that water flow has been appropriately incorporated within the TSPA for the repository.

At YM, cooler and wetter conditions would increase infiltration and could also significantly affect future human populations in the region, leading to changes in patterns of groundwater and land use. These changes should be considered to a reasonable extent in estimating future doses to the critical group identified for the repository.

For DOE to adequately demonstrate and quantify in its Total System Performance Assessment (TSPA) the effects that climate change might have on repository performance, it should consider how these effects interplay with the other factors within and between key elements in the engineered and natural subsystems of the repository. As shown in Figure A-1 (Attachment A), climate change and its hydrologic effects are important factors that need to be abstracted into three of the key elements of the engineered and natural subsystems: (1) spatial and temporal distribution of flow; (2) flow rate in water production zones; and (3) location and lifestyle of critical group (includes consideration of water-table rise).

- NRC and CNWRA Sensitivity Studies

See Section 3.7.

3.3 PRESENT-DAY SHALLOW INFILTRATION

The importance to performance of this subissue was originally provided by the staff (see Attachment F, Section 3.3; NRC, 1997b). Present-day shallow infiltration is a key hydrologic factor in the isolation of HLW within a proposed geologic repository at YM. It should be reasonably understood to provide initial conditions for projecting future hydrologic changes, because the Earth's climate could change significantly during the time that wastes will remain hazardous. Climate controls the range of precipitation that, in part, controls the rates of infiltration, deep percolation, and groundwater flux through a geologic repository located in an unsaturated environment. Water flow through a geologic repository and its environs depends on both surface processes (precipitation, evapotranspiration, overland flow, and infiltration) and subsurface processes (deep percolation, moisture recirculation, and lateral flow). Changes in infiltration will likely induce other changes, such as regional fluctuations in the elevation of the water table. Water-table rise would reduce the thickness of the unsaturated zone barrier. Therefore, future changes in climate could alter infiltration from present-day rates and significantly influence the ability of a repository to isolate waste.

The importance of groundwater flux as the key parameter for repository performance in an unsaturated zone is well known, and has been further emphasized by DOE's most recent report (DOE, 1995) on total system performance assessment (TSPA). On page ES-30 of that report it is stated that:

> ...in the overall TSPA analyses, an over-arching theme comes back again and again as being the driving factor impacting the predicted results. Simply stated, it is the amount of water present in the natural and engineered systems and the magnitude of aqueous flux through these systems that controls the overall predicted performance.... Therefore, information on...[this topic]...remains the key need to enhance the representativeness of future iterations of TSPA.

Sensitivity studies clearly showed the predominance of percolation flux in estimating cumulative radionuclide releases and peak radiation doses over a 10-ky (1 ky=1000 years) period (see DOE, 199 pp. 10-6 and 10-7).

DOE's "Waste Containment and Isolation Strategy" (DOE, 1996, p. 5) likewise states that "performance assessments have shown that seepage into the emplacement drifts is the most important determinant of the ability of the site to contain and isolate waste." This conclusion was reiterated in DOE's recently published Repository Safety Strategy (DOE, 1998c). The importance of infiltration as a hydrologic parameter was recognized by the staff in its Iterative Performance Assessment Phase 2. NRC (1995, p. 10-4) states that "Although the flux of liquid water through the repository depends on...infiltration, hydraulic conductivity, and porosity, performance correlates most strongly to infiltration."

For DOE to adequately demonstrate and quantify in its TSPA the effects that present-day infiltration might have on repository performance, it should consider how these effects interplay with the other factors within and between key elements in the engineered and natural subsystems of the repository. As highlighted in Figure A-2 (Attachment A), present-day shallow infiltration is an important factor that needs to be abstracted into one of the key elements of the engineered and natural subsystems, i.e., spatial and temporal distribution of flow.

- NRC and CNWRA Sensitivity Studies

See Section 3.7.

3.4 DEEP PERCOLATION (PRESENT AND FUTURE [POST-THERMAL PERIOD])

The importance of groundwater flux as the key parameter for waste isolation at YM is well known and h been further emphasized by the DOE report (TRW Environmental Safety Systems, Inc., 1995) on TSF (see previous section).

As highlighted in Figure A-3 (Attachment A), deep percolation is related to two of the key elements of the engineered and natural subsystems: (1) quantity and chemistry of water contacting waste packages and waste forms; and (2) spatial and temporal distribution of flow.

- NRC and CNWRA Sensitivity Studies

See Section 3.7.

3.5 SATURATED ZONE AMBIENT FLOW CONDITIONS AND DILUTION PROCESSES

This subissue is important to repository performance because it constitutes an important potential pathway for radionuclide transport from the repository to the environment and receptor locations. The SZ influences repository performance through: (1) magnitude and direction of groundwater flow; (2) geochemical retardation; and (3) dilution of radionuclides. The time of arrival and the concentration of radionuclides at the receptor locations are based on the groundwater fluxes and velocities and the geochemical conditions encountered along the flow paths. Longer residence times will provide opportunity for radioactive decay, and the groundwater pathways will affect transport due to retardation and adsorption.

The concentration of radionuclides at the receptor locations is also affected by the dilution processes during transport (dispersion and groundwater intrabasin mixing) and pumping. The importance of dilution of radionuclides in the groundwater is a central issue for dose reduction in the PA. The DOE report on Total System Performance Assessment–Viability Assessment (TSPA-VA) identifies dilution in the SZ below the repository as one of the five major system attributes most important for PA (TRW Environmental Safety System, Inc., 1997a).

The Repository Safety Strategy (DOE, 1998c, p. 13) notes that "Significant flow must occur in the saturated zone in order for the radionuclide-bearing flux that percolates to the water table to be diluted...The magnitude of mixing and dispersion also must be established because certain conditions have been noted to lead to persistence of contaminant plumes...However, even persistent contaminant plumes may themselves be subject to significant dilution when mixed with other water in a producing well."

As highlighted in Figure A-4 (Attachment A), ambient flow conditions in the saturated zone provide input to three of the key elements of the engineered and natural subsystems: (1) flow rates in water-production zones; (2) dilution of radionuclides in groundwater (dispersion and well pumping); and (3) location and lifestyle of the critical group.

- NRC and CNWRA Sensitivity Studies

See Section 3.7.

3.6 MATRIX DIFFUSION IN SATURATED AND UNSATURATED ZONES

As highlighted in Figure A-5 (Attachment A), matrix diffusion is related to two of the key elements of the natural subsystems: (1) distribution of mass flux between fracture and matrix; and (2) retardation in water-production zones and alluvium (valley fill). At YM, the process of matrix diffusion may impact repository performance because groundwater flow, away from the repository, occurs primarily in fractures that account for only a small fraction of total formation porosity. In such hydrologic systems, matrix diffusion can attenuate migration of radionuclides in two ways: (1) it can spread them physically from the flowing fractures into stagnant matrix pore water; and (2) rock matrix can provide a vast increase in mineral surface available for geochemical surface reactions (e.g., sorption) as compared to fracture surfaces alone. The extent to which matrix diffusion can affect repository performance is controlled by the rate of solute diffusion from fractures into rock matrix relative to the time scale for flow through the fracture system to the receptor point. When diffusion is very slow relative to the transport time, the impact is negligible in terms of solute arrival time, but there is a slight long-term attenuation of peak solute concentration. If diffusion is fast relative to transport time, the impact is a significant delay in solute arrival at the receptor point. At intermediate diffusion rates, the impact is a modest delay in initial solute arrival time with significant attenuation of solute concentration.

The Repository Safety Strategy (DOE, 1998c, p. 12) noted that concentrations of radionuclides in groundwater can be reduced by matrix diffusion and sorption. If matrix diffusion is limited there can still be sorption on fracture walls, but the depletion effect will be much smaller.

- NRC and CNWRA Sensitivity Studies

See Section 3.7.

3.7 NRC/CNWRA Sensitivity Studies for USFIC Subissues

USFIC staff examined the influence of hydrologic parameters in the flow and transport modules of TPA 3.1.1. The contributions of the hydrologic parameters to different measures of repository performance were evaluated. The measures were: (1 maximum total effective dose equivalent (TEDE); (2) cumulative release to the location of the critical group; (3) unsaturated zone travel time; and (4) SZ travel time. Receptor groups were located 5 km and 20 km away from the repository. Simulations were carried out to 50 kyr and 100 kyr for the respective groups. In this model, groundwater infiltration is directly correlated to the varying average annual precipitation.

All of the 64 hydrologic parameters were varied concurrently and treated as uncorrelated variables. The response of each of the four measures of repository performance to each of the hydrologic parameters was evaluated. Stepwise regression was used to rank the explanatory power of each of the independent variables. Multiple and univariate linear regression models were constructed with the estimated linear model coefficients and were then scaled. USFIC staff also conducted sensitivity studies where parameters were varied one at a time, while all other parameters were fixed.

Infiltration-affecting parameters were found to be important contributors for most of the performance measures examined. Transport through UZ stratigraphic units is neglected for those units where groundwater residence time is less than 10 yrs or 10 percent of the residence time for the entire UZ below the repository. In differential analyses, where UZ transport calculations were omitted, maximum TEDE showed no sensitivity to those stratigraphic units excluded from the calculations. For example, in the region of parameter space where all parameters are set at their mean values, all UZ transport time calculations can be omitted and maximum TEDE predictions will not change. Maximum TEDE 20 km away from the repository was the only performance measure where infiltration-affecting parameters we not among the most important contributors. In contrast, parameters affecting dilution at the wellhead (i.e., well pumping rate and production zone thickness) appeared to have the greatest influence on maximum TEDE at 20 km and were important for explaining maximum TEDE at 5 km.

Groundwater flow in the UZ units was assumed to take place in the matrix for some realizations and in fractures for others. This arises from assumed ranges for matrix K_{sat} overlapping the assumed range of the expected infiltration rates. If infiltration is greater than the sampled K_{sat} for a given unit, then flow is through fractures; otherwise, groundwater flow is through the matrix. Fracture properties, for a unit experiencing matrix flow, do not enter into the calculation. Likewise, matrix properties are not used.

Fracture flow tends to be orders of magnitude faster than matrix flow, with water passing through a layer in a matter of decades or less. On the time scale of repository performance and radionuclide decay of the controlling radionuclides, travel times through fractures are almost negligible. In the sensitivity studies, the majority of the transport time radionuclides spent in the UZ was in the nonwelded, vitric layers of the Calico Hills (CH_v), where matrix flow dominated. Therefore, hydrologic properties of the CH_v matrix are important. Since flow through other stratigraphic units usually occurred in fractures, UZ travel time and maximum TEDE are not very sensitive to properties in these stratigraphic units. Finally, separate analyses performed at CNWRA suggest that matrix heterogeneity effects may support the use of bulk matrix properties with significantly greater matrix K_{sat} values. Larger K_{sat} values could result in matrix flow through other stratigraphic units and increase their influence on UZ travel time.

Saturated Zone groundwater travel time was most sensitive to fracture porosity values. Relative groundwater travel times through segments in the SZ streamtubes depend on segment length, mean cross-sectional area, effective porosity and hydraulic conductivity. Therefore, longer streamtube legs and legs with higher effective porosities or lower hydraulic conductivity will tend to have longer groundwater travel times; parameters that strongly influence travel times through these segments also may influence total SZ groundwater travel time and, potentially, maximum TEDE. Maximum TEDE is sensitive to the effective porosity of the composite tuff-valley fill leg, the fractured tuff leg, and the Amargosa Valley (valley fill) leg. Saturated zone dispersion length also has some significance.

The USFIC sensitivity studies treated flow parameters as uncorrelated variables. Since some flow parameters were found to be important contributors to groundwater travel time and, consequently, maximum TEDE is correlated with other parameters, the influence of these correlations on the transport calculations needs further investigation. The transport calculations also are influenced by assumed distributions of parameters, which are a function of the available data. In particular, the amount of hydrologic information for the saturated valley fill is extremely sparse and is insufficient to adequately constrain the performance of valley fill. Additional information about the valley fill/alluvium is needed. For example, hydraulic conductivity, porosity, measured head, location of the tuff/alluvial contact, and the ability of valley fill to retard radionuclides.

Americium and plutonium were significant contributors to maximum TEDE for a receptor group 5 km away from the repository. This indicates that sorption does not become effective in the model for these radionuclides. Although these radionuclides have a great tendency to sorb to most types of earth minerals, they are experiencing little retardation. This low retardation resulted from modeling assumptions where flow is predominantly through fractures for the 5 km receptor group, allowing little contact with sorbing minerals. Normally, americium and plutonium would not be expected to migrate significant distances unless associated with substantial colloidal transport.

The following aspects were identified as requiring additional characterization and examination: (1) well pumping rates (5 km and 20 km receptor groups); (2) mixing zone thickness (5 km and 20 km); (3) maximum hydraulic head in the SZ; and (4) width of the streamtubes at 20 km. Also, the treatment of matrix diffusion and/or the parameters related to sorption of radionuclides such as americium and plutonium need confirmation. Sorption is addressed in detail in the IRSR on Radionuclide Transport (NRC, 1998d).

4.0 REVIEW METHODS AND ACCEPTANCE CRITERIA

The staff's technical review of DOE's treatment of subissues under unsaturated and saturated flow under isothermal conditions will be based on the completeness and applicability of data and analyses. The staff will determine whether DOE has reasonably complied with the acceptance criteria listed in this section for each subissue.

4.1 CLIMATIC CHANGE

4.1.1 ACCEPTANCE CRITERIA

(1) Climate projections used in performance assessments of the YM region are based on paleoclimate data, considering, at a minimum, information contained in Forester, et al. (1996); Winograd, et al. (1992); Szabo, et al. (1994).

(2) DOE has evaluated long-term climate change based on known patterns of climatic cycles during the Quaternary, especially the last 500 k.y.

(3) If used, numerical climate models are calibrated with paleoclimate data and their use suitably simulates the historical record, before being used for projection of future climate.

(4) Climate-affected parameters (e.g., onset times for climate change, MAP, and MAT) used in YM performance assessment models include, as a bounding condition, a return to full pluvial climate (higher precipitation and lower temperatures) for at least a part of the first 10-k.y. period, using parameter values that are supported by scientific data and analyses.

(5) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

4.1.2 TECHNICAL BASIS FOR REVIEW METHODS AND ACCEPTANCE CRITERIA (CLIMATE CHANGE)

The NRC staff has determined that methods based on paleohydrologic, paleoclimatic, and geochemical information can be used to gain an adequate understanding of the range of past climates in the YM region. These insights can then be used to estimate the range of future climate variability, information that is needed to conduct meaningful performance assessments for a potential repository at YM. Multiple sources of data are needed to help reconstruct past environmental conditions. These include information from: paleodischarge sites; packrat (*Neotoma*) middens; pollen studies; paleolake levels and sediments; groundwater isotopic data; soil properties; tree rings; erosion studies; and other sources.

Paleoclimatic and paleohydrologic data can serve as "windows" to the past. They can provide "snapshots" of climatic conditions at various time intervals. To provide meaningful results, data sources must provide paleoclimate and paleoenvironmental indicators, along with materials that can be dated with radioisotopes or fossils.

Some data sources are relatively continuous and represent averaged or regional conditions. Ice cores from Greenland and Antarctica have been used to reconstruct high-latitude climate conditions over tens to hundreds of thousands of years. An example from the Great Basin is the 500-kyr temperature proxy record from Devils Hole, which is now recognized as one of the longest and best paleorecords on Earth.

This record can be used to directly compare ancient climates of the Great Basin to proxy records from around the world. The Devils Hole site shows how aquifers can serve as "archives" of ancient climatic conditions.

Tree rings provide a relatively continuous record over a shorter time interval, ranging from decades to as much as several millennia for long-lived species. Some paleo data are discontinuous and representative of highly localized conditions. For example, ancient packrat middens preserve plant remains and pollens that can be used to identify local paleo-assemblages of plants. The limited foraging radius of < 50 m of modern packrats requires that plant fragments found in ancient middens came from the immediate vicinity. Numerous ancient middens have been found throughout the Great Basin, including a number near YM.

Paleodischarge sites, like the Lathrop Wells Diatomites near YM, are especially powerful sources of information. If they can be dated and verified as having been produced by discharge from the regional water table, then they can establish times of increased groundwater recharge. The data can be used to help understand the response of the hydrologic system to the range of late Pleistocene climatic conditions. The past extent of pluvial lakes in the Great Basin also reflects enhanced recharge conditions on a regional scale.

The staff's technical review of DOE's treatment of future climate will be based on professional judgments regarding the completeness and applicability of the data and evaluations presented by DOE. It is expected that DOE will summarize or document the results of all significant paleo-studies that have been conducted in the YM region. The staff will determine whether DOE has reasonably complied with the Acceptance Criteria.

- Overview of Climate Change

Climate change is one of the most important factors that can influence the isolation of HLW in a geologic repository. Therefore, it is necessary for DOE to estimate the range of future climatic conditions to provide inputs to performance assessments. The study of climate change seems a formidable task because it involves both natural and anthropogenic components. Long-term natural variations in climate are clearly seen in the paleoclimatic record of the last 500 kyr. Five glacial/interglacial cycles occurred during that interval, each lasting roughly 100 kyr.

Climate has been changing since the world began, billions of years ago. Earth's early atmosphere was probably dominated by carbon dioxide (CO_2), and it took billions of years for algae in the world's oceans to remove most of that gas and replace it with enough oxygen to sustain life on the continents. The sheer mass of carbonate sedimentary rocks on Earth shows the effectiveness with which biological and chemical mechanisms have gradually removed carbon from the atmosphere (see Krauskopf, 1967, Table 21-2).

The causes of climate change are receiving close scrutiny from the scientific community. Natural variations in the Earth's orbital parameters (Milankovitch hypothesis) must play a significant role. But exactly how long-term climate shifts occur is unclear because complex, non-linear, feedback mechanisms probably exist within the atmosphere-hydrosphere-cryosphere system. Plate tectonics also plays a role by controlling the distribution of land masses and major topographic features.

Human influences on the climate are very recent, providing no long-term history of human influences th could help to project future anthropogenic changes or the manner in which natural cycles may be alte Only unreliable speculation is available to predict the manner and degree to which future human activities would affect climate over many thousands of years. Human activities could, under various circumstances, delay or even advance a transition to the next glacial stage. But there is general agreement that the chief concern is the addition of greenhouse gases to the atmosphere caused by combustion of fossil fuels. The average temperature at the Earth's surface is thought to have risen by about 0.5 °C (0.9 °F) in the last century, and sea level along the U.S. coast is estimated to be rising 2.5-3.0 mm/yr. But these changes cannot yet unambiguously be labeled as results of greenhouse warming. One reason for this is that recent ice core data have revealed natural oscillations in climate on a scale of 10-100 years. Also, during the last interglacial (about 125 kyr ago), sea level stood for a time about 6 m above the present level. This was caused by natural variation because there were no significant human influences on climate at that time.

Substantial reserves of fossil fuels still exist on Earth, but most of the remaining resources will probably be depleted on a time scale of centuries rather than millennia. The question then remains. How long will the legacy of an enhanced greenhouse effect continue after fossil fuels are gone? The answer to this question is uncertain, although it is possible that centuries will pass before excess CO_2 concentrations in the atmosphere could return to pre-industrial levels. The complex oceanic and terrestrial mechanisms that remove carbon from the atmosphere continue to be the foci of extensive research. General circulation models have been applied to these problems, but the data required to greatly improve general circulation modeling are not yet available. General circulation models themselves have limitations, as do all numerical models.

It has been argued that the next 200 years of anthropogenic climate change may create conditions unprecedented in human history. There are predictions of drought-induced famines, the spread of trop diseases, coastal flooding from sea-level rise, a dramatic increase in the numbers and intensities of hurricanes, and even "run-away" greenhouse effects with drastic biological consequences. The scientific literature includes examples of heated debate about the rate of atmospheric change and the national and international actions that should be taken. Recent assessments of climate change have scaled back the estimated rate of greenhouse warming, one reason being that oceanic and terrestrial carbon sinks may be more effective than previously thought. The climate is still susceptible to so-called "abrupt transitions," which have occurred naturally on time scales of decades or less even during the Holocene. Chaotic changes in ocean currents may be partly responsible for this. Fortunately, on a global scale there is a built-in resistance to drastic climate change, mainly because of the enormous heat capacity of the hydrosphere. This fact is undoubtedly responsible for the long-term evolution and abundance of life on Earth. The complex interactions between the atmosphere, cryosphere, and the hydrosphere provide mechanisms that help to buffer global climate shifts.

Given the realities outlined above, and the need to proceed with reasonable performance assessments, the staff recommends a pragmatic approach to address climate change and its effects. The staff has determined that anthropogenic changes to the atmosphere are detectible and likely to increase with time. The effects of global, enhanced, greenhouse warming will be presumed to last no more than several thousand years, and that, about 3 kyr in the future, the climate at YM will resume or continue the global cooling predicted by the Milankovitch orbital theory of climate. Staff will postulate that full pluvial (cooler and wetter) conditions will dominate at least several thousand years of the next 10 kyr. Current information suggests that past climate conditions were cooler and wetter than today, about 60 to 80 ɔercent of the time. In other words, anthropogenic effects will be assumed to delay but not prevent an ıevitable return to pluvial conditions at YM. Pluvial conditions of higher effective moisture would be reasonably challenging to repository performance, providing conservatism for NRC's safety analysis.

- Natural Variations in Climate

Lamb (1972, 1977) provides a detailed overview of the many mechanisms and phenomena that contribute to climate variability and change. The present-day global climate is part of a sequence that began about 2 million years ago, the beginning of the Quaternary Period. The Quaternary itself is divided into the Pleistocene and Holocene epochs. The Holocene began about 10 kyr B.P. The Quaternary differs climatically from the earlier, generally warmer Tertiary Period because the glaciations were more severe and extensive than those of the late Tertiary. The Tertiary and Quaternary periods comprise the Cenozoic era. The Pleistocene glacial/interglacial cycles were most pronounced in the past million years, during which ten cycles are thought to have occurred. The best long-term records of this climate variability are provided by ice cores, cores from vein calcites, and samples from deep ocean sediments (Dansgaard, et al., 1993; Winograd, et al., 1992; Lamb, 1977).

The reasons for the climate cooling of the late Cenozoic are unknown, but an interesting hypothesis involves plate tectonics. Raymo and Ruddiman (1992, p. 119) propose that

> ...late Cenozoic uplift of the Himalayan region and Tibetan plateau would have resulted in regionally, and hence globally, higher chemical erosion rates, causing a drawdown of atmospheric CO_2 and global cooling. The timing of this tectonically driven CO_2 decrease should be post-Eocene, coincident with the formation of the Tibetan plateau and in agreement with geological evidence for when global cooling was most rapid.

: this tectonic uplift hypothesis is ever verified, it would demonstrate the sensitivity of global climates to relatively small changes in atmospheric composition. Other events that may have helped lead to cooler climates include the occupation of the south polar region by Antarctica and creation of a nearly enclosed Arctic Ocean fringed by mountainous lands (Lamb, 1972, p. 38). However, Raymo and Ruddiman (1992) state that these events cannot account for the observed magnitude of Cenozoic global cooling.

It seems likely that more than one mechanism must be responsible for the Tertiary/Quaternary climate shift. Broecker (1997) points out that water vapor is in fact the principal greenhouse gas in the Earth's atmosphere. He speculates that climate shifts could be caused by changes in the water-vapor budget for the atmosphere, perhaps caused by chaotic changes in global ocean currents, which play a major role in the transfer of heat from the tropics to the poles (Broecker, 1995 and 1997). The potential for climate to be influenced by changes in the energy output of the sun was investigated by Wigley and Raper (1990). They used solar irradiance reconstructions back to 1874 to estimate the effects on global-mean temperatures. Modeled temperature changes were shown to be relatively insensitive to model uncertainties. They concluded that the direct effects of irradiance changes on global-mean temperature are likely to be very small. However, given limitations of available data, the question of low-frequency solar effects on climate remains open (Wigley and Raper, 1990, p. 2171) and can only be addressed by decades of additional data collection. More recent work suggests that low-frequency solar effects are reflected in global temperatures (Lean and Rind, 1994; Kerr, 1996).

The astronomical theory of Milankovitch is a widely accepted model for the stimulus of long-term, natur climate change. Crowley (1996, p. 5) states that the "...onset and recovery from Ice Age conditions is [are] now attributed to slow changes in the Earth's orbit -- the so-called Milankovitch effect -- that modify the seasonal cycle of solar radiation at the Earth's surface." Lamb (1972, p. 30) compared the Milankovitch effect with the effects of solar variations.

> Much greater variations of the Earth's annual radiation budget must occur through very long-term, periodic changes in the Earth's orbit, the tilt of its rotation axis and the seasonal variation of the Earth's distance from the sun characteristic of epochs defined by the orbital situation. Such epochs commonly change their character only slowly, over some thousands of years. But the changes are big, and some effects on climate appear inescapable, probably including the causation of the alternation of ice ages and warm interglacial periods during the Quaternary era...when the large-scale geography has been much as now.

Changes in insolation caused by precessional variations of the earth's orbit and varying tilt of the Earth's rotation axis (Milankovitch model) are known to correlate to some degree with past variations in global ice volumes. Tilt varies with an average period of 41 kyr and precession with an average period of 21 kyr (Kominz and Pisias, 1979). The periodicity of variations in the eccentricity of the earth's orbit is about 100 kyr. Kominz and Pisias (1979) found that, based on simple linear models, less than 25 percent of the variation in global ice volume during the last 730 kyr is related to tilt and precession. They concluded that Pleistocene glacial variations are largely stochastic in nature. No evidence was found for a linear relationship between eccentricity and ice volume, but Kominz and Pisias did note the existence of a dominant 100-kyr cycle of climatic change. Although tilt and precession are not strongly correlated to global ice volume, they evidently have the potential to trigger or enhance climatic shifts.

Lamb (1977, p. 312) found that the periodicity seen in paleoclimate data was "...so close to the periods the Earth's orbital variables as to constitute a remarkable vindication of Milankovitch's ...hypothesis regarding the origin of the Quaternary glacial-interglacial cycles.... It is only curious that the 100,000-year time scale is always more prominent than the theory suggests." Historical proof of the gradually changing tilt of the Earth's axis may be found in the monuments throughout the world that mark former latitudes of the Tropic of Cancer and the Tropic of Capricorn (Chao, 1996). The Tropic of Cancer will continue to move south another 90 km (56 mi) before it reverses in about 9.3 kyr and migrates northward.

In a milestone paper, Hays, et al. (1976, p. 1131) likewise concluded that "...changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages." Their conclusion was based on analyses of long-term (> 20 kyr) variations in paleoclimate data compared with predictable orbital and insolation changes. They noted that an explanation of the correlation between the dominant 100-kyr climate cycle and orbital eccentricity probably requires an assumption of nonlinearity. At variance with Hays, et al., Winograd, et al. (1992, p. 259) concluded that the paleoclimate record from the carbonate aquifer at Devils Hole was

> ...inconsistent with the Milankovitch hypothesis that orbitally controlled variations in solar insolation play a direct role in Pleistocene climate change. The hypothesis fails to predict the timing of deglaciations during the period 500 to 100 ka [kyr]. During the middle-to-late Pleistocene the increase in the duration of glacial cycles from about 80,000 to 130,000 years suggests that climate shifts were aperiodic. Interglacial climates lasted on the order of 20,000 years.

Winograd, et al. (1992, p. 258) did note that "Obliquity and precession periodicities are evident in the DH-1 record [based on a 36 cm (14 in) core of vein calcite from Devils Hole]. Such periodicities suggest that although solar insolation may not be the primary determinant of the onset of glacial-interglacial shifts, astronomical geometry could still be one of several factors contributing to Pleistocene paleoclimate changes." An independent confirmation of two samples from the Devils Hole chronology has been provided by Edwards, et al., 1997. They used a dating technique based on protactinium-231 to check both the Devils Hole record and records of sea-level change in Barbados corals. Compared with previous dating methods, the Devils Hole samples yielded consistent dates. Therefore, if the samples are representative, the record is accurate. The Barbados data support the astronomical theory of climate change. Differences found in the Devils Hole record are apparently real, but may represent local climatic events (Edwards, et al., 1997; Kerr, 1997).

An important new paper on Devils Hole was published in 1997, and the main conclusions are presented below. These do not lead the NRC staff at this time to change the previously developed acceptance criteria. Winograd, et al. (1997) examined the Devils Hole paleoclimatic record in light of the widely held view that interglaciations lasted 11 ky to 13 ky and constituted only about 10% of middle-to-late Pleistocene climatic cycles. They concluded that the previous interglacial (Sangamon, or substage 5e) lasted significantly longer, about 22 ky, consistent with the Vostok ice core record which suggests a duration of about 19 ky for this event in Antarctica. The three preceding interglacials in the Devils Hole record (analogs of marine isotopic substages 7e, 9c, and 11c) lasted 20 ky to 26 ky. The warmest intervals of each interglacial in the Devils Hole record indicate apparent climatic stability for periods lasting 10 ky to 15 ky. Winograd, et al. (1997, p. 153) also note that "Phase offsets of thousands of years are likely between different climate proxy records (especially temperature and ice volume) of the same interglaciation." They also speculated about the possible duration of our current interglacial climate, assuming only natural variation. With no anthropogenic warming, Holocene-like temperatures could remain with us for up to another 5 ky, or alternatively, the next millennium could experience steadily lowering temperatures.

Regardless of the actual causes of the Pleistocene climates, four glacial stages have occurred in the last 400 kyr. Forester (1996) considers that a full glacial "mega cycle" lasts about 400 kyr and contains glacial/interglacial subcycles of roughly 100 kyr. Forester believes that the Devils Hole record shows that the southern Nevada climate responds to solar insolation on a millennial time scale.

The present Holocene climate has remained relatively stable, even in view of intervals like the so-called "Little Ice Age" that occurred during the period from about 1450 to 1890 (Crowley, 1996). However, Dansgaard, et al. (1993) raised the question of whether the Holocene will remain stable despite anthropogenic effects. They reported evidence for general instability of past climate based on ratios of stable oxygen isotopes in Greenland ice cores. Their high-resolution data suggest that, except for the Holocene, the North Atlantic region has been relatively unstable during the last 230 kyr. Their conclusions apply even to the two previous interglacial stages.

Following the report by Dansgaard, et al. (1993), the previous interglacial has been studied extensively to gain insights about climate variability during warmer intervals (see *Quaternary Research*, Vol. 43, No. 2, March 1995). The last interglacial (oxygen isotope substage 5e) occurred from about 133 to 114 kyr B.P. (before present), based on Greenland ice core data (Dansgaard, et al., 1993). In North America this interglacial is known as the Sangamon; in Europe it is called the Eemian or Eem. For a time during the Sangamon, sea level stood about 6+ m higher than today (Muhs, et al., 1994; Brigham-Grette and

Hopkins, 1995; Neumann and Hearty, 1996). This higher sea level corresponded to a significant reduction in global ice, equivalent to a large percentage of the ice volume in present-day Greenland. There were no significant anthropogenic effects on climate during the Sangamon. It is therefore interesting that a natural sea-level rise occurred that is similar in magnitude to that predicted by some future scenarios of enhanced greenhouse warming. Even higher sea-level rises have occurred in the geologic past. For example, global sea level may have been 25 to 35 m above present-day sea level during the Pliocene (Cronin and Dowsett, 1993).

- Comments on Anthropogenic Climate Change

Karl, et al. (1997) present an excellent summary of the possible causes and consequences of human-induced climate changes. Because of the complex interactions of the Earth's hydrosphere, atmosphere, and cryosphere, the long-term effects of anthropogenic changes to the atmosphere and to the earth's surface (e.g., increase of greenhouse gases, deforestation, abundance of jet contrails, etc.) are still unclear. They could, under various circumstances, delay or even advance a transition to the next glacial stage. Miller and de Vernal (1992) outline conditions in which increased concentrations of greenhouse gases in the atmosphere might lead to ice-sheet growth and an accompanying drop in sea level. It is even possible that reductions in fossil fuel emissions could cause some global warming because of the rapidity with which sulfate aerosols, which are thought to exert a cooling effect, are removed from the atmosphere (Wigley, 1991).

Many of the current concepts regarding anthropogenic changes to climate are predicated on increasing atmospheric CO_2 caused by the use of fossil fuels and biomass burning. Such practices are likely to change as fossil fuels are consumed. Anthropogenic activities also release other greenhouse gases, such as methane and nitrous oxide. Large supplies of fossil fuels still exist on Earth, but the remaining resources will likely last for centuries rather than millennia. Proven energy reserves do not represent t resources, but do provide the best picture of readily available fossil fuels. Proven commercial energy reserves of coal, oil, and natural gas for the world have been estimated at 34.6×10^6 petajoules (3.28×10^{19} BTUs) (WRI, 1994). Coal is by far the most abundant fossil fuel, and proven world reserves could sustain current production rates for 209 years (WRI, 1994, Table 9.2). Proven reserves of oil and gas could sustain current production for 45 and 52 years, respectively. Crowley (1996) claims that only about 5 percent of the available fossil fuel reservoir has been consumed to date, but his estimate may not have considered the recent decline in estimated coal reserves in China (WRI, 1994).

As evidence of global warming, investigators have examined whether subtle, long-term changes exist in the temperature record. A report by the Forum on Global Change Modeling (Barron, 1995) gives consensus conclusions about climate change, and specifically temperature. The report found that average global surface air temperatures are about 0.5 °C (0.9 °F) higher than in the last century. However, the change "...cannot yet be unambiguously ascribed to increased concentrations of greenhouse gases." Based on the assumption that greenhouse gases will increase, the report found that it is very probable that mean precipitation will increase, northern sea ice will decrease, and sea level will rise at an increasing rate. If atmospheric CO_2 doubles, global mean surface temperatures will increase by 1.5 to 4.5 °C (2.7 to 8.1 °F), with 2.5 °C (4.5 °F) considered most likely. Mean surface temperatures are estimated to rise 0.5 to 2 °C (0.9 to 3.6 °F) by 2050. But there is also an estimated 10 percent chance that temperatures will rise by over 4 °C (7 °F) by 2100 (Carlowicz, 1995). Carlowicz noted other research that supports the view that even minor changes in global temperature are amplified in the polar regions.

In addition to temperature change, another key variable in tracking global warming is sea-level rise. Titus and Narayanan (1995) reported that sea level is currently rising 2.5 to 3.0 mm/yr (0.10 to 0.12 in/yr). In a detailed report, they assessed the probability of future sea-level rise. Their study consisted of two phases. In the first phase they developed a simplified model for estimating sea level rise as a function of 35 major uncertainties. The report by Titus and Narayanan (1995, p. 1 of summary)

> develops probability-based projections that can be added to local tide-gauge trends to estimate future sea level at particular locations. It uses the same models employed by previous assessments of sea level rise. The key coefficients in those models are based on subjective probability distributions supplied by a cross section of climatologists, oceanographers, and glaciologists. The experts who assisted this effort were mostly authors of previous assessments by the National Academy of Sciences and the Intergovernmental Panel on Climate Change (IPCC).

In phase two the results were documented in a draft report that was circulated to a panel of experts. Feedback from the experts was then used to revise the analyses. Titus and Narayanan (1995, p. 2 of summary) concluded that "Global warming is most likely to raise sea level 15 cm by the year 2050 and 34 cm by the year 2100. There is also a 10% chance that climate change will contribute 30 cm by 2050 and 65 cm by 2100. These estimates do not include sea level rise caused by factors other than greenhouse warming."

Overall, Titus and Narayanan (1995) concluded that sea level is likely to rise less than estimated by earlier studies. The lower estimates reportedly result from a downward revision of future temperatures, and growing consensus that Antarctica will probably not add to sea-level rise in the next one hundred years. Also, recent revisions in carbon cycle models have lowered estimates of CO_2 concentrations. Carbon "sinks" continue to be the subjects of intensive research. For example, Sabine, et al. (1997) estimated that the oceans remove about 37 percent of the CO_2 produced each year from the burning of fossil fuels. This estimate is being improved by a program of direct measurements of carbon in seawater. The oceans naturally contain much more carbon than the atmosphere, mostly in the form of bicarbonate ions (Sabine, et al., 1977).

DeWispelare, et al. (1993) reported the results of an expert elicitation study on future climate in the YM region. Three of five climate experts believed that the principal greenhouse warming effects might last about 3-5 kyr. The other two experts believed that anthropogenic effects could last significantly longer. In fact, one researcher stated (DeWispelare, et al., 1993, p. H-63) that "Human induced atmospheric and surface changes (e.g., greenhouse gas changes, land surface alterations including increased agriculture, and absolute human population growth) will lead to such dramatic climate changes that the paleoclimate record will not be the key to the distant future."

The staff recognizes that, in the end, predictions about the manner and degree to which human activities would affect climate in the distant future will remain highly uncertain. Anthropogenic effects could significantly influence world climates during the next several thousand years. However, realistically, there are limits on how long greenhouse warming can last. After fossil fuels are depleted the natural carbon sinks will gradually remove excess amounts of CO_2. Therefore, the staff's current view is that there is no reason to presume that anthropogenic effects will be of sufficient magnitude and duration to indefinitely postpone a new glacial cycle. More importantly, with respect to a safety analysis of YM, it would not be conservative to presume that present-day conditions will persist for 10 kyr or longer. Instead, the presumption that cooler and wetter conditions will return promotes analyses that are more challenging to repository performance. These kinds of analyses are needed to provide confidence in the results of a HLW safety analysis.

In summary, predictions about the magnitude and duration of future anthropogenic changes in world climates are expected to remain highly uncertain. However, for purposes of evaluating repository performance, it is both pragmatic and conservative to postulate that such changes will be relatively short (several thousand years at most) and that global cooling will return, gradually leading to the next glacial stage. That would lead to pluvial climatic conditions at YM which, as in the past, would be generally cooler and wetter than today's climate.

- Climate Models and High-Level Waste

Various national and international efforts, such as those of the World Climate Research Programme, are analyzing climate change through the development of general circulation or global climate models (GCMs), intercomparison of model results, and the acquisition of paleoclimatic data. For example, 29 atmospheric GCMs participated in the Atmospheric Model Intercomparison Project (Gates, 1992). GCMs have considerable societal value in studying the potential effects of deforestation and burning of fossil fuels, etc., on global and regional climate patterns. Possible benefits of global warming will not be addressed here. Global warming could have various adverse consequences, such as increasing the prevalence of drought conditions in grain-producing regions or increasing the numbers and intensities of tropical storms. Over the next several centuries sea level may rise enough to inundate coral atolls and low-lying continental coasts and cities around the world. Portentous as these possibilities are, they are not relevant to potential HLW disposal at YM unless they would indirectly lead to higher rates of groundwater infiltration.

Timbal, et al. (1997) describe a continuing multi-phase project that seeks to improve GCM results by better integrating land-surface and atmospheric models. Nonetheless, attempts to use GCMs to predict climatic changes over tens of thousands of years would almost certainly remain controversial, leading to debate over the competence of one model and data set vs. another. Heated debates have even arisen over studies of present-day anthropogenic effects on climate (Risbey, et al., 1991a,b; Schlesinger and Jiang, 1991a,b,c; Bolin, 1992; Harvey, 1992; Oeschger, 1992; Schlesinger, 1992; Feder, 1996). A staff concern is that GCM results could be used to suggest that greenhouse warming might postpone the return of pluvial conditions at YM for more than 10 kyr. The staff considers GCM predictions inadequate to support such a claim. Efforts to validate GCMs will likely result in continual model calibration. These difficulties, along with known limitations of GCMs (Stone and Risbey, 1990), have led the staff to conclude that climate modeling will not be required to support HLW licensing. Instead, a more direct approach is available.

- Representation of Future Climate at YM

With respect to a HLW repository, the staff considers that it is adequate to forecast and bound future hydrologic conditions by studying conditions during past pluvial climates (Coleman, et al., 1996). This kind of work has included the collection and interpretation of regional and global paleoclimatic data to better understand the past range of climates at YM. The data include information from paleodischarge sites, packrat (*Neotoma*) middens, pollen studies, paleolake levels and sediments, groundwater isotopic data, soil properties, tree rings, erosion studies, and other sources. These data are often used to calibrate GCMs, but they can be used directly to bound past climates.

Given the difficulties and realities outlined above, and the need to proceed with realistic performance ssessments, the staff recommends a pragmatic approach to address climate change and its effects. Current information does not support an assumption that the present-day climatic regime at YM will persist unchanged for 10 kyr or more. Therefore, it will be presumed, based partly on the results of a climate expert elicitation that the staff sponsored, that an enhanced greenhouse warming will last at most several thousand years, and that about 3 kyr in the future the climate at YM will resume or continue the global cooling predicted by the Milankovitch orbital theory of climate. In other words, anthropogenic effects will be assumed to delay but not prevent an inevitable return to pluvial conditions at YM.

To ensure realism in its safety analysis, staff will postulate that full pluvial (cooler and wetter) conditions will dominate at least several thousand years of the next 10 kyr. Such conditions would be reasonably challenging to repository performance because groundwater fluxes through a repository are expected to be higher during pluvial episodes. The staff's presumption is somewhat conservative if, as appears to be the case, full pluvial conditions at YM are associated with the onset, duration, and waning of glacial maxima in the northern hemisphere. In reality the paleorecord shows that much more than 10 kyr are needed for glacial stages to reach their maxima. There is another safety benefit that accrues by presuming full pluvial conditions will recur. It recognizes the possibility that unforeseen human effects or the natural recovery of global climate from these effects could cause cooler and wetter conditions at YM than otherwise expected. And finally, any safety analysis that covers time periods longer than 10 kyr into the future should simulate climate change using 100 kyr cycles of glacial/interglacial stages, similar to those seen in the paleoclimate record.

This approach to climate representation is consistent with the findings of Dansgaard, et al. (1993), who reported evidence for general instability of past climate based on ratios of stable oxygen isotopes in Greenland ice cores. They raised the question of whether the Holocene will remain stable despite anthropogenic effects. No other period during the last 250 kyr has apparently enjoyed such a stable limate. This climate approach is also consistent with Milankovitch cycles, because a minimum in northern-hemispheric summer insolation will occur during the next 10-15 kyr, based on the solar insolation curves of Vernekar (1968, 1972) as reproduced in part by Lamb (1977). A summer insolation high equivalent to the one centered around 11-kyr B.P. will not recur at northern latitudes >45° during the next 105 kyr (Lamb, 1977, pp. 314-315). The next substantial peak in summer insolation at these latitudes is predicted to occur about 65-75 kyr in the future. Updated solar insolation calculations have been performed by A. Berger and others, and these should be used to evaluate time periods greater than 50-100 kyr after present (AP), if necessary (see references in Winograd, et al., 1992, note 22).

The assumption that pluvial conditions will return to YM during the next 10 kyr has the advantage that useful estimates of future climate can be obtained even though the scientific debate about the causes of climate change continues unabated. This approach clearly demonstrates that conditions challenging to repository performance will be considered in performance assessments because these conditions would invoke higher rates of precipitation and groundwater infiltration than are occurring at the site today. Such an approach is consistent with conclusions reached by the National Research Council (1995, p. 9), which concluded that the probabilities and consequences of climate change (and other processes) are sufficiently boundable that these factors can be included in performance assessments that extend over a time frame of 1000 kyr.

- Comments by the U. S. Nuclear Waste Technical Review Board (NWTRB)

The NWTRB discussed climate issues in a report to the U.S. Congress and the Secretary of Energy (NWTRB, 1993). Chapter 3 of that report was entitled "Resolving Difficult Issues - Future Climates." They stated (p. 55) that

> While there is no guarantee that future climatic and hydrologic states will be similar to those in the past, the Board believes that it is appropriate to assume that the paleoclimatic and paleohydrologic data base (to the extent that it is both sufficiently accurate and complete) can serve as an excellent foundation for predicting the range of these future states at Yucca Mountain...however, this assumption falls short when trying to assess the impacts of modern industrial society on future climate.

The NWTRB report also states (p. 57) that "Past analogues of future greenhouse-gas-changed climate have not been found. Thus while paleoclimates can assist in building confidence by hindcasting, they cannot yet be used as predictions of regional climate change due to future increases in greenhouse gases." With respect to GCMs, the report states that (p. 57)

> ...it is unclear at what time in the future climate models will be sufficiently mature to provide confident detailed long-term predictions of climate at regional and local scales, such as those associated with the Yucca Mountain site. Climate models could, however, provide valuable insights as to the processes affecting future climate, the likelihood of past climate states occurring in the future, and, perhaps, most importantly, the occurrence of climate states such as the enhanced greenhouse effect, which are not reflected in the paleoclimate data base.

One of the NWTRB's (1993, p. 59) recommendations was that "Future climate states should be estimated primarily through the use of paleoclimatic and paleohydrologic data. Numerical modeling can play a supplementary, but important, role in overcoming the limitations of the paleoclimate data and estimatin the likelihood of adverse climate states." The NWTRB also states (p. 58) that DOE will have to "...dec when it has reached the point of diminishing returns with respect to its climate-related studies.... The key element in this decision should not be the ability to predict future climate at Yucca Mountain, but rather the ability to determine, with sufficient confidence, whether future climate states will or will not cause the repository to fail."

The staff generally agrees with the NWTRB (1993) report, although it believes that enough information is already available to reasonably estimate the range of future climates at YM and to analyze their effects on repository performance. DOE's current use of climate modeling can provide additional information, but the staff will not require such work to estimate the range of future climatic conditions at YM over many thousands of years.

4.2 HYDROLOGIC EFFECTS OF CLIMATE CHANGE

Review methods, acceptance criteria, and technical bases for the subissues (climate change and hydrologic effects of climate change) were provided in a previous version of this IRSR (NRC, 1997a). The acceptance criteria, with slight modification, are repeated below for the convenience of the reader.

4.2.1 ACCEPTANCE CRITERIA

(1) If bounding analyses are used to predict climate-induced effects (water table rise, for example), the analyses are based on a reasonably complete search of paleoclimate data pertinent to water-table rise and other effects (for example, changes in precipitation and geochemistry), including, at a minimum, information contained in Paces, et al. (1996), Szabo, et al. (1994), Forester, et al. (1996).

(2) Regional and sub-regional models for the SZ that are used to predict climate-induced consequences are calibrated with the paleohydrology data, and are consistent with evidence that the water-table rise during the late Pleistocene was up to 120 m.

(3) DOE has incorporated future climate changes and associated effects in its performance assessments. For example, available information does not support an assumption that present-day climate will persist unchanged for 10 k.y. or more.

(4) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

(5) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

4.2.2 TECHNICAL BASIS FOR REVIEW METHODS AND ACCEPTANCE CRITERIA - EFFECTS OF CLIMATE CHANGE

It will be necessary for DOE to develop one or more representations of future climate, to estimate the ranges of future precipitation, temperature, and water-table rise at YM. Water-table rise would clearly be an "effect" of the climate changing to cooler and wetter conditions. Changes in precipitation and temperature will be discussed as though they were also "effects" of climate change, but the staff recognizes that climate itself is largely defined by prevailing conditions of precipitation and temperature. Staff will review DOE's future climate representations to determine whether they are consistent with known trends of past climatic variation.

4.2.2.1 Technical Bases for Review Procedures and Acceptance Criteria (Climate Change - Future Precipitation and Temperature)

Recent published work suggests that future pluvial climates could experience an MAP upper threshold that is significantly greater than present-day MAP. Various researchers have used paleoecological methods to estimate the range of MAP and MAT during the late Quaternary in the Great Basin. Forester (1994, p. 2750) stated that "Preliminary estimates from fossil plant and animal records suggest that during the last glacial (14 to 25 ka [kyr]) mean annual precipitation may have been as much as five times modern, while mean annual temperatures were 8-10 °C lower than today." Forester and Smith (1994) studied fossil ostracodes from deposits in the upper Las Vegas Valley. They concluded (p. 2560) that "...during the late Pleistocene average climate conditions in southern Nevada may have been about four times wetter than today and perhaps as much as 10 °C colder." In a presentation to the U.S. Nuclear Waste Technical Review Board, Forester (1996, p. 18) stated that "During the last glacial within 100 miles of YM, MAP likely varied from about 15 to more than 20 inches at some localities between 5 and 6 k feet with as yet unknown standard deviation and regional variability." This estimated range of MAP (380-510+ mm, or 15.0-20.1 in) is roughly two to three times the present-day MAP of 150-160 mm (5.90-6.30 in)(DOE, 1988b, p. 5-17).

Morrison (1996) forecasts that, consistent with the last interglacial/glacial transition, the coming transitional period will consist of repeated extreme changes in global climate. He concludes that the southern Great Basin will experience frequent episodes with order-of-magnitude increases in effective precipitation, flood magnitudes, and erosion rates. Based on a discussion with staff, Morrison defines effective precipitation as effective moisture, which is the residual precipitation (not lost to evapotranspiration) that contributes to surface-water runoff and groundwater recharge.

Mifflin and Wheat (1979) noted that there is evidence for 53 pluvial lakes of Wisconsin age in Nevada. They studied the variability of modern climates and hydrologic regimes in the Great Basin to infer what conditions were like during past pluvials. Mifflin and Wheat (1979, p. 5) concluded that "...the observed pluvial lake paleohydrology could have been maintained by: a) mean annual temperatures approximately 5 °F lower than those of today; b) by corresponding pluvial mean annual precipitation averaging 68 percent over modern precipitation; c) by mean annual pluvial lake evaporation averaging 10 percent less than mean annual modern lake evaporation." Mifflin and Wheat (1979) also summarized conclusions of earlier, pioneering researchers who studied paleoclimates in the Great Basin.

Mifflin (1990) described the regional hydrologic effects of past pluvial climates in the YM region. Based on the extent of former pluvial lakes in the Great Basin, effective moisture (runoff and recharge) was elevated by about an order of magnitude over modern conditions, and regional water tables rose as much as several hundred feet. That would be consistent with the findings of Oviatt (1997) who described climatic fluctuations of Lake Bonneville for the period from 30 to 10 kyr B.P. This period includes the Wisconsin glacial maximum. Lake Bonneville was the largest of the late Pleistocene pluvial lakes, located in northern Utah in the northeastern portion of the Great Basin.

Spaulding (1985, p. 50) estimated departures of MAT and MAP for various intervals from 45 to 10 kyr B.P. He estimated that MAP during the Wisconsin glacial maximum (around 18 kyr B.P.) was 30 to 40 percent greater than modern. Spaulding (1990) described contrasts between Middle and Late Wisconsin fossil records. He found that mesophytic species (plants needing moderate amounts of moisture) appear to have been more abundant during the Middle Wisconsin, while steppe shrubs appear dominant during the Late Wisconsin. Spaulding concluded that effective moisture and temperature may therefore have been lower during the late Wisconsin, especially during the glacial maximum ca. 18 kyr B.P. Referring to the glacial maximum, Spaulding (1990, p. 1255) concluded that "An estimated increase in average annual precipitation (Pa) of 40% is all that is required to account for the paleobiotic record in this [YM] region. With the fossil record dominated by xerophytic species [plants tolerant of dry habitats] it is difficult to see how the increase could have been greater."

Spaulding (1995) summarized past climatic conditions at YM based on paleoecological data accumulated to date.

- In the YM region, maximum recharge occurs during warmer climatic intervals (interstadials). The last occurred between ca. 14 kyr and 8 kyr B.P. and was characterized by long-term increases in MAP of up to 100 percent. Short-term (decadal to century) departures of MAP may have approached 400 percent of modern values.

- The Wisconsin glacial maximum (ca. 18 kyr B.P.) was cold and dry, with a decline in MAT of about 7 °C (13 °F) and an increase in MAP of about 40 percent.

- The period ending around 23 kyr B.P. (unit D time) had higher MAP (and recharge) than later periods. This period was characterized by more common deep-water environments in valley bottoms, and early episodes with poorly constrained ages were as wet or wetter.

Wigand, et al. (1994) documented late Holocene climate shifts at various sites in the Great Basin. Their main conclusion was that shifts to times of higher effective moisture were not accompanied by rapid shifts in plant communities. The result was a lag time during which there was less competition for water and greater opportunities for groundwater recharge. There was more competition for moisture and less recharge after plant communities adjusted to the wetter conditions. Wigand, et al. (1994, Figure 2) also presented evidence from Tule Springs (upper Las Vegas Valley) and from various mountain sites that suggests MAP was 2-3 times higher than today from 18 kyr to >23 kyr B.P.

An NRC-sponsored study elicited the opinions of five experts regarding climate change over the next 10 kyr (DeWispelare, et al., 1993). In the next 10 kyr, one expert predicted a doubling of precipitation; one foresaw 15 percent less precipitation; and three others ranged from no change in precipitation to 30-40 percent increases over the present. The experts believed that the montane rain shadow that dominates the Great Basin climate would continue to exert a strong regional influence. A discussion of the rain shadow and its long-term effect is given by Winograd and Szabo (1988).

The milestone report produced by Forester, et al. (1996, p. 33) provides estimates of MAP for 8 intervals over the period from 12 kyr to 35 kyr B.P. They draw several conclusions with respect to past precipitation and effective moisture (p. 65).

> Effective moisture throughout the last glacial was greater than present, but the reasons for its increase differed. In the cool wet periods, gains in MAP probably played as important a role as those [declines] in MAT. During the cold dry periods substantial depressions in MAT with only modest gains in MAP probably explain the greater levels of effective moisture. Average gains in MAP appear to be about 1.5X to 2X modern, with an unknown standard deviation. Present MAP standard deviations are about fifty percent of the mean value, which, if applicable to the past, would place typical MAP in a range from modern-like to about 3X present MAP. The white fir episodes likely had higher mean MAP. Depressions in MAT appear to range from about 5 to perhaps more than 10 °C below modern. Refinement of past MAP and MAT estimates in both time and space and determining the standard deviations about those means remains a key item to be completed.

These MAT and MAP conditions representing a pluvial climate at YM are similar to the present-day climate in northern Nevada and eastern Oregon, based on data from the U. S. Geological Survey (USGS)

(1970). The following table summarizes the precipitation increases during past pluvials as estimated by various workers.

Table 1. Estimates of increases in precipitation during past pluvial climates.

Forester, et al., 1996	YM region	Average gains in MAP appear to be about 1.5X to 2X modern, with unknown standard deviation (range from modern-like to about 3X modern).
Forester, 1996	Area within 100 miles (161 km) of YM	Roughly two to three times modern MAP during last glacial.
Morrison, 1996	Southern Great Basin	Order of magnitude increase in recharge [effective moisture] - implies at least 100 percent increase in MAP.
Spaulding, 1995	YM region	Latest Wisconsin to early Holocene: up to 100 percent increase in MAP (short-term increases in MAP near 400 percent of modern). Glacial maximum: about 40 percent increase in MAP. Middle Wisconsin: greater MAP and recharge than later periods.
Forester, 1994	YM area	Up to five times modern MAP.
Wigand, et al., 1994	Various Great Basin sites	MAP 2-3 times higher than modern (from 18 kyr to >23 kyr B.P.).
Forester and Smith, 1994	Upper Las Vegas Valley	Late Pleistocene average conditions about four times modern MAP.
DeWispelare, et al., 1993 (elicitation of five expert opinions)	Vicinity of YM	For 10 kyr future period, one estimate was 15 percent less precipitation; three estimates were for no change or 30-40 percent increase; and one expert foresaw doubling of precipitation.
Mifflin, 1990	YM region	Order of magnitude increase in effective moisture (runoff and recharge) compared with present-day climate.

Spaulding, 1985	YM region	Over the period from 39 to 10 kyr B.P., MAP increases ranged from 10 to as much as 40 percent higher than modern.
Mifflin & Wheat, 1979	Basin areas of former paleolakes	About 70 percent increase over modern MAP.

The staff have noted an apparent convergence of professional opinions regarding precipitation during past pluvials. For example, higher estimates of MAP have been revised downward, from about 5 times modern MAP (Forester, 1994) to a factor of 2 to 3 (Forester, 1996; Forester, et al., 1996). Lower estimates have been revised upward (Spaulding, 1985; Spaulding, 1995). The revised MAP estimates approach that by Wigand, et al. (1994) and are more consistent with the estimates provided by other workers. The staff has determined that MAP during past pluvials at YM is the best indicator of what to expect during future pluvial climates. This kind of information can be used to estimate a range for future pluvial MAP, which can further be used to estimate rates of infiltration and deep percolation.

Compared with Wisconsin conditions, groundwater recharge has been significantly reduced during the Holocene interglacial. This is best illustrated by the disappearance or dramatic reduction in size of pluvial lakes. There is no reason to believe that future pluvial climates will not be similar to those of the Wisconsin glacial stage. Since glacial stages last longer than interglacials, future climates at YM will be wetter than today most of the time. Based on currently available information, the NRC staff has determined that the potentiometric data from Brown's Room in Devils Hole provide the best available indicators of the duration of higher recharge conditions in the Great Basin during the Wisconsin (Szabo, et al., 1994).

4.2.2.2 Technical Bases for Review Procedures and Acceptance Criteria (Effect of Climate Change - Water-Table Rise)

There are various lines of evidence that bear on past water-table stands at YM. Taken as a whole they can be used to define a reasonable upper limit to which the water table may rise in response to increased recharge under future pluvial conditions.

- Location and nature of paleospring deposits known as the Lathrop Wells diatomites

Quade (1994) and Quade, et al. (1995) studied fossil spring deposits over a large part of the southern Great Basin. From their survey of fine-grained sediments in this region, they concluded that the deposits were associated with elevated water tables and increased groundwater discharge at various times during the Pleistocene. At various locations, inferred water-level changes since late Wisconsin time vary from as little as 15 m to as much as 95-115 m. One set of paleospring deposits is located only 20 km SW of YM in the southern part of Crater Flat. The water table may have been at or near ground level as recently as 12 kyr ago. The deposits contain mudstones and diatomites, and have been informally named the Lathrop Wells diatomites by Quade, et al. (1995).

Previously, Paces, et al. (1993) estimated ages for several of the Lathrop Wells Diatomites. Using uranium-series disequilibrium, they determined that the deposits represent active springs at 18 ± 1, 30 ± 3, 45 ± 4, and > 70 kyr. They found that two samples from different sites yielded identical ages, suggesting that the springs may have been contemporaneous and were likely part of the same hydrodynamic system. Uranium isotopic compositions suggested that groundwater from the regional Tertiary-volcanic aquifer was the source of the spring flow, and that the water table had formerly risen 80-115 m above present levels and may have fluctuated repeatedly. Forester (1996), in a presentation to the NWTRB, noted that analysis of the diatomite deposits (Horsetooth Site) suggests groundwater discharge from the regional aquifer and from a perched flow system.

Stuckless (1994) discussed dating of the diatomite deposits in a presentation to NRC's Advisory Committee on Nuclear Wastes (ACNW). The apparent ages of one deposit range from 16 kyr to 133 kyr, with six sample ages occurring in the interval of the last glacial maximum, broadly 15 to 21 kyr B.P. Another deposit yielded dates of 12 kyr to 28 kyr B.P. The two youngest dates represent the latest Wisconsin. Stuckless caveated the data as preliminary and predecisional.

Additional details about the Lathrop Wells Diatomites and their estimated ages were described by Paces, et al., 1996. They found evidence that the deposits were formed during two distinct periods, from about 15 to 60 kyr and an older episode of 90 to 180 kyr. They report that isotope and paleontological data rule out a surface-water source for the deposits. Drainage from perched-water systems was also discounted as a source. Paces, et al. (1996, p. 1) found that

> ...regional, saturated-zone ground water most likely supplied discharge during pluvial episodes. This conclusion requires the regional water table to fluctuate up to about 100 to 120 m between pluvial and interpluvial periods. Fluctuations of the same magnitude occurred over the last two glacial cycles...much of the late Pleistocene was characterized by higher water tables (as much as 60 to 80% of the last 200 ka [kyr]). Therefore...it is anticipated that this hydrologic state will recur in the future.

The staff recognizes that the exposed setting of the Lathrop Wells Diatomites could cause geochemical open-system behavior, an adverse factor in radiometric dating. However, parts of these deposits are certainly Pleistocene in age, as suggested by radiometric dating, because fossil remains of mammoth (*Mammuthus*) have been found there (Quade, et al., 1995).

Consistent with Paces, et al. (1993), Quade (1994) and Quade, et al. (1995) noted that if water table gradients were similar to modern-day gradients, then a 115-m rise could be extrapolated to YM. This degree of rise could possibly be used to define a reasonable upper limit for rise of the water table at YM during future pluvial climates. Such a rise would significantly reduce the thickness of the unsaturated zone barrier at YM, but it would not saturate a hypothetical repository in the Topopah Spring tuff. A water-table rise of this magnitude would generate spring flow in areas south of YM, which would provide surface drainage outlets for groundwater and perhaps reduce the potential for greater rise.

The depth of the water table beneath the Lathrop Wells Diatomites has now been confirmed by Nye County's 1999 drilling program. The water table is only 16 m below land surface in well 1D, and 30 m below land at 9S. Therefore, at these sites, the water table has declined no more than 30 m since the paleosprings last flowed at the end of the Wisconsin, about 12 kyr B.P. The shallow groundwater solves a bit of a mystery, the nature of Rose's well, an old hand-dug well (now dry) not far distant from well 1D. The water table was evidently shallow enough to reach through hand-digging.

The staff recognizes that there is continuing discussion about the nature and age of the Lathrop Wells Diatomites. However, they should be interpreted as evidence of former water-table rise unless compelling evidence becomes available to prove that the deposits resulted entirely from the surface discharge of perched water. It is remotely possible that similar, undiscovered deposits may exist at higher altitudes and closer to YM. However, it seems unlikely that such deposits would have escaped the notice of geologists and soil scientists who have extensively mapped the region.

- Strontium isotopic evidence for calcites in the unsaturated zone

Marshall, et al. (1993) compared strontium isotope ratios for five different types of samples, including the paleospring sites, pedogenic (or near-surface) calcites, fracture-fill calcites from the unsaturated and saturated zones, and groundwater from the Tertiary aquifer. The fracture calcite samples came from five boreholes at YM. The calcites in the unsaturated zone have strontium ratios almost identical to the pedogenic calcites, suggesting that they have a similar origin. The only exceptions are four samples from fractures about 85 m above the water table in hole G-2. These four samples have strontium ratios that suggest a significant non-pedogenic component as a source for their strontium. Their strontium ratios are similar to those found in groundwater from the Tertiary tuff aquifer. Based on this, Marshall, et al. (1993) concluded that the water table may have been about 85 m higher than now. Marshall, et al. (1993) also noted that fracture-filling calcites from above and below the water table show different colors under ultraviolet light. Unsaturated zone calcites have a white to purplish fluorescence, whereas those from the saturated zone fluoresce from pink to orange.

- Glassy nonwelded material thins and disappears where the basal Topopah Spring occurs close to the water table

Bish and Vaniman (1985) used X-ray diffraction methods to study mineral distributions in tuffs at YM. They prepared cross-sections to show the distribution of minerals and glassy, or vitric, material. Their work was updated a few years later by Bish and Chipera (1989). An interesting pattern was found in the disappearance of vitric material in the tuffs. Below the dark layer of volcanic glass that forms the basal vitrophyre of the Topopah Spring is the Calico Hills non-welded tuff. The top of the Calico Hills contains abundant pumice and glassy shards in voids. This vitric zone occurs just below the vitrophyre. However, closer to the water table the glassy material mostly disappears. Bish and Vaniman state that the glassy material has been progressively altered to zeolites where the zone is closer to the water table. Based on the data from Bish and Vaniman (1985) and Bish and Chipera (1989), it appears that the base of the glassy (vitric) tuff is about 80-100 m above the current water table. This suggests to the staff that the water table was previously higher than now for extended periods, especially since the alteration process may have required thousands of years. The data do not indicate when the water table was higher, but do suggest that the water table may have risen no more than about 100 m higher than at present.

Levy (1991) further discussed the use of geochemical indicators in nonwelded tuffs to interpret paleohydrology. She notes that most zeolites in these tuffs appear to be products of diagenetic alteration in which zeolites were precipitated when the original glassy material dissolved at ambient temperatures in a water-rich environment. Levy suggests that zeolitization may require time periods on the order of 10 kyr, and that much of the zeolitization may have occurred long ago. The static water level (SWL) is presently about 100 m below the glassy-zeolitic boundary, a stratigraphic transition zone that is about 10 m thick. Levy (1991) states (p. 482) that

...the vitric-zeolitic transition in the central-eastern part of Yucca Mountain probably marks the hig' SWL established at the mountain during the last 12.8 myr. The SWL remained at its highest posi. no more than 1.2 myr. Subsequent water levels may have existed at higher elevations than the present SWL (about 120 m below the zeolitic transition in [well] G-4), but have not been any higher than 16 m below the zeolitic transition and perhaps no higher than 59 m below the transition (adding the 43-m thickness of the devitrified zone in H-6 to the 16-m depth of glassy tuff below the transition).

Levy also stated that, compared to mineralogic changes, features such as paleospring mounds are more direct indicators of former hydraulic conditions because they were formed by aqueous transport and deposition. Levy (1991) concluded that the highest groundwater levels were reached and receded downward 11.6 to 12.8 million years ago, and since that time the water level at YM has probably not risen more than about 60 m above present levels. DOE (1992, p. 2-66) cites Levy's (1991, p. 2-66) estimate that the water table has probably not been higher than 60 m above its present level for prolonged periods. However, Levy's work occurred before more recent studies of the Lathrop Wells Diatomites that suggest higher potential rises of the water table.

- Other geochemical evidence

Quade and Cerling (1990, p. 1549), writing in the journal Science, reached the following conclusions:

> Comparison of the stable carbon and oxygen isotopic compositions of the fracture carbonates with those of modern soil carbonates in the area shows that the fracture carbonates are pedogenic in origin and that they likely formed in the presence of vegetation and rainfall typical of a glacial climate. Their isotopic composition differs markedly from that of carbonate associated with nearby springs. The regional water table therefore remained below the level of Trench 14 [located on the eastern side of YM] during the time that the carbonates and silica precipitated, a period probably covering parts at least the last 300,000 years.

- Presence of a perennial paleodischarge site in Fortymile Wash

To the northeast of YM there is paleoecological evidence of higher recharge and precipitation in the past. A perennial discharge site existed in Fortymile Canyon about 50 kyr ago. Spaulding (1994) and others have studied ancient packrat nests, or middens, in the region. Modern-day packrats have a foraging radius of < 50 m, and materials preserved in the fossilized nests of their ancient ancestors can help identify local assemblages of prehistoric plants.

Spaulding and others (1994) found a set of ancient middens in northern Fortymile Canyon. They occur near the UE-29 boreholes about 12 km (7.4 mi) northeast of YM. Most of these ancient middens have carbon isotope ages of 13 to 22 kyr and contain no evidence of water-loving plants. But one midden was much more ancient, about 50 kyr or older (at the limit of radiocarbon dating), and contained remains of willows (*Salix*), knotweed (*Polygonum*), and wild rose (*Rosa*). These plants must have constantly damp soil or proximity to the water table to survive and reproduce (see the description of indicator plant species described by the National Research Council, 1992, p. 208-211). Spaulding (1994) refers to this older midden site as FMC-7, or Fortymile Canyon sample #7. It is on the eastern flank of Fortymile Wash about 60 m above the Canyon floor. The site is about 460 m north of wellsite UE-29. At this location the water table is presently more than 400 m higher than at YM. The water table at UE-29 is shallow, only 27 m deep, because this area is north of the so-called zone of high hydraulic gradient. At this canyon site a modest water-table rise of less than 30 m could generate spring flow in Fortymile Wash. Based on the location of FMC-7, inferred erosion rates, present-day groundwater elevations, and fossil plants, Spaulding (1994) concluded that the water table was 75 to 95 m higher during the period from 73 kyr to 47 kyr B.P.

- Inferences based on the extent of paleolakes

Mifflin (1990) described the regional hydrologic effects of past pluvial climates in the YM region. Based on the extent of former pluvial lakes in the Great Basin, effective moisture (runoff and recharge) was elevated by about an order of magnitude over modern conditions, and regional water tables rose as much as several hundred feet.

- Timing in changes of potentiometric levels of the carbonate aquifer at Devils Hole

Winograd and Szabo (1988, p. 151-152) stated that "...the continuing uplift of the Sierra Nevada...and Transverse Ranges, and lowering of Death Valley...relative to surrounding regions, should result in a continued progressive decline of the regional water table in the next 100,000 to 1 million yr (and beyond?) in response to increasing aridity and to lowering of ground-water base level." However, Winograd and Szabo (1988, p. 151) noted that their suggestion of a long-term lowering of the regional water table does not preclude relatively rapid fluctuations in response to pluvial climates of the Pleistocene, as indicated by data from Devils Hole in the Amargosa Desert.

There is solid evidence from Devils Hole of a Wisconsin-age rise of potentiometric levels in the Paleozoic carbonate aquifer. Szabo, et al. (1994) reported a record of water-table fluctuations in Brown's Room at Devils Hole. Their data are extensive enough to suggest that the water table may have been more than 4 m higher than present-day levels throughout the Wisconsin. They specifically conclude that the paleo-water table stayed more than 5 m above present levels between about 116 kyr and 53 kyr ago, that the level fluctuated between about +5 m and +9 m from 44 kyr to 20 kyr ago, and then declined rapidly from about +9 m to its present level during the last 20 kyr. Szabo, et al. (1994) considered climate change to be the main cause of water-table fluctuations over the last 100 kyr.

The water-level changes at Devils Hole relate only to the Paleozoic carbonate aquifer within the Ash Meadows groundwater basin and cannot be used to determine water levels in other aquifers. But groundwater levels in this regional aquifer must exert a major control on water levels in overlying tuff and valley-fill aquifers. Because the Ash Meadows groundwater basin is very large, Szabo, et al. (1994, p. 68) suggested that the data from Brown's Room "may record the timing of regional hydrologic changes that occurred in the southern Great Basin." The staff agrees with this, and believes that the timing of significant water-level fluctuations at YM should correlate reasonably well with those at Devils Hole. This is reasonable even though YM and Devils Hole may exist in different subbasins of the regional Death Valley groundwater flow system (Laczniak, et al., 1996). The fact that the water table at YM may have risen more than at Devils Hole would not be unusual, because of the proximity of YM to areas of higher elevation where recharge would have been enhanced. Higher transmissivities in the Paleozoic carbonate aquifer would also result in smaller fluctuations of the potentiometric surface at Devils Hole. It should also be mentioned that the Wisconsin-age rise of the potentiometric surface at Devils Hole may have been controlled, to some extent, by local topography. The present water table is only 17 m below the land surface (Szabo, et al., 1994). Areas close to Devils Hole occur at lower elevations where surface discharges of groundwater could occur during times of elevated water tables. This could perhaps limit the

Wisconsin-age rise of the water table to less than 10 m at Devils Hole, as inferred from calcites in the subterranean Browns Room.

The staff's views about water-table rise are strongly influenced by the fact that paleoclimatic indicators throughout the Great Basin are reasonably consistent. For example, the Wisconsin-age high stands measured at Devils Hole are consistent with a long-duration high stand of Searles Lake, and with the reported dates of paleospring flow at the Lathrop Wells Diatomites. Likewise, there is reasonable correlation between proxy paleoclimatic records for Searles Lake, Las Vegas Valley, Grand Canyon travertine, south-central Nevada plant records, and Brown's Room at Devils Hole (Szabo, et al., 1994). A high stand of Lake Manley in Death Valley (Li, et al., 1996, Fig. 16) also coincides with the general timing of high stands of Searles, Lahontan, and Bonneville Lakes, and with a high groundwater stand in Devils Hole. Long-term records of paleolake levels in particular show important differences that must be related to local hydrologic conditions. For example, Lake Manly was the last in a chain of "overflow" lakes, and it therefore did not always receive a substantial surface-water influx.

Szabo, et al. (1994) and other investigators have noted inconsistencies in the paleoclimatic data that have yet to be explained. But in general, except for the temperature proxy data from Devils Hole, the paleoclimatic data are discontinuous and only provide "snapshots" of prevailing conditions at various sites and times. The well-dated, relatively continuous 500-kyr record of paleotemperatures from Devils Hole (Winograd, et al., 1992) is one of the best paleoclimate records in existence and has been used to link past climate change in the Great Basin to changes elsewhere. The staff has determined that this and other paleoclimate records could reasonably be used to estimate the likely range of future climate variability at YM.

- Inferences from hydrologic modeling of the saturated zone flow system

Czarnecki (1985) used a finite-element model to simulate the effects of a future increase in precipitation and recharge on water levels. He concluded that a doubling of precipitation could lead to a 15-fold increase in recharge and a water-table rise of 130 m beneath YM. Although Czarnecki's (1985) work suggests that water-table rises greater than 120 m are not impossible, the preponderance of field evidence suggests that the water table has risen less than 120 m above present levels for extended periods since the deposition of the volcanic tuffs. The Paintbrush and Calico Hills tuffs were deposited more than 10 million years ago (DOE, 1988a, p. 1-56).

Ahola and Sagar (1992) developed a regional flow model and analyzed various phenomena that could influence the regional water table. They estimated that a water-table rise of about 75-100 m could occur in response to a 10-fold increase in groundwater recharge. This particular analysis included a zone of enhanced recharge that represented Fortymile Wash. They concluded that the water table near Yucca Mountain is relatively sensitive to variations in recharge along this wash.

The following table briefly summarizes the degree of former water-table rise that has been estimated by various workers.

Table 2. Estimates of former water-table rise.

Nye County, 1999	Lathrop Wells Diatomites, SW of YM	Well NC-EWDP-1D (water table is 16 m below land surface) Well NC-EWDP-9S (water table is 30 m below land surface)
Forester, et al., 1996	YM and southern Nevada	Up to 100-120 m at various times during the last two glacial cycles.
Paces, et al., 1996	Lathrop Wells Diatomites, SW of YM	100-120 m (data suggest elevated regional water tables as much as 60-80 percent of the last 200 kyr).
Quade, Mifflin, et al., 1995; Quade, 1994	Lathrop Wells Diatomites, 20 km (12 mi) SW of YM	< 115 m
Szabo, et al., 1994	Brown's Room, Devils Hole (Ash Meadows - Paleozoic carbonate aquifer)	up to +9 m
Spaulding, 1994	Fortymile Canyon NE of YM (FMC-7 packrat midden site)	75-95 m
Paces, et al., 1993	Lathrop Wells Diatomites, SW of YM	80-115 m
Marshall, et al., 1993	YM boreholes	< 85 m
Ahola & Sagar, 1992	YM (regional groundwater model)	75-100 m
Levy, 1991	YM boreholes	< 60 m
Mifflin, 1990	YM region	Less than 100 m in the YM region
Bish & Vaniman, 1985; Bish & Chipera, 1989	YM boreholes	< 100 m (inferred by NRC staff)
Czarnecki, 1985	YM (regional groundwater model)	< 130 m

This status report has focused on the effects of past climate change on the regional water table and w may reasonably be expected in the future. Wisconsin-age water-table rise occurred under natural conditions uninfluenced by humans. Future human activities will undoubtedly have a major influence on the regional flow system. The most recent water-supply forecast for southern Nye County (Nevada) is presented by Buqo (1997). Despite access to Lake Mead, the city of Las Vegas is experiencing water supply problems. Las Vegas continues to be one of the fastest growing cities in the United States. WRMI (1992) reported that, even if responsible water conservation is imposed, all available water resources would be fully used by the year 2006, and after that time additional water sources would be needed. Groundwater is the most likely new source of water supplies for Las Vegas Valley, and given the very low rates of groundwater recharge in southern Nevada it will be necessary to adopt a regional approach to groundwater development to prevent local potentiometric drawdowns from becoming extreme. This means that a large region will have to be developed for groundwater supplies, including areas to the north and west. The YM site and the Amargosa Desert occur in this extended region northwest of Las Vegas Valley.

DOE may consider that human activities could cause future water-table rise to be less than occurred in the past. However, DOE's safety analysis should assume that the climate-related component of future water-table rise will be at least as great as has occurred in the past. DOE must reasonably demonstrate that predicted future water-table conditions are consistent with postulated dose scenarios, which may include groundwater pumping, irrigation, and other activities.

4.3 PRESENT-DAY SHALLOW INFILTRATION

Review methods, acceptance criteria, and technical bases for the subissue of present-day shallow infiltration were provided in a previous version of this IRSR which is provided as Attachment E (NRC, 1997b). Those acceptance criteria have been simplified and are listed below. The status of issue resolution is given in Section 5.3.

4.3.1 Acceptance Criteria

(1) DOE has estimated present-day shallow infiltration at YM for use in TSPA using mathematical models that are reasonably verified with site-specific climatic, surface, and subsurface information, and the fundamental effects of heterogeneities, time-varying boundary conditions, evapotranspiration, depth of soil cover, and surface-water runoff have been considered in ways that do not underestimate infiltration.

(2) DOE has analyzed infiltration at appropriate time and space scales for performance assessment, and has tested the abstracted model against more detailed models to assure that it produces reasonable results.

(3) DOE has characterized shallow infiltration in the form of either probability distributions or deterministic upper-bound values for performance assessment, and provided sufficient data and analyses to justify the chosen probability distribution or bounding value.

(4) If DOE can show through TSPA and associated sensitivity analyses that refinements of shallow infiltration estimates will not significantly alter performance predictions, no further refinement will be necessary.

(5) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

4.3.2 Technical Basis for Review Methods and Acceptance Criteria

See NRC (1997b) for a description of the technical basis for review methods and acceptance criteria for the subissue on present-day shallow infiltration (see attachment E). Our revised map of estimated shallow infiltration at YM is shown in Figure 2. It supercedes Figure B-2 in attachment E. Several components used in the estimation process have been updated in the revised shallow infiltration map. The revised map uses a grid resolution with sides 7.5 m long, obtained through cubic interpolation from the digital elevation model using 30-m pixels; the soil thicknesses estimated using the finer grid better represent the topography and are less subject to numerical artifacts. The bedrock representation is now based on the Day et al. (1997) central-block geologic map. The soil, bedrock, and fracture properties have been updated. Revised abstractions for mean annual infiltration as a function of soil, bedrock, and fracture properties were developed. Also, the effects of transpiration are heuristically included in the

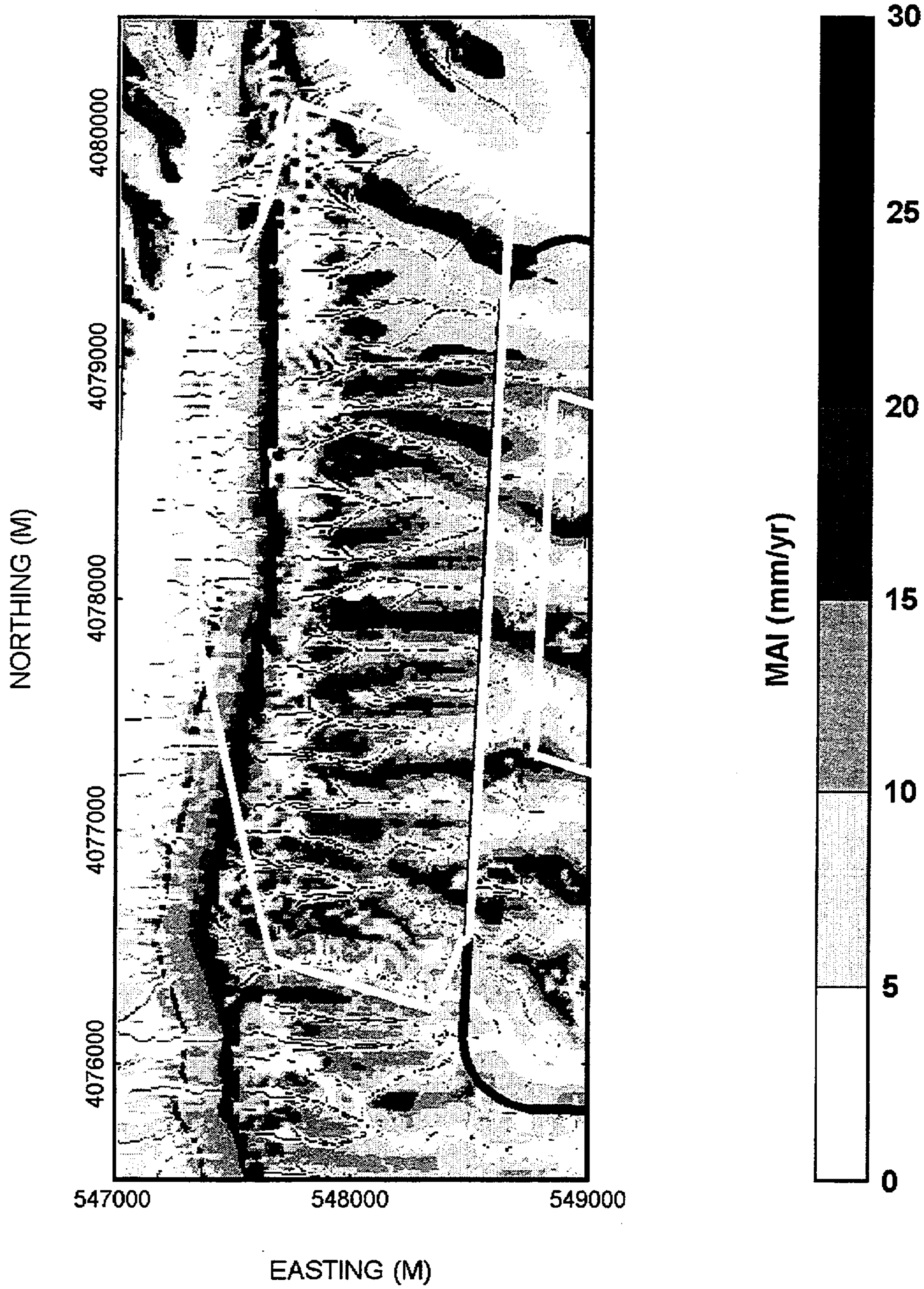

Figure 2. Revised estimate of net infiltration in the vicinity of the proposed repository footpri

model by reducing bare-soil net infiltration predictions increasingly as soil thicknesses increase. The heuristic model assumes that vegetation will prevent almost all infiltration if the soil thickness is at least 1 m in thickness and will be ineffective if there is no soil. Ongoing work will provide additional bases for the heuristic model.

The revised interpretation shows lesser infiltration over the footprint than did the previous estimate. The finer grid does not change net infiltration over the footprint itself, although over a larger area net infiltration increases by a factor of 1.5. The combination of updated properties used in the model and an updated abstraction for bare-soil net infiltration tends to increase net infiltration. However, the heuristic model accounting for vegetation significantly decreases predictions of net infiltration in deeper soils, enough that overall model predictions are lower than before. Depending on assumptions, the revised interpretation of net infiltration over the repository footprint is roughly in the range of 6 to 12 mm/yr, while the previous interpretation was in the range of 15 to 22 mm/yr.

4.4 DEEP PERCOLATION (PRESENT AND FUTURE [POST-THERMAL PERIOD])

The staff's technical review of DOE's treatment of deep percolation will be based on an evaluation of the completeness and applicability of the data and evaluations presented by DOE. It is expected that DOE will summarize or document the results of all significant-related studies that have been conducted in the YM vicinity. The staff will determine whether DOE has reasonably complied with the acceptance criteria listed below.

4.4.1 Acceptance Criteria

(1) Estimates of deep percolation flux rates and the fraction of flux that occurs in fractures will be acceptable provided that they are: (i) shown to constitute a conservative upper bound, or (ii) based on a technically defensible UZ flow model that reasonably represents the physical system, including flow in fracture systems and matrix-fracture interaction. The flow model has been calibrated using site-specific hydrologic, geologic, and geochemical data.

(2) To estimate deep-percolation flux, spatial and temporal variability of model parameters and boundary conditions must be considered. Model parameters must be averaged over appropriate time and space scales. DOE must also consider climate-induced change in soil depths and vegetation.

(3) For estimates of the amount of water that may contact waste packages DOE must (i) demonstrate that coupled thermal-mechanical-chemical changes in rock mass properties will not focus deep percolation into the drifts; and (ii) rigorously justify estimated diversion of deep percolation away from the waste package footprints. This must include direct observations of dripping in test drifts or tunnels under ambient (unventilated) conditions in the repository horizon, or in an analog horizon with similar characteristics. Also needed are model calculations that account for the effects of backfill (if used) drift collapse, and coupled thermal-mechanical-chemical changes to rock properties. The models have been calibrated to niche studies and tracer tests in the ESF, or using an analog with characteristics similar to the repository horizon.

(4) In predicting likely flow and transport pathways beneath the proposed repository horizon, DOE must either (i) conservatively assume that all deep percolation below the repository level bypasses the bulk of the non-welded units, either by lateral movement above the units or through vertical flow through fractures and faults; or (ii) demonstrate that the estimated fraction of deep percolation that flows vertically through the matrix of the non-welded units is supported by (a) characterization data and (b) two-dimensional or three-dimensional modeling that accounts for spatial and temporal variability that may result in lateral diversion of flow, and uses model parameter values appropriate for the scale of model discretization.

(5) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

\.4.2 Technical Basis for Review Methods and Acceptance Criteria

- **Definitions**

To ensure clarity, the staff have developed definitions for various terms related to deep percolation. The terms infiltration, shallow infiltration, net infiltration, percolation, seepage, and recharge refer to flow across a boundary or datum. The NRC staff associates the term infiltration with near-surface processes and the term percolation with processes deeper in the unsaturated zone. Emphasis is placed on the types of processes as well as on the vertical delineation in the following definitions:

Shallow Infiltration Flux - The liquid-water flux that has moved beyond the zone of evapotranspiration and remains in the rock is called shallow infiltration. In other words, this is the fraction of precipitation that has penetrated the ground surface and moved just below the zone of evaporation and the zone of plant roots. Relative to the entire UZ column, shallow connotes both a spatial delineation and a distinction of the type of processes affecting flow. Shallow infiltration incorporates the surface and near-surface processes of precipitation, runoff, heat flux, and evapotranspiration. These processes impact groundwater flow in the colluvial and alluvial sediments as well as the top few meters of bedrock. Although there may be evaporation from the fracture system down to the PTn and further, especially as suggested by the high air permeability in the TCw, the amount is not considered significant with respect to the MAI. Net infiltration is used interchangeably with shallow infiltration.

Deep Percolation Flux - The liquid-water flux below the zone of shallow infiltration that moves downward through the UZ is called deep percolation flux. Excluding lateral flow, the upper bound for the magnitude of average vertical deep percolation flux is the average shallow infiltration flux. The zone of deep percolation covers the 500 to 700 meters of the unsaturated domain below the shallow infiltration zone down to the water table. Percolation is governed by flow processes in the fractured bedrock comprising ıe portion of the UZ below the impact of evapotranspiration, hence the deep portion of the unsaturated column. The study of deep percolation addresses flow processes above, near, and below the repository horizon, including lateral flow, perched water formation, and matrix/fracture interaction.

Seepage Flux - The fraction of the deep percolation at the repository horizon that enters the drifts is the seepage flux. The physics of flow at the interface of the bedrock and the drift, such as capillary diversion of matrix flow around the drift and the spatial relationship between fractures and drift, determine the fraction of percolation flux above the drifts that becomes seepage flux into the drift.

Recharge - The downward liquid-water flux across the boundary delineated by the water table.

Under the assumptions of steady state and downward flow with no lateral component, all of these flux values are equal in magnitude. At YM, the assumptions are not likely valid at the drift boundary and below the repository.

Evaluation of the following topics provided key support for review methods and acceptance criteria for deep percolation.

General discussion about deep percolation
Measurements and modeling related to deep percolation at YM (Bodvarsson, et al., 1997a)
Conceptualization of site-scale flow from the near surface to the water table (Geomatrix, 1997)
Conceptualization of small-scale flow in fractures and fracture/matrix interactions

Estimates of deep percolation from geochemical, thermal, and water distribution data (Bodvarsso' al., 1997a)
Estimates of deep percolation based on numerical simulations (Bodvarsson, et al., 1997a)
Past evidence and impact of future climate changes on deep percolation (NRC, 1997b)
Pneumatic responses at YM (Ahlers, et al., 1996; 1997)
Evidence for fast pathways (Fabryka-Martin, et al., 1997)
Calculated distribution of percolation at the repository horizon (Flint, et al., 1996a; NRC, 1997b)
Summary of deep percolation topics that warrant further analysis

4.4.2.1 General Discussion About Deep Percolation

It can be simply (and conservatively) assumed, for the purposes of PA, that all net shallow infiltration (i.e., water entering the subsurface below the root zone) within and updip of the repository footprint enters the waste packages (WP) and contacts waste. However, this assumption is not realistic. Geometric arguments alone suggest that only a small fraction of this total flux should be intercepted by the emplacement drifts because the area occupied by drifts is a small fraction of the area of the repository footprint. There are several additional ways that the fraction of shallow infiltration contacting waste may be reduced or that some portion may bypass the WPs, including

- Evaporation from below the root zone
- Lateral diversion due to capillary or permeability contrast, such as might occur at the Paintbrush Tuff nonwelded (PTn) unit
- Local lateral diversion due to capillary or permeability contrast, such as might occur at the rock/drift interface
- Lateral diversion within the drift (e.g., by drip shields or other engineered systems)

On the other hand, some heterogeneities such as fracture and fault zone may focus the infiltration into flow paths that may carry a larger fraction of flux than would normally be expected from geometric arguments alone.

If flow is predominately within the matrix, the drifts would tend to be protected through capillary-barrier effects, and migration through the UZ would tend to be quite slow (e.g., assuming 1 mm/yr fluxes and 10 percent average moisture content, water travel times for 100 m would be 10^4 yr and sorption processes might retard many radionuclides further). The relatively low permeabilities of the matrix at the repository horizon would tend to require large saturations everywhere in space and many drifts might be affected by matrix fluxes. On the other hand, if flow is predominantly through the fractures, the drifts would be less well-protected through capillary-barrier effects and travel times to the water table would be drastically reduced. Also, as permeabilities of the fractures are rather large relative to the current estimates of percolation flux, it is possible that relatively few fractures might carry the bulk of the water and only a few drifts would be contacted by a flowing fracture. Accordingly, it is important to characterize percolation flux in terms of the capacity for driving fracture flow at and below the repository horizon.

Net vertical infiltration from the ground surface is the predominant source of moisture for deep percolation, with the water table potentially contributing a small amount of water through capillary rise and vapor redistribution due to the geothermal gradient. Deep percolation patterns can be strongly dependent on the ature of infiltration due to the intermittent pattern of precipitation in arid and semiarid climates. For example, consider a homogeneous fractured welded tuff with a matrix saturated hydraulic conductivity (K_{sat}) of 10 mm/yr and a fracture K_{sat} of 10^4 mm/yr. If a source of water is applied at a steady rate of 5 mm/yr, then the fractures will not be active due to capillary effects. On the other hand, if the same total volume of water is due to an extreme precipitation event and is applied over a short period, for example 1 month out of every 10 yr, the average flow during that month is equivalent to 600 mm/yr and, at best, the matrix can carry 1.7 percent of the total flux, leaving the remainder to the fractures. Higher flux rates may occur, as a significant rainfall might be 1 cm over a period of a day (equivalent to 3,650 mm/yr). Even larger proportions of total flux may be carried in the fractures if the same total inflow is focused into small areas, such as stream channels. If the pulses are not attenuated with depth, one would expect flows at the repository horizon to be episodic and dominated by fracture flow. On the other hand, if the pulses are strongly attenuated with depth, such that average infiltration rates are sufficiently low, flows would tend to be matrix-dominated at the repository horizon. Accordingly, the episodicity of infiltration, the localization of influx, and the ability of the vertical profile to attenuate the wetting pulses are issues that should be appropriately evaluated in order to characterize the behavior of deep percolation. The use of steady-state percolation fluxes may significantly misrepresent the partitioning of deep percolation into matrix and fracture fluxes.

The ability of any method to estimate deep percolation under climatic variation is another issue to be considered. This issue is only briefly discussed in this IRSR. However, the performance of the potential repository should be assessed over periods of time long enough that climatic variation will be a factor. Percolation flux changes in response to climatic variations may be translated from changes to shallow infiltration and may primarily be reflected both in magnitude and distribution of flux. Therefore, methods for estimating deep percolation that are suitable for such long time periods are more useful for PA than methods that can only be applied for current climatic conditions.

4.2.2 Measurements and Modeling Related to Deep Percolation at Yucca Mountain

A wide variety of methods are used to model the movement of water in fractured porous media. Good overviews of some of the more common methods to study rock fractures and fluid flow are presented in Evans and Nicholson (1987), Bear, et al. (1993), and National Research Council (1996). Prior to the intensive work at YM, unsaturated flow in fractured porous media received little attention. Saturated fractured porous media received more attention due to topics of water supply, petroleum, and potential nuclear repository sites in other countries (Canada, Sweden, France). The development of methods to study unsaturated flow in fractured rock domains was primarily driven by YM as evidenced by the appropriate sections of Evans and Nicholson (1987), Bear, et al. (1993), and National Research Council (1996) on unsaturated flow. The methods have evolved as new information was gained. As such, the following sections contain descriptions of the current status of methodologies applied to YM, which taken as a whole, present a convergence of estimates for percolation for present day conditions. However, specific aspects of flow at YM remain unclear thus necessitating a close review of the methods used; appropriate comments are discussed in each section.

The primary source of integrated information for UZ flow at YM is the work on the site-scale model by Lawrence Berkeley National Laboratory (LBNL). The LBNL UZ model of YM (Wittwer, et al., 1995; Bodvarsson and Bandurraga, 1996; Bodvarsson, et al., 1997a) is an ongoing synthesis of data focused on the development of numerical models that capture the important features of flow both at the site scale and at the smaller drift scale. Concurrent studies of site scale processes at Sandia National Laboratories (SNL) (Arnold, et al., 1995; Altman, et al., 1996) and at Los Alamos National Laboratory (LANL)

(Robinson, et al., 1997) focus on groundwater velocities and transport of radionuclides through the UZ Concurrent drift-scale experiments (niche and alcove) and modeling is being done by Lawrence Liverr. National Laboratories (Nitao, 1997) and LBNL (Wang, et al., 1998; Birkholzer, et al., 1997a).

- **Unsaturated Zone Hydrostratigraphy**

The LBNL site-scale UZ hydrogeologic model of YM (Bodvarsson, et al., 1997a) has been the primary mechanism of data synthesis for numerical simulations. Recently the Geologic Framework Model (GFM) ISM2.0, created by the Management and Operations (M&O) contractors at YM, became the standardized model.

Following Montazer and Wilson (1984), the primary hydrostratigraphic units consist of alternating zones of moderately to densely welded, highly fractured tuffs and non- to partially-welded, highly porous tuffs. From highest to lowest, these units are:

- The Tiva Canyon Welded (TCw) unit, consisting of the moderately to densely welded portions of the Paintbrush Group.
- The PTn unit, consisting of the partially welded to nonwelded portions of the Tiva Canyon Tuff underlying the TCw, alternating layers of bedded tuffs of the Yucca Mountain Tuff and Pah Canyon Tuff and the partially welded to nonwelded portions of the Topopah Spring Tuff.
- The Topopah Spring Welded (TSw) unit, consisting of the moderately to densely welded portions of the Topopah Spring Tuff.
- The CHn unit consisting of the formations underlying the basal vitrophyre of the TSw and including the nonwelded to partially welded portions of the lower part of the Topopah Sprir Tuff, the Calico Hills Formation, the Prow Pass Tuff of the Crater Flat Group, and the nonwelded to partially welded portion of the Bullfrog Tuff of the Crater Flat Group.
- The Crater Flat Undifferentiated (CFu) units consisting of the lower Bullfrog and Tram Tuffs of the Crater Flat Group (only found in the UZ below Yucca Crest south of the repository).

Table 3, taken from Hinds, et al. (1997), illustrates the relationship between the hydrostratigraphic units and the geologic units as delineated by Buesch, et al. (1996). The geologic units are illustrated in cross-sections (Figure 3) from Hinds, et al. (1997). Detailed geologic descriptions of the PTn subunits are in Moyer et al. (1996) with the description of the fracture characteristics in Sweetkind, et al. (1995, 1997). Descriptions of the CHn and Prow Pass Tuff are found in Moyer and Geslin (1995) and Loeven (1993). Measurements of core samples including porosity, saturation, bulk density, and permeability for the major hydrostratigraphic units are reported in Flint (1997). A synthesis of the stratigraphic and fracture data, as combined with a geologic site-scale model into a hydrostratigraphic model, is described in Bandurraga and Bodvarsson (1997) and Sonnenthal, et al. (1997a).

In general terms, the nonwelded bedded tuffs have high porosities and low fracture frequencies, whereas the welded tuffs typically have low matrix porosities and high fracture frequencies (Hinds, et al., 1997). In terms of fracture data, there is a high density of fractures near vitric (both crystal-rich and crystal-poor) and nonlithophysal units, relatively high fracture density within nonlithophysal as compared to lithophysal units, relatively lower fracture density within the nonwelded PTn, and very low fracture density within the CHn.

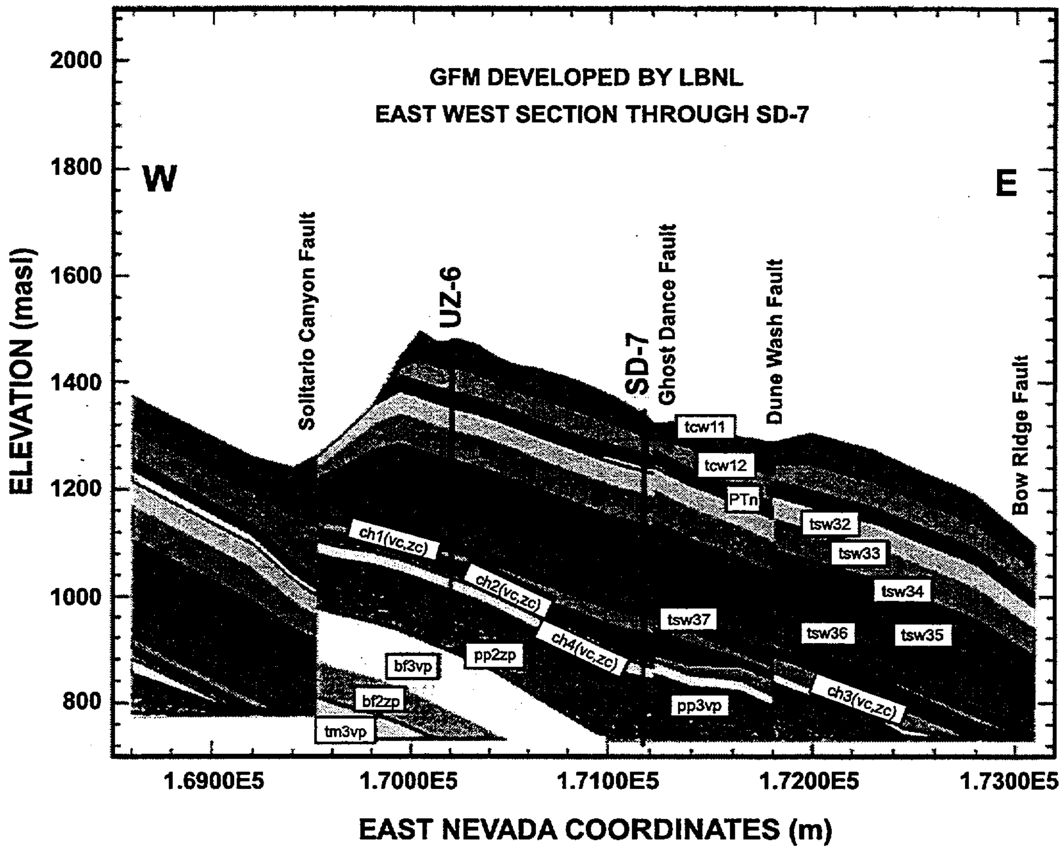

Figure 3. East-west geologic cross-section across the repository from Hinds, et al. (1997).

Table 3. Relationship between model hydrogeological units and geological formation (Lawrer Berkeley National Laboratory geological model from Hinds, et al., 1997)

Geological Unit	Welding Intensity/Formation Name (Buesch, et al., 1996)	Model Layer Name	Hydrogeological Unit
Paintbrush Group			
Tiva Canyon Tuff	M,D[1] (Tpcxxxx)	tcw11 tcw12	Tiva Canyon
	D-Basal vitrophyre (Tpcpv3) M (Tpcpv2)	tcw13	
	N,P (Tpcpv1)	ptn21	Paintbrush
Bedded Tuff	N (Tpbt4)		
Yucca Mountain Tuff	N,P,M (tpy)	ptn22	
Bedded Tuff	N (Tpbt3)	ptn23	
Pah Canyon Tuff	N,P,M (Tpp)	ptn24	
Bedded Tuff	N (Tpbt2)	ptn25	
Topopah Spring Tuff	N,P (Tptrv3)		
	M (Tptrv2) D-Upper vitrophyre (Tptrv1)	tsw31	Topopah Spring
	M,D (Tptrn)	tsw32	
	M,D,L[2] (Tptrl) M,D,L (Tptpul)	tsw33	
	D (Tptpmn)	tsw34	
	M,D,L (Tptpll)	tsw35	
	D (Tptpln)	tsw36	
	D-Basal vitrophyre (Tptpv3)	tsw37	
	N,P,M; may be altered (Tptpv1, Tptpv2)	ch1(vc or zc)	Calico Hills
Bedded Tuff	N; may be altered (Tpbt1)		
Calico Hills Formation	N; unaltered (Tac-vitric)	ch2(vc or zc)	
	N; altered (tac-zeolitic)	ch3(vc or zc)	
Bedded Tuff	N; may be altered (Thtbt)	ch4(vc or zc)	

Geological Unit	Welding Intensity/Formation Name (Buesch, et al., 1996)	Model Layer Name	Hydrogeological Unit
Crater Flat Group			
Prow Pass Tuff	N; may be altered (Tcp) Unit 4[3]		
	P,M Unit 3	pp3vp	
	N,P; generally altered Units 2,1	pp2zp	
Bedded Tuff	N; generally altered (Tcpbt)		
Upper Bullfrog Tuff	N;P; generally altered (Tcb)		
Middle Bullfrog Tuff	P,M	bf3vp	
Lower Bullfrog Tuff	N,P; generally altered		Crater Flat Undifferentiated
Bedded Tuff	N; generally altered (Tcbbt)	bf2zp	
Upper Tram Tuff	N,P; generally altered (Tct)		
Older tuffs and lavas	Generally altered (Tct)	tr3zp	
		tr2zp	

[1]Welding Intensity N=Non P=Partially; M=Moderately; D=Densely
[2]L=Lithophysal Zone
[3]Units per Moyer and Geslin (1995)

Features that increase matrix porosity and hydraulic conductivity are a lower degree of welding and the presence of lithophysae in the welded units.

The TCw hydrostratigraphic unit is subdivided into 3 model layers (Table 3) for the LBNL site-scale model. As an indication of the importance of fracture flow in the TCw, the delineations preserve units of generally similar fracture characteristics (Sweetkind, et al., 1997). As the uppermost unit, the TCw varies in thickness based on erosional features. The PTn hydrostratigraphic unit is subdivided into 5 model layers that generally correspond to both the lithostratigraphic units of Buesch, et al. (1996) and the delineations based on pneumatic testing (Sweetkind, et al., 1997). The overall thickness of the PTn varies from about 20 m in the south to 170 m in the north in the area of the LBNL site-scale model (Wittwer, et al., 1995). The 7 model layers of the TSw hydrostratigraphic unit correspond to lithostratigraphic units of Buesch, et al. (1996). The delineations correspond to variations in porosity, saturation, and capillary pressure measurements. The overall thickness of the TSw is greatest in the center of the LBNL site-scale model area and decreases to the north, varying from 340 m to 50 m thick (Wittwer, et al., 1995). The Calico Hills hydrostratigraphic unit is divided into 7 model layers of which the top 4 model layers may transition from vitric to zeolitic. The Calico Hills hydrostratigraphic unit includes a portion of the basal TSw vitrophyre, the Calico Hills Formation, Prow Pass, and upper portion of the Bullfrog Tuffs. The thickness of the Calico Hills Formation ranges from about 30 m in the southwest to 300 m in the north, whereas the Prow Pass Tuff varies from about 200 m in the east to 80 m in the west (Moyer and Geslin, 1995).

The LBNL and the ISM2.0 models correlate well except for several instances of grouping of layers in the latter model, and for the delineation of units below the TSw (Hinds, et al., 1997). The Calico Hills hydrostratigraphic unit is a zone of the geologic section that is particularly important to repository performance. The LBNL model uses altered zones as a basis for sublayering and delineates a transition within each sublayer based on a threshold zeolite weight percent. The LBNL model follows the Moyer and Geslin (1995) interpretation that describes a gap in the alteration in the southwest portion of the repository that extends through all sublayers of the CHn. However, Chipera, et al. (1997) state that there is no gap in the alteration. LANL site-scale modeling (Robinson, et al., 1997) uses the ISM2.0 geologic framework model and adds a mineralogic model that modifies CHn sublayer properties in order to incorporate hydrologic properties of zeolites in the CHn unit. In contrast, the LBNL modeling (Hinds, et al., 1997) assigns appropriate hydrologic property values to zeolitic and to vitric model sublayers of the CHn. This topic is discussed in more detail in a later section.

Structural features of importance to flow in the UZ are faults, fractures, joints, and bedding planes. These discontinuities form interconnected networks at varying scales. The central part of YM is a relatively undeformed block of Miocene tuff bounded on the west by the Solitario Canyon Fault (SCF) and by the Bow Ridge fault (BRF) located about 3.5 km to the east (see Figure 3). These block-bounding faults have predominantly dip-slip separations with cumulative displacements between 100 and 1000 m (Day, et al., 1997; Scott, 1990). Both dip moderately to steeply to the west (Day, et al., 1997). Within the YM block are north-south striking normal and northwest-southeast striking dextral strike-slip faults. These secondary faults are often discontinuous or *en echelon* and have displacements between 1 and 50 m. The Ghostdance Fault (GDF) is one of the largest intrablock faults, having up to 25 m of dip-slip offset separation. It is discontinuous at the surface. The Sundance (SDF) and Drill Hole Wash (DHW) faults are two of the better known strike-slip faults. Because of localized fracturing and the possible connectivity through numerous thermal mechanical units associated with the structures, these faults can be important to groundwater flow in the UZ. On a smaller scale, the fracture and joint systems and bedding planes also important to groundwater flow in the UZ. Fracture systems may cross or interfinger across lithologic and thermal-mechanical boundaries. Cooling joint systems are generally confined within thermal-mechanical units (e.g., Sweetkind, et al., 1997). Each thermal-mechanical unit has a characteristic set of fracture and joint attributes, including orientation, distribution, intensity, and length (e.g., Sweetkind and William-Stroud, 1996). Lateral flow along sub-horizontal cooling joints, fractures, and bedding planes can be locally important to flow in the UZ. Layering in the fault blocks dip 5 to 15 degrees to the east (Day, et al., 1997). Details of the important structural features and lithologic and thermal mechanical layering of YM are summarized in the Structural Deformation and Seismicity (SDS) IRSR (NRC, 1998a).

4.4.2.3 Conceptualization of Site Scale Flow from the Near Surface to the Water Table

The NRC conceptual model of flow from the near surface to the water table is broadly similar to the conceptual model proposed by Montazer and Wilson (1984). The Montazer and Wilson (1984) conceptual model has been generally supported by subsequent field studies and modeling. The work presented by Bodvarsson and Bandurraga (1996) and Bodvarsson, et al. (1997a), using available field observations to calibrate 1D, 2D, and 3D models, provides updated support for the Montazer and Wilson (1984) conceptual model. The conceptual models and measurements were reviewed by an expert-elicitation panel (Geomatrix, 1997), reinforcing the general agreement on conceptual models and elucidating disagreements. The following discussion presents the NRC conceptual model.

Water that flows through the zone of potential evapotranspiration, thus becoming net shallow infiltration, is believed to proceed via rapid flow through the highly fractured and relatively impermeable TCw matrix to the less fractured but highly porous and permeable PTn unit. The notion that fast flow occurs through the TCw is supported by the extensive presence of bomb-pulse ^{36}Cl throughout the TCw and into the top of the PTn. Pneumatic pulses are minimally attenuated within the TCw, suggesting that fast pathways are available for moisture flow as well. Rapid changes in gas pressure and temperature in boreholes, attributed to a pulse of water from a previous season (Bodvarsson and Bandurraga, 1997), are additional evidence suggesting that water moves quickly through the TCw. Velocities in the TCw may be as high as tens of meters per year based on the ^{36}Cl, temperature and gas pressure data. Once water moves below the rooting zone, some removal of vapor is believed to occur due to air flow within the TCw bedrock. Estimates for vapor removal, in terms of water flux, range from 0.1 mm/yr for a local value (Rousseau, et al., 1998) to 0.02 mm/yr (E. Weeks, presentation at the Unsaturated Zone Expert Elicitation Workshop, February 4, 1997).

As the water enters the PTn unit, the rate (and perhaps direction) of flow changes. Capillarity and the large storage capacity of the PTn may strongly dampen infiltration pulses, as is shown by numerous modeling studies. Depending on the fluxes from infiltration and the hydraulic properties of the PTn, water may pass through the PTn to the TSw unit through several pathways:

- Predominantly vertical movement through the matrix of the PTn, thereby strongly damping out infiltration pulses.
- Predominantly vertical movement through the PTn, with some local lateral flow focusing water into slump faults, thereby damping out infiltration pulses to a lesser extent.
- Predominantly vertical movement through local fast pathways formed by small-scale heterogeneities in the PTn matrix, thereby bypassing the bulk of the matrix and not strongly damping out infiltration pulses. In modeling exercises, this component of movement is termed fracture flow, but field observations do not support significant fracture flow *per se*.
- Lateral movement downdip at a permeability barrier at the base of the PTn, thereby damping pulses but perhaps significantly redistributing water to the east. The redistributed water may be focused into larger faults or may move into the fracture system to the west of the Ghost Dance Fault. Infiltration pulses are expected to be strongly dampened.
- Lateral movement downdip at the capillary barrier at the base of the TCw, again with a potential for focusing flows into larger faults or the fracture system. TCw matrix waters are likely to move downdip at a steady state, but only a small component of flux is likely to be involved. TCw fracture waters are likely to move downdip in (possibly large) transient pulses if the stratabound TCw fractures are not well connected to the PTn matrix.

There is substantial evidence suggesting that fast flow paths exist through the PTn (e.g., geochemical and bomb-pulse data below the PTn). These fast flow paths may carry a substantial portion of the entire infiltration flux. The actual pathways by which flow bypasses the PTn have not been determined. Most current DOE modeling efforts predict that bypass flows are predominantly vertical, as does expert elicitation (Geomatrix, 1997).

As with the TCw unit, flow in the TSw is believed to be predominantly in the fracture and fault systems. Strong damping of wetting pulses in the PTn would cause all flows below the PTn to be approximately steady state. The TSw matrix is likely to be approximately at a steady state regardless of the PTn, due to its low matrix permeability. If bypass fluxes are minimally damped, TSw fracture flows may be transient. The TSw matrix water contents are near saturation values, with little capacity for capillary action, and thus minimal fracture/matrix interaction is expected. The disparity between geochemical signatures of pore waters and perched waters further suggests that the matrix has little connection with fast paths. The fine pores of the TSw matrix are likely to provide a strong capillary barrier to entry into mined cavities, even if backfill were to be emplaced, so that water in the matrix is likely to be diverted around the cavities. On the other hand, TSw fracture flows have less of a capillary barrier to overcome in order to enter mined cavities, particularly if backfill were emplaced, so that the dominant mode of water entering drifts is likely to be through TSw fracture flow.

Portions of the vitric non-welded tuff in the Calico Hills Formation have been altered into zeolitic horizons. These zeolitic horizons may represent the single most effective barrier for radionuclides between the repository horizon and the water table. Combined with the hydraulic barrier represented by low fracture densities and low matrix permeability, the large adsorptive capacity of these zeolitic horizons provides a significant geochemical barrier to radionuclide transport (RT), realized only if flows do not bypass the bulk of the zeolitic horizons through vitric horizons or fast pathways. Perched-water bodies are present in portions of the repository footprint where significant zeolitization is present, suggesting that vertical percolation is slow in these areas. The absence of perched water bodies where the vitric units have not been zeolitized suggests that any percolation fluxes entering these zones can be accommodated through vertical percolation. Further, lateral flow from the perched water bodies may divert substantial quantities of water away from the zeolitic units into vertical flow through the vitric units. There may also be substantial lateral flow into faults such as the GDF, or downdip to the east of the GDF. If lateral flow is significant along the top of zeolitic units, the volume of the perched water bodies may be controlled by geometric factors (e.g., particular perching height may be required to encounter a lateral fast pathway) rather than the hydrostatic pressures required to force waters through low-permeability zeolitic zones. If any of these potential lateral-flow pathways carry significant quantities of water, rapid transport to the water table may be considerably facilitated.

The factors affecting deep percolation most, from the standpoint of repository performance, are related to initiation and sustenance of fast-pathway flow. Transport of radionuclides from non-backfilled drifts is likely to be minimal if there is not significant fracture flow in the TSw. Transport from the repository to the water table is likely to be very slow for pathways significantly occurring within the matrix. Accordingly, later sections address issues regarding fast pathways and fracture/matrix interactions in some detail.

4.4.2.4 Conceptualization of Small-Scale Flow in Fractures and Fracture/Matrix Interactions

Flow through an unsaturated, fractured rock involves two systems - matrix and fracture - that exhibit greatly different hydraulic behavior. Assuming isothermal conditions, liquid flow is governed by capillary, gravity, and viscous forces. As these effects are relatively well understood in the porous media representation of the matrix, most of the uncertainty in combined systems is associated with describing flow in the fractures. In contrast to porous media flow and transport theories, there are no widely acceptable theories for the study of fracture flow under unsaturated conditions (Bagtzoglou, et al., 1994). The flow process that dominates repository performance, flow in the fracture system, is also the process with the most uncertainty. Four issues pertinent to fracture flow in the UZ will be discussed in this section:

flow in small-aperture fractures, flow in large-aperture fractures, matrix/fracture interaction, and the distinction between discrete fracture and dispersed fracture flow.

The classical view of flow in unsaturated, fractured rocks is that flow will not occur in fractures unless the matrix is saturated. Unsaturated fractures were viewed as barriers to flow because of capillary forces that preferentially draw water into finer matrix pores. Given low estimates of average annual infiltration rates for YM, minimal flow in fractures would be expected due to the capillary forces. Another model of flow in fractured rocks is based on transient wetting pulses in the fractures, occurring due to precipitation events that promote fracture saturation at the ground surface. The wetting front in the fractures is not likely to coincide with the front in the matrix unless the matrix and fractures are strongly coupled. A pulse initiated near the ground surface penetrates to depth based on the connectivity of the fracture system and the properties and conditions of the pathway. These two views of flow in fractured rocks can be considered as modes corresponding to different stresses at the ground surface (National Research Council, 1996).

Fractures are void spaces. An understanding of the control that void space geometry plays on hydraulic flow properties is important in ascertaining the appropriateness of models developed to match conditions or predict future behavior. Fractures are often visualized as parallel plates separated by a gap, the fracture aperture. A more accurate and meaningful conceptualization accounts for areas where surfaces are in contact and areas with no contact, which can also be viewed as large-scale differences in roughness between the two sides of the fracture (National Research Council, 1996). The points of roughness between the two sides of the fracture will lead to partial saturation of the fracture as the matrix saturation is increased. Following the model of Peters and Klavetter (1988), flux in the fracture begins to exceed the flux in the matrix as the matrix becomes saturated. Any amount of percolation above the transmission capacity of the matrix will be in fractures. Often used for quick estimates, transmission capacity of the matrix is generally taken as a direct function of the effective conductivity at the steady state matrix saturation; the limiting case, assuming no ponding above the matrix, is a unit gradient under saturated conditions.

The voids of a fracture form a planar interconnected network, thus the analogy with porous media. However, the fracture voids are limited to a 2D (albeit not necessarily smooth) plane, thus increasing the possibility of phase interference over that of 3D porous media. Phase interference, or capillary exclusion, occurs when one phase in the plane of the fracture creates barriers to flow of the other phase. Fine fractures imbibe water, which then has the potential to block further water movement because of capillary effects in small apertures. In large-aperture fractures, film flow may occur that is impacted not by capillary forces across the width of the fracture but rather by the roughness of the fracture wall on which flow is occurring (Brown, 1987). For unsaturated flow in fractures, therefore, the geometry of the flowing pulse may differ from the aperture geometry (Glass, et al., 1996).

Transient, nonequilibrium flow in response to surface infiltration processes is another mechanism that initiates and sustains fracture flow. Flint, et al. (1996a) suggested that significant infiltration events occur at YM, on the average, once every 5 yr, noting that there were major runoff events in 1969, 1983-84, 1991, and 1995. Based on watershed modeling in Solitario Canyon using historical precipitation data, Woolhiser, et al. (1997) suggest that large runoff events, and hence large possible infiltration events, occur once or twice every 10 yr. A large pulse of water entering the fracture system near the ground surface may percolate at a high rate in large open fractures as sheet or rivulet flow. Fracture flow in this situation will be driven by a combination of viscous and gravity forces, and the 2D pore structure of the fracture.

Factors which affect the depth to which transient pulses of water may travel are the matrix saturation adjacent to the fracture, the water sorptivity of the matrix, the presence of fracture coatings, and the fracture aperture. Near-saturation matrix water contents, low matrix sorptivity, and low-permeability fracture coatings will all promote penetration of transient pulses to greater depths. Measurements by Thoma, et al. (1992) and simulations by Soll and Birdsell (1998) illustrate the strong impact that fracture coatings have on imbibition into the matrix. Small-aperture fractures would have the tendency to produce more tortuous paths and a higher possibility of phase interference due to capillary forces; if positive pressure heads drive the pulse, however, the impact of capillarity is lessened. If the flow of water is along rivulets in the rough-surfaced fractures rather than as sheet flow along smooth fractures (Kapoor, 1994), pulse penetration to greater depths is supported by reduction of the surface area available for imbibition. Measurements and observations by Tokunaga and Wan (1997) demonstrate that water preferentially flows in fractures with rougher walls. Flow in rough-walled fractures has been numerically simulated by Preuss and Tsang (1990), Tsang (1984), Tsang, et al. (1988), Brown (1987), and Silliman (1989). Coatings on the footwall and not the hanging wall of some fractures or faults at YM indicate that sheet or rivulet flow occurs in at least some fractures or faults at YM.

Paces, et al. (1998a) describe the distribution and isotopic composition of hydrogenic minerals in fractures and cavities in the ESF. The presence or absence of coatings in fractures may not be a good indicator of which fractures would likely carry flow. The chemistry of the fluids migrating down the fracture system should control whether precipitation or flushing (dissolution) is occurring. The fluids could either be undersaturated or oversaturated with respect to the minerals in the coatings. For example, percolating water that is undersaturated with respect to calcite would not lead to precipitation of calcite along the water pathways, and hence, the fractures with no coatings would be expected to carry the percolating water. If the percolating water is oversaturated with respect to calcite, then calcite would be precipitated along the flow path, and hence, the fractures with coatings would be expected to carry the percolating water. Another possibility is that the percolating water is initially undersaturated with respect to calcite, but evaporation along the pathway causes the water to become oversaturated. Coatings on open fractures the ESF imply that the percolating sheet flow was either oversaturated initially or became oversaturated due to evaporation. For the latter case, the strong air connectivity of some large fault features to the atmosphere at the surface may allow for evaporation to be significant even at large depths. If a significant amount of the percolation occurs in large aperture fractures, where coatings occur on the footwall, the implication for fracture/matrix interaction is that the portion of the fracture surface across which flow to the matrix may occur could be reduced. Dependent on the hydraulic properties of the coatings, they may restrict or enhance fracture/matrix interaction. Since the water chemistry of percolating water is poorly constrained at YM, it is prudent to consider that all possibilities of water chemistry occur, and therefore it would seem that all fracture pathways should be considered. However, Paces et al. (1998b, p. 37) notes that "Secondary mineral deposits occur as thin coatings on a relatively small number (less than one percent) of fractures and lithophysal cavities within the welded tuffs." They also state that mineral occurrences correlate to mapped fault and shear frequency. Fabryka-Martin et al. (1998, p. 96) showed Cl-36 data from the ESF. Bomb-pulse levels were not found on all fracture pathways. Only a few major faults and some unmapped faults show evidence of recent infiltration.

Paces et al. (1998b, p. 39) state that "Subsurface secondary calcite and opal deposits coating fracture footwalls and cavity floors within the thick UZ....provides records of downward percolating low-T solutions." The presence of secondary minerals identifies the location where fracture flow occurred in the past and does not necessarily indicate locations of future flow. The lack of observable minerals does not preclude flow from having occurred or occurring in the future.

Approaches used to model fracture flow and matrix/fracture interaction draw on classic porous flow concepts. Parameters used for the modeling are briefly described below along with brief mention of some of the limitations due to molding classic porous media concepts to fracture flow. Under the assumption that the fractures can be modeled as a classic porous media continuum, hydraulic properties valid for a representative elementary volume of fractures are needed. Air-permeability tests are used to infer indirect information on, and constrain the range of values for, the unsaturated constitutive relationships for water retention and relative permeability. However, inverse modeling is relied upon for their determination for each sublayer in the LBNL model (Bandurraga and Bodvarsson, 1997). Conceptually, the step from air permeability to constitutive relations is through variability of fracture spacing and fracture apertures. The constitutive relationships used for porous media are applied to estimate the fracture-continuum properties. No measurements of unsaturated-fracture constitutive relationships have been made at YM, although they may be highly variable given the range of fracture geometries and the nature of unsaturated flow in rough-walled fractures. Glass, et al. (1996) demonstrated that air entrapment in fractures can lead to prominent hysteresis in the constitutive relations. Reitsma and Kueper (1994) illustrate a technique to measure water retention curves on a single fracture; however, they noted that the Brooks-Corey relation was more applicable than the van Genuchten relation (which is usually used at YM) due to the physics of water entry into fractures. Given the small amount of hydrologic data on fractures at YM, the unsaturated parameters are primarily determined by inverse modeling (Bandurraga and Bodvarsson, 1997).

Two parameters have been introduced into unsaturated zone modeling at YM to link flow in the tuff matrix to flow in the fracture system. The first factor, matrix/fracture conductance, is essentially the fracture surface area multiplied by an imbibition rate into the matrix. Model calibrations suggested that the potential conductance was too large to match the data (Bandurraga and Bodvarsson, 1997). Accordingly, the fracture surface area fraction became a calibration parameter, justified by qualified observations of channeling or rivulet flow in fractures. A second factor, satiation, was included in models using similar arguments of difficulty in matching model results to field observations. Capillary theory dictates that flow from the matrix into a fracture will not occur until the matrix is fully saturated (Bear, et al., 1993). The term satiation was introduced to account for flow initiating in the fractures at pressure heads slightly less than atmospheric. In measurements of flow along fractures in the nonwelded Bishop tuff, Tokunaga and Wan (1997) found that film flow in the fracture had velocities of 2 to 40 m/d at -250 Pa, although the volumetric rate may not be significant. Tokunaga and Wan (1997) note that similar behavior may occur at much greater suctions in welded tuffs. Three reasons can be used to justify using a satiation value less than full saturation. The first argument is based on small-scale heterogeneities leading to local areas of saturated matrix adjacent to fractures even though the larger-scale average of matrix saturation is less than one. A second argument is nonequilibrium of the matrix in the vicinity of the fracture. Matrix saturations may reach full saturation adjacent to the fracture, but the rest of the matrix, some distance from the fracture, remains relatively drier. The third argument addresses the conceptualization of fractures as smooth parallel plates. Small-scale surface roughness on the fractures, or heterogeneities of the fracture surface leading to "point connections" (Glass, et al., 1996), may lead to wetted regions and contact points where water may enter the fracture.

The NRC staff considers that spatial and temporal variations in flux through the YM unsaturated flow system are dominated by the fracture flow system, particularly in welded and altered layers. Defining the flow system requires either detailed data on the fractures, especially those that dominate the flow system, or detailed information on the hydrologic response. At YM most of the available fracture data for the UZ has been obtained from the ESF. The east-west drift (enhanced characterization of the repository block, or ECRB) will likewise add to the fracture data base. However, it is difficult to directly evaluate modes and rates of water flow through fractures and faults in unsaturated rocks. In addition, little is known about the mechanisms and parameters that control flow: (i) between matrix and fracture; (ii) in open and coated fractures; (iii) in capillary films, sheets, or rivulets in open fractures; and (iv) along fracture planes and intersections. When insufficient data are present, the necessary fracture flow parameters can be estimated by inverse modeling given the constraints of other information at YM such as thermal and geochemical data and the presence and extent of perched water bodies. Groundwater tracers such as ^{36}Cl and ^{3}H are especially useful for detecting zones of enhanced downward flow in the UZ. Given the uncertainty, field observations and measurements should be a critical part of validating both site-scale and drift-scale models.

4.4.2.5 Estimates of Deep Percolation Based on Geochemical, Thermal, and Water Distribution Data

There is a wide variety of information and approaches for estimating deep percolation at YM. Geochemical, thermal, and water saturation conditions can potentially be used to indirectly estimate residence times, percolation rates, or volumetric flux rates. Table 4 contains a partial list of shallow infiltration and percolation flux estimated using different methods. Here, percolation flux is taken to be equal to the shallow infiltration rate under the assumptions of steady state, vertical flow. Most estimates prior to 1990 were less than 5 mm. Over time the estimates have increased, with an apparent convergence on the range 1 to 10 mm/yr for an aerially averaged mean annual rate of percolation. Locally, infiltration and deep percolation can exceed this average range or can approach zero.

Table 4. Estimates of shallow infiltration and deep percolation rates under current climatic conditions using different methods (in approximate chronologic order).

Estimate (mm/yr)	Location	Methodology	Source
1.5	YM	elevation & precipitation	Rush (1970)
2	Yucca Flat	parameter values	Winograd (1981)
1 to 10	YM	drill hole geothermal	Sass and Lachenbruch (1982)
4	YM	elevation & precipitation	Rice (1984)
0.5	YM	matrix Ksat data	Sinnock, et al. (1984)
0.5 to 2	YM	elevation & precipitation	Czarnecki (1985)
0.1 to 0.5	UZ-1	core & *in situ* data	Montazer, et al. (1988)
2 to 5	YM	drill hole geothermal	Sass, et al. (1988)
0 to .001	H-1	core data	Gauthier (1993)
4 to 35.1	UZ-4,5,7	Tritium and ^{14}C	Kwicklis, et al. (1993)
0.6 to 1.9	YM	1D modeling	Long and Childs (1993)
0 to 5.4	YM	Cl mass balance	Fabryka-Martin, et al. (1994)
6 to 15	YM channel	bomb-pulse ^{36}Cl	Fabryka-Martin, et al. (1994)

Estimate (mm/yr)	Location	Methodology	Source
0 to 13.2	YM	outcrop Ksat data	Flint and Flint (1994)
0.001 to 0.5	YM	3D UZ site-scale	Wittwer, et al. (1995)
0.1 to 10	YM	inverse modeling	Bodvarsson and Bandurraga (1996)
1.7	YM	1D modeling	EPRI (1996)
6.5	YM	100-yr 1D modeling	Flint, et al. (1996)
0.1 to 18	north YM	heat flux	Rousseau, et al. (1998)
0.001 to 0.29	north YM	perched water balance	Rousseau, et al. (1998)
1.8 & 3.4	ESF	fracture coatings	Marshall, et al. (1998)
1 to 15	YM	3D UZ site-scale	Wu, et al. (1998)
3.9 to 21.1	YM	expert elicitation	Geomatrix (1997)

Some of the methods provide only indications of pathways whereas other methods provide flux estimates that may be reflective of bulk response of the system. Percolation rate is taken to be a Darcy flux, the average flow perpendicular to a cross-sectional area. Pore-water velocity, particle velocity, and seepage velocity all refer to the velocity of a solute or water particle from one point to another point. The Darcy flux is related to the particle velocity by an effective porosity, or water content if unsaturated, through which the flow occurs. The effective porosity, or water content, may be difficult to determine, especially for the individual portions of dispersed fracture and fast-pathway fracture flow. The presence of environmental tracers at different depths at YM provides indications of pore-water velocity along a pathway with no indication of the amount of flow between two locations unless a mass balance can be developed, or it can be shown that the environmental tracer moved in all the fractures pathways, not just a portion.

The following subsections focus on various approaches for estimating rates of deep percolation. Key citations are noted.

In Situ Observations and Measurements (Wang, et al., 1997)
Net Shallow Infiltration Related to Deep Percolation (Flint and Flint, 1994; Flint, et al., 1996a).
Temperature Gradients and Heat Fluxes (Sass, et al., 1988; Wittwer, et al., 1995)
Isotopes (Fabryka-Martin, et al., 1997; Yang, et al., 1996b)
Chloride Mass Balance (Fabryka-Martin, et al., 1997)
Saturation and Water Potential (Flint, 1997)
Fracture Coatings (Paces, et al., 1996b; Marshall, et al., 1998)
Perched Water (Wu, et al., 1996)

- ***In Situ* Observations and Measurements**

Damp fractures or joints that quickly evaporate due to the required ventilation have been observed at the ESF. Seeps in niches and alcoves of the ESF also evaporated rapidly when exposed to the ventilation. Closing off niche 3566 (near the SDF) after finding a seep allowed re-equilibration of the relative humidity in the niche but no visual rewetting of the seep, reported Wang, et al. (1997). Damp features have also been noted in niche 3650 and the ESF directly. At the Expert Elicitation for Unsaturated Flow (Geomatrix, 1997), reference was made to an estimate of deep percolation based on vapor flow and the shutdown of the ventilation system on weekends. It was established that the average moisture flux from the rocks into the ESF was 50 mm/yr (Geomatrix, 1997). The ambient percolation flux within the rock does not exceed the transfer rate with the ESF in place, hence the 50 mm/yr would be an upper limit.

Given its close proximity and similar lithology, Rainier Mesa is considered a possible analog site for YM. Percolation estimates from seepage into the tunnels at Rainier Mesa are approximately 24 mm/yr under current mean annual precipitation of 320 mm (Russell, et al., 1987; Wang, et al., 1993), or about 8 percent of the precipitation.

- **Net Shallow Infiltration Related to Deep Percolation**

Infiltration is the source of virtually all deep groundwater flux in the UZ. This section summarizes, for completeness, the detailed discussion of infiltration modeling approaches of both NRC and DOE at YM that was provided by NRC (1997b). Models of infiltration processes provide information on the spatial and temporal variation of net infiltration, which can then be used as boundary conditions in models of deep subsurface processes. Infiltration models and deep subsurface models consider time scales so disparate that it would be computationally infeasible to consider infiltration processes and deep subsurface processes simultaneously. There are sufficient uncertainties arising from the use of infiltration models, including lack of understanding of flow processes, lack of knowledge of parameters, and lack of resolut that infiltration models cannot be relied on to provide accurate estimates of infiltration magnitudes without significant corroborating evidence. Infiltration models can provide estimates of the spatial distribution of relative magnitudes and frequencies of wetting pulses. Most importantly, infiltration models may provide the primary source of information regarding infiltration and deep percolation under future climates.

The infiltration maps provided by Flint, et al. (1996a) (based on detailed 1D numerical modeling) have superseded the maps by Flint and Flint (1994) (based on matrix properties of bedrock outcrops) for use in boundary conditions in DOE site-scale and cross-sectional studies (Bodvarsson and Bandurraga, 1996; Bodvarsson, et al., 1997a; Robinson, et al., 1997). The Flint, et al. (1996a) map is derived from sequences of 50 to 100 yr of weather, applied with a daily time step, using a 30-m by 30-m grid of independent 1D infiltration simulations. The 1D bucket model for each grid element considers evapotranspiration but not lateral redistribution.

The Flint, et al. (1996a) map is generally supported by neutron-probe observations during the period of October 1984, through April 1995, which Hudson and Flint (1996) used to create an infiltration map based on regressions taking into account precipitation, elevation, geomorphic class, and soil thickness. These maps suggest that infiltration occurs primarily on ridgetops and sideslopes, where surficial materials are shallow, and little infiltration occurs where alluvium is deeper than 1 to 2 m. The base infiltration map used by Bodvarsson, et al. (1997b) provides 6.7 mm/yr infiltration over the repository footprint and 4.9 mm/yr over the site-scale model.

The NRC model (Bagtzoglou, et al., 1997; NRC, 1997b), based on abstractions of detailed nonisothermal 1D simulations, predicts roughly three times as much infiltration as does the Flint, et al. (1996a) model, but is broadly in agreement with USGS predictions of the spatial distribution of mean annual infiltration (MAI). The NRC model neglects transpiration but has much finer spatial and temporal resolution than the USGS model. The agreement between the USGS and NRC models is not unexpected, as both are based on 1D approaches and both neglect lateral redistribution.

- **Temperature Gradients and Heat Fluxes**

This section outlines the use of borehole temperature measurements at YM to estimate percolation. Solution of the conduction equation using borehole temperature measurements to infer temperature gradients, heat conductivity of each unit, estimates of heat flux, and the assumption that the heat flow in YM is controlled by conduction, leads to a temperature profile which differs from the actual profile. The difference is interpreted to be due to either downward flux of cool water or upward flux of vapor.

Temperature data from boreholes, reported by Sass, et al. (1988) for a regional study, and by Rousseau, et al. (1998) in an area near the North Ramp of the ESF, were compared by those authors to predictions from models using the conductive heat equation. Although most of the heat flux could be explained by the conductive model, vertical heat-flux deficits were present that could be explained either by percolating water or by evaporation of water. Sass, et al. (1988) estimated that either 2 to 5 mm/yr percolation through the PTn and into the TSw or 0.1 mm/yr vaporization with 15 m/yr upward air discharge would account for the apparent deficits. The spatial distribution of infiltration rates estimated by Sass, et al. (1988), using the approach outlined above, is generally consistent with infiltration maps produced by Flint, et al. (1996a). Although vaporization and advective transport of vapor may be locally important in the highly fractured, densely welded tuffs such as the TCw, site-scale numerical modeling suggests that these effects are secondary to the effects of percolation (Rousseau, et al., 1998), particularly below the pneumatic barrier represented by the PTn. Temperature data from boreholes UZ#4 and UZ#5, in Pagany Wash, suggest that percolation may be on the order of 10 to 20 mm/yr (Rousseau, et al., 1998). In both studies, an average heat flux for the area was assumed in order to estimate percolation. Sass, et al. (1988) noted that the actual heat fluxes used in the analysis are difficult to measure.

Bodvarsson, et al. (1997c) re-analyzed the borehole data without assuming an average heat flow for the area. Percolation fluxes were estimated by matching the borehole temperature data with predictions from analytical solutions for the layered system, using both constant heat flux and constant temperature lower boundary conditions. Estimates ranged from 0 to 63 mm/yr. Low heat-flux boreholes appeared to be affected by vapor transport in the TCw, and high heat-flux boreholes appeared to be affected by proximity to fault zones. In both cases, the assumptions for the analytical solution are violated. For the remaining 18 boreholes, percolation estimates ranged from 0 to 15 mm/yr.

The thermal properties of the welded and nonwelded tuffs used in the studies are summarized by Wittwer, et al. (1995), Rautman, et al. (1995), and Rautman and McKenna (1997). Heat flux modeling by Rousseau et al. (1998) and by Bodvarsson, et al. (1997c) found that the regression equation of Rautman, et al. (1995) for thermal conductivity of the welded and nonwelded lithologies as a function of porosity, temperature, and saturation worked well in their modeling of the temperature profiles.

The different thermal properties and heat flow in the TCw, TSw, and CHn are reflected in the temperature profiles and subsequent percolation estimates. Estimates of percolation flux through the CHn are less than those estimated for the TSw (Bodvarsson, et al., 1997c). The temperature gradient through the CHn is much larger than that of the TSw, which, in part, may be explained by the lower effective thermal conductivity of the CHn. Another possible explanation is lateral flow above the zeolitic horizons of the CHn. The thermal conductivity of the CHn varies depending on the vitric or zeolitic content of the layer as well as the degree of welding and the water content. Temperature gradients and heat flux estimates in the TCw may be problematic due to the effects of vapor flow on the temperatures.

An indication of the temporal aspect of a percolating pulse was noted by Sass, et al. (1988). In 1983, about 15 months after the previous reading, temperature perturbations were observed in UE-25a#7 following a major storm. Borehole UE-25a#7 lies on or near the Drillhole Wash fault zone. The temperature response was recorded to a depth of 150 m, which Sass, et al. (1988) assessed as possibly attributable to perturbation along the borehole-annulus. If temperature fluxes along the annulus of UE-25a#7 were significant, the temperature anomalies are meaningless. Since the temperature anomaly persisted for at least 1 yr and was different from previous conditions, the anomaly may represent an infiltration event moving through the fault. If so, the moisture penetrated 47 m of alluvium, 4 m of TCw, 42 m of PTn, and 58 m of TSw in about 15 months.

- **Isotopes**

Environmental isotopes ^{36}Cl, ^{14}C, and $^{87}Sr/^{86}Sr$ have been used to estimate percolation rates and residence times as well as to confirm the presence of fast pathways at YM. As discussed by Tyler and Walker (1994), bomb-pulse tracers can overestimate recharge by an order of magnitude or greater when the impact of transpiration on the flow velocities is neglected. Isotopic interpretations must account for numerous factors that can influence the results, including sampling techniques, analytical methods, detection limits and error bars, transport behavior, and site activities. For example, air drilling of core samples has contaminated unsaturated zone samples measured for 14C (Yang, et al., 1998).

Elevated levels of ^{36}Cl in the ESF and in boreholes at YM are traceable to global fallout in the nuclear t from 1952 to 1958 (Levy, et al., 1997). A report by Fabryka-Martin, et al. (1997) contains the currently available set of ^{36}Cl measurements from boreholes and the ESF. Of 247 samples from the ESF, 13 percent had an unambiguous bomb pulse signal. In a straightforward approach, the presence of unambiguous bomb pulse ^{36}Cl in the ESF suggests pore-water velocities on the order of 7.5 m/yr assuming a depth of 300 m and onset of testing as 40 yr ago. However, these pore-water velocities may only represent a fraction of pathways, those that are faster preferential pathways, and may not be directly used to estimate percolation rates even for the fast pathways, since the effective porosity (or water content) for fast pathways is also unknown.

Another environmental tracer, ^{14}C, has been used not only for calculation of residence times of water but has also been used to infer velocities. Interpretation of the ^{14}C data is complex because of its transport mechanism, movement both in the aqueous and vapor phases, and carbon exchange with older calcite or younger gas. Yang, et al. (1996b) report a wide range of isotopic dates from ^{14}C data in the CHn that may support multiple origins for the perched water. The ambiguity of ^{14}C dating carries over to estimates of percolation rates. From data at a depth of 100 m in borehole UZ-25, Murphy (1995) estimated pore-water velocities of 20 to 100 mm/yr. Flow and transport models with varying degrees of geochemical complexity incorporated have been used to model borehole ^{14}C data. Using tritium and ^{14}C data, estimates are 35.1 and 20 mm/yr for UZ-4 and 4 mm/yr for UZ-5 (Kwicklis, et al., 1993). Moridis, et al. (1997) used optimization of two 1D models for wells UZ-1 and UZ-14 to determine a percolation rate of 4.2 mm/yr.

Strontium isotope ratios in pore waters are a function of dissolution and exchange with the rock as well as total strontium concentration and water percolation rates. Strontium geochemistry and isotopic ratios have been measured at only a few boreholes. Based on the analysis at one borehole (SD-7), using the dissolution rate from fractured basalts, an estimate of percolation based on $^{87}Sr/^{86}Sr$ ratios ranges from 0.5 to 5 mm/yr (Sonnenthal, et al., 1997b).

- **Chloride Mass Balance**

The percolation flux at depth can be estimated by a meteoric chloride mass balance method by using the average precipitation rate, Cl^- concentration corresponding to the typical near-surface infiltrating water, and Cl^- concentration in a well-mixed reservoir at depth (Fabryka-Martin, et al., 1997). This method assumes that precipitation, net infiltration, and chloride deposition rates have been constant for sufficient time to reach steady state and further assumes that matrix and fracture waters have fully mixed. The chloride mass balance approach also assumes piston-like flow, a uniformly downward movement of water that displaces the initial water in the profile (Scanlon, et al., 1997). This assumption may not be valid at YM because of the potential for preferential fast flow paths in the unsaturated zone.

Estimates of percolation tabulated by Fabryka-Martin, et al. (1997, Table 5-2) were calculated using the geometric mean of Cl^- values for hydrostratigraphic units in six wells, 170 mm/yr for precipitation, and a Cl^- concentration of 0.62 mg/L for near-surface infiltrating water. Percolation estimates calculated using the Cl^- mass balance method described above for the PTn range from 1.1 to 3.4 mm/yr with an average of 2.0 mm/yr. Similarly calculated percolation estimates for the CHn range from 2.2 to 5.3 mm/yr with an average of 3.9 mm/yr, while estimates for the perched water range from 11 to 23 mm/yr with an average of 16 mm/yr. Assuming unit gradients and values of saturated hydraulic conductivity of 0.9 and 1.9 mm/yr for the TCw and TSw units, respectively, percolation in the units above the PTn and CHn exceed their transmission capacity, the difference showing the portion of total flow due to flow in fractures. Higher fractions due to fracture flow would result if effective conductivity was used instead of saturated hydraulic conductivity. An important observation is that the perched water has lower concentrations of Cl^-, and, hence, larger percolation estimates, than the PTn. The implication is that the water reaching the perched zone either bypassed the PTn or percolated quickly through the PTn through fast paths, possibly as nonuniform fronts. Another interpretation is that variations in percolation water chemistry are due to climatic changes. Holocene percolation over the past 10 kyr contains larger concentrations of dissolved solids, partly due to drying of playa lakes, that may have mixed with dilute superpluvial Pleistocene percolation. Therefore, calculated changes in percolation rates based on chloride mass balance may indicate transient precipitation and percolation rather than 'bypassing' of the PTn.

Yang, et al. (1996b) report Cl^- concentrations in perched water of 4.1 to 15.5 mg/L, with 15 of the 17 reported values no greater than 8.3 mg/L and a Cl^- concentration of 7 mg/L at NRG-7a (the nearest borehole to UZ-4 and UZ-5 with a reported perched-water sample). Using the same precipitation rate (170 mm/yr) and Cl^- concentration for near-surface infiltrating water (0.62 mg/L) as Fabryka-Martin, et al. (1997) and assuming that the perched water is well mixed with the matrix waters, calculated net infiltrations are 25.7, 12.7, and 6.8 mm/yr for concentrations of 4.1, 8.3, and 15.5 mg/L, respectively. A percolation value of about 26 mm/yr would represent an upper bound based upon the perched-water chloride data; if the matrix waters do not mix completely with the perched water, percolation values may be lower.

- **Saturation and Water Potential**

Observations of both saturation/water content and water potential can yield independent estimates of water fluxes, in addition to providing calibration data for numerical simulators. When the hydraulic characteristics of a matrix sample are known, saturation, water content, and water potential each can be used to estimate the unsaturated hydraulic conductivity. Knowing the unsaturated hydraulic conductivity at a particular water content and assuming gravity drainage, the percolation rate is directly calculated using Darcy's law. If capillary effects are negligible, so that the assumption of gravity drainage is appropriate, the vertical flux is numerically equal to the unsaturated hydraulic conductivity.

The question of whether or not gravity drainage is an appropriate assumption was addressed by Rousseau, et al. (1998) who presented *in situ* water potential measurements from five boreholes (UZ-1, UZ#4, UZ#5, NRG-6, and NRG-7a). None of the profiles had unequivocally returned to initial conditions in the time frame examined (several months to years), but, generally, it appears that, upon equilibration, all five boreholes will exhibit minimal vertical variation in water potential (implying gravity drainage) and no profile will be drier than five bars of suction. In boreholes UZ#4 and UZ#5, available core sample potentials are scattered within one or two bars of the *in situ* values; overall, the core values tend to be wetter than the *in situ* values.

The expert elicitation process (Geomatrix, 1997) revealed limitations on the use of water content and potentials for estimating percolation rates. There are two primary sources of saturation and water potential data: (1) measurements from core samples obtained during drilling; and (2) *in situ* measurements. A great number of core-sample measurements were obtained during drilling the more recent boreholes (Flint, 1997). Although care was taken during sampling to preserve *in situ* conditions in the core, some drying apparently occurred during sampling and the resulting data should be considered suspect (L. Flint, 1997, presentation to Site-Scale Unsaturated-Zone Flow Model Expert Elicitation Panel). Drying becor more of an issue as the degree of welding increases, as the same amount of evaporation distorts the d more by removing a larger fraction of the available moisture. Independent estimates of fluxes obtained from these potentials are dependent on the independent estimates of hydraulic properties, particularly saturated hydraulic conductivity and van Genuchten α. A factor of two change in van Genuchten α (which is small compared to the uncertainty associated with the parameter) may change estimates of relative permeability by an order of magnitude. Accordingly, estimates of flux obtained from *in situ* saturations or water potentials are not considered reliable.

- **Fracture Coatings**

The percolation flux can be estimated from fracture coatings of calcite and silica (e.g., opal). It has been proposed that all of the fracture coating in the UZ was precipitated from downward percolating waters (Johnson and DePaolo, 1994). The finely layered coatings suggest periodic deposition with no textural indication of chemically undersaturated water from large pulses to dissolve the coating (Paces, et al., 1996b). In the ESF, Paces, et al. (1996b) noted that fracture coatings occurred exclusively on the footwall, that the thickest deposits were in the low-angle fractures, and that coatings occurred where apertures generally exceeded several millimeters.

Paces, et al. (1996b) and Marshall, et al. (1998) provide preliminary estimates of the percolation fluxes required to deposit calcite and opal in the form of fracture fillings and lithophysae coatings at YM. Assuming that the fracture characteristics and filling patterns observed in the ESF are representative of the entire UZ, all cations are deposited within the UZ, and infiltrating water has the composition observed under current conditions, the average percolation flux rate required to match the observed patterns is calculated to be 2.1 mm/yr for calcite and 0.3 mm/yr for opal (Paces, et al., 1996b). Marshall, et al. (1998) updated these to 3.4 and 1.8 mm/yr, respectively. As noted by Paces, et al. (1996b), these are minimum estimates, as almost certainly not all calcium and silica in the percolating water is deposited as coatings.

Dating of fracture coatings using ^{14}C measurements range from 16 to 44 kya, whereas, the ages calculated using $^{230}Th/U$ measurements range from 28 to over 500 kya (Simmons, 1996; Paces, et al., 1996b). However, sampling difficulties due to the fine layering make interpretations of the fracture coating ages using isotopic measurements difficult. The older ages for the coatings may be consistent with calcite deposition models that suggest that deposition will only occur where flux is slow. Fast moving pulses of water in the fractures might be expected to dissolve the existing calcite. The use of isotopes to date layers of fracture coatings does not appear to have produced reliable information. This may be a result of apparent ages of fracture coatings being representative of mixtures of older and younger minerals, or representative of precipitation, dissolution, and re-precipitation along flow paths.

- **Perched Water**

A summary of perched water data from YM is provided by Wu, et al. (1996). The presence of perched water in and immediately above the CHn unit can be used as a lower constraint for estimation of percolation flux. Estimates of residence times, volume estimates, material properties, and head gradients can be used in this regard. Volume of perched water is also an important constraint on calibrating the site-scale model, as noted by Wu, et al. (1997); adjustment of rock properties in the layers in and adjacent to the perched zones was required to match the volumes of water in the perched zone.

A flux estimate required to form and sustain perched water above the CHn in the vicinity of UZ-14 was made by Rousseau, et al. (1998). Seepage rates both laterally along and through the perched zone and seepage rates through adjacent vitric zones were weighted by their areal distribution to estimate the percolation through the TSw in the combined areas of the vitric and the perched zones. In addition to the residence time data, estimates of head gradient, permeability, perched water volume, and area were required. Flux through the vitrophyre below the perched zone was estimated to range from 0.0014 to 0.29 mm/yr, a range corresponding to effective porosity values between 0.001 to 0.10 (Rousseau, et al., 1998). However, since the origin of the perched water is not clear and the presence of two distinct waters in the CHn is indicated by geochemical data (Yang, et al., 1996a), estimates of percolation flux may not be reliable.

- **Summary of Deep Percolation Estimates**

There is a wide range of flux estimates, based on various methods and assumed climatic conditions. Concurrence of values from widely different approaches leads to confidence in the estimates, leaving the extreme values as an indication of less reliability. The UZ Expert Elicitation Panel provided estimates of deep percolation, considering all presented approaches, with estimated mean values ranging from 4 to 21 mm/yr (Geomatrix, 1997).

The use of tracers to robustly estimate percolation rates in the YM area is limited. Difficulties with estimating the impacts of lateral flow and multiple pathways would appear to limit their use over most of the repository footprint. Nevertheless, unambiguous bomb pulse signatures observed at depth in the ESF are interpreted as occurring where high infiltration occurs over a zone having a fault that provides a fas pathway through the PTn unit (Levy, et al., 1997). The bomb pulse data were instrumental in demonstrating that fast pathways exist and, by implication, that, at least locally, there are areas where infiltration might be much higher than previously thought.

Despite the limitations on tracer methods, the chloride mass balance technique does provide a means of estimating an upper bound for net infiltration. The upper-bound value obtained by chloride mass balance on perched water, 26 mm/yr, is remarkably consistent with the upper-bound value obtained by geothermal heat-flux calculations.

Collectively, the geochemical, thermal, and water distribution data suggest that flow in the UZ is better represented by conceptual models that consider fast pathways and limited matrix/fracture interactions than by models which consider predominantly matrix flow. The NRC staff review should ensure that fast pathways and limited matrix/fracture interaction are reasonably represented by DOE numerical models.

4.4.2.6 Estimates of Deep Percolation Based on Numerical Simulations

Numerical modeling of flow processes at YM is unavoidable due to the large spatial and temporal scale of the repository performance relative to the scope of conceivable investigation. Numerical modeling enables observations at limited observational points and times to be extended in time and space. In modeling flow through the UZ at YM, it is important to capture both fracture flow and matrix flow processes. However, fracture flow may be more important from the perspective of PA, as releases and transport are apparently more strongly affected at YM by fracture flow than matrix flow.

A wide variety of methods and formulations have been applied to site- and drift-scale modeling at YM. Current estimates of the spatial distribution of percolation using the site-scale model of LBNL (Bodvars et al., 1997a) are developed using separate, but interacting, continua for matrix and fracture systems. drift-scale modeling, no definitive choice has been made (TRW Environmental Safety Systems, Inc., 1997a), although Birkholzer (1998) recently presented a fracture continuum model. Inherent in both scales of modeling are the estimates of physical and hydraulic parameters. As such, the first portions of this section discuss issues related to parameter estimation for matrix and fracture systems. The last portion of this section discusses alternative methods and formulations for modeling flow at YM.

- **Matrix Properties and Parameter Estimates**

A large database of bedrock physical and hydraulic properties for units at YM has been collected, correlated to lithologic structure, and analyzed for spatial trends, using samples collected from outcrops and from boreholes (Peters, et al., 1984; Klavetter and Peters, 1986; Flint and Flint, 1990, 1994; Rautman and Flint, 1992; Istok, et al., 1994; Cromer and Rautman, 1995; McKenna and Rautman, 1996; Rautman, et al., 1995; Schenker, et al., 1995; Flint, et al., 1996b; Moyer, et al., 1996; Rousseau, et al., 1998; Flint, 1997; Rautman and McKenna, 1997). Easily measured physical properties (i.e., porosity and bulk density) have been collected for most of these samples, but hydraulic properties have only been sparsely collected. Rautman and McKenna (1997) summarize the available data, much of which is described by Flint (1997) in greater detail, and extrapolate the data to model grids. Bodvarsson and Bandurraga (1996) and Bodvarsson, et al. (1997a) use much of this information to constrain values of grid-block-scale hydraulic parameters derived through inverse modeling.

Porosity is generally used as a surrogate variable for K_{sat} (Flint, 1997; Rautman and McKenna, 1997), because: (1) porosity has been measured on virtually all core samples; (2) values of other hydraulic properties have not been determined for most core samples; and (3) porosity appears to be fairly well correlated to hydraulic properties. Interestingly, a staff comparison of *in situ* water saturation and core-sample K_{sat} suggests that saturation may be a better predictor of K_{sat} than porosity. This correlation may warrant further study. In addition to K_{sat}, the van Genuchten parameters for the UZ constitutive relations are required for UZ flow modeling. Matrix retention parameters require the most effort to obtain and, therefore, have only been determined for a small number of core samples; many of the measurements exhibit a great deal of scatter both within units and for similar rock types. Accordingly, estimates of matrix retention parameters have a great deal of uncertainty.

Measurements from core samples are at a much smaller scale than typical model grid blocks (i.e., several cubic centimeters as opposed to grid blocks 1 to 100 m on a side, which is at least 8 orders of magnitude difference). One way to reconcile the disparity in scales is through inverse modeling to obtain effective properties [e.g., the LBNL 3D site-scale model approach (Bodvarsson and Bandurraga, 1996; Bodvarsson, et al., 1997a)]. Since inverse modeling approaches are inherently mathematically ill-posed and nonunique, it is most effective when only a few parameters need to be determined; thus, heterogeneity is not easily accommodated. For this reason, the LBNL inverse-modeling approach assumes that all parameters are homogeneous within each layer. It appears that each physical layer is modeled with at most two computational layers, which may tend to mask processes occurring on a sub-layer scale such as lateral diversion in the PTn unit (Wilson, 1996). Further, the LBNL inverse-modeling does not use an approach that estimates all properties simultaneously, and inconsistently estimates some properties using the assumption of 1D vertical flow despite the lateral flow exhibited in subsequent 2D and 3D simulations using the parameters. The NRC staff considers that the LBNL 3D site-scale model may be too coarse to provide more than a general indication of subsurface processes at YM but notes that significant model refinement may be computationally infeasible. Despite these reservations, NRC staff endorse the LBNL philosophy of using all available sources of information to calibrate the site-scale model, and agree that, for many purposes, homogeneous effective properties for each layer obtained through inverse modeling may be adequate.

Another way to reconcile the disparity in scales is through upscaling. Schenker, et al. (1995), attempting to estimate layer-wide hydraulic properties from core-sample data, recognized that bulk variability is usually less than the core-sample variability and, therefore, reduced the coefficient of variation for hydraulic properties according to the vertical correlation length and layer thickness.

The sophisticated approach adopted by Rautman and McKenna (1997), building upon a series of previous SNL efforts, generates heterogeneous parameter fields based on cross-correlation of hydraulic conductivity, bulk density, and thermal conductivity. A significant advantage of this approach, relative to the inverse-modeling approach, is that heterogeneity readily can be accommodated into modeling efforts. Porosity, K_{sat}, and thermal conductivity (in the TSw unit) are considered by Rautman and McKenna (1997), although the methodology could be extended to include retention parameters. The Rautman and McKenna (1997) methodology minimizes statistical artifacts potentially introduced by faults by using the depositional environment (before faulting occurred) to perform statistical analyses, although this procedure may add statistical anomalies when considering alteration (which occurred after faulting).

Despite the attractive characteristics of the Rautman and McKenna (1997) procedure, it appears that the procedure projects core-scale properties to the grid-block scale (100 m × 100 m × 2 m) rather than projecting averaged or upscaled properties. Rautman and McKenna (1997) note that the procedure do not address the issue of upscaling. However, the procedure could be adapted to generate a fine-scale of hydraulic properties on a subgrid within each grid block; the fine-scale properties could then be formally upscaled to arrive at effective properties. Formal upscaling that accounts for flow characteristics may generate effective properties that are different from averaged properties, as noted by Rautman and McKenna (1997), who further note that advective processes (e.g., percolation) are more likely to be affected by upscaling issues than diffusive processes (e.g., heat conduction).

If one upscales using the many-tubes approximation, which assumes that the porous medium is composed of many tubes (at the scale of core samples) in parallel, all with vertical gravity flow and all at the same suction (essentially assuming that local lateral flow is not restricted), staff analysis determined that a small percentage of the tubes (local fast pathways) carry the bulk of the flow when the cores are as heterogeneous as those reported by Flint (1997) for the PTn subunits. The assumption of locally unrestricted lateral flow may be appropriate for bedding planes in bedded units such as the PTn. If, in fact, local fast pathways carry the bulk of the percolating water, most observations from the PTn used for calibration would be representative of the bypassed portion of the matrix. Further, flow along these fast pathways may penetrate the PTn rapidly enough to account for bomb-pulse observations, even accounting for potentially tortuous lateral paths. Unfortunately, hydraulic parameters that are upscaled, accounting for the local flow paths during ambient conditions, may not be appropriate during the repository thermal pulse, during which all of the matrix would presumably participate in flow redistribution.

Modeling efforts rely heavily on these laboratory-determined rock properties, upscaling, or inverse modeling. As a check on consistency, Winterle and Stothoff (1997) modeled imbibition, using METRA (Seth and Lichtner, 1996) to verify that the hydraulic parameters used by Bodvarsson, et al. (1997a) would reproduce sorptivity measurements by Flint (1997). If reported rock properties are accurate, and the underlying physics of the UZ flow models are correct, then models should be able to predict rock matrix sorptivity that is very close to the observed sorptivity. However, comparison of model-predicted sorptivity and observed sorptivity yielded an interesting result: numerically determined sorptivity was consistently greater than the observed sorptivity. Furthermore, the ratio of modeled to observed sorptivity varied in proportion to K_{sat}. This relationship was interpreted by Winterle and Stothoff (1997) to be suggestive of hysteretic behavior in rock moisture retention characteristics. That is, at a given saturation, capillary suction is less in a rock that is undergoing a wetting cycle that it would be in the same rock undergoing a drying cycle. Moisture retention characteristics reported by Flint, et al. (1996b) were measured in the laboratory by incrementally oven drying rock samples and measuring capillary suction; however, imbibition is a wetting process. Thus, laboratory-reported values of van Genuchten's α parameter may be too low for use in models where the flow of infiltration pulses in fractures is of interest. Implications are that infiltration at YM may travel farther in fractures than would be predicted by models using moisture-retention characteristics based on drying curves. Interestingly, calibration of the YM site-scale UZ flow model (Bandurraga and Bodvarsson, 1997) required an increase in the α values relative to mean values reported by Flint (1997).

The NRC staff considers that approaches used by DOE to estimate parameters for flow and transport simulations generally use sound methods, particularly in the most recent work. The NRC staff notes, however, that subgrid heterogeneity is not explicitly and transparently addressed in the approaches and caution that failure to consider subgrid heterogeneity may lead to qualitatively incorrect results. Small-scale modeling of heterogeneous zones is one approach that may be used to support use of uniform properties in hydrostratigraphic units of the site-scale UZ flow model.

- **Hydraulic Properties of the Fracture System**

A general understanding of fracture geometry, surface characteristics (e.g. roughness), size distributions, and spatial variation is important for modeling UZ flow in the fracture bedrock of YM. These characteristics will affect hydraulic conductivity, hydraulic connectivity, matrix imbibition, chemical diffusion, and flow channeling in the fracture system. This section includes a discussion of fracture characteristics in relation to hydraulic properties. An analysis of the fracture system characterization at YM is included in the SDS IRSR (NRC, 1998a).

Fracture characteristics are used both to estimate hydrologic properties of the fracture system and to constrain conceptual models of UZ flow at YM. Fracture geometries, orientations, and distributions, combined with permeability measured by air injection testing and modeling of pneumatic response to atmospheric pressure changes, have been the source of data used to estimate physical and hydrologic properties for the fracture system for numerical modeling of the UZ at YM. There are few direct measurements of hydrologic properties of fractures or fracture systems in the UZ (Wang, et al., 1998). Most estimates involve indirect calculation of hydrologic properties based on gas permeability data and constraints by thermal and geochemical evidence. Air injection and gas permeability data are used to estimate apertures and aperture distributions that are then used to estimate hydraulic properties of the fracture systems. Since air-injection testing is a critical component of estimating hydraulic properties of fracture system, and there was some controversy about methods and interpretation of previous air-injection testing at the site, a peer review was performed by an independent, three-member panel. Recommendations of the peer review are summarized in attachments to a U.S. Geological Survey letter (USGS, 1995). The estimates of hydraulic fracture property values are used to constrain the range of possible values in the LBNL site-scale UZ inverse modeling; as such, the fracture parameters of saturated hydraulic conductivity and van Genuchten alpha are calibrated values.

Hydrogeologic parameters for fractures are difficult to characterize through direct measurement at YM because fractures vary widely in length, connectivity, orientation, aperture, and coating type and amount. These parameters depend on the scale of observation. For example, scale dependency in conductivity of a fractured rock is attributed to three properties: (1) the variation of length or consistency of the fractures; (2) the distribution of the fractures as related to the connectivity of the fracture system; and (3) the variation in conductivity or transport capacity. Sonnenthal, et al. (1997a) provide the best available summary and analysis of data on hydrologic properties of fractures and faults in the UZ, based on data from the detailed line surveying (DLS), borehole measurements, and the air injection tests (for permeability) (Ahlers, et al., 1996; Anna, 1996; Sweetkind and Williams-Stroud, 1996; LeCain, 1997; LeCain and Patterson, 1997; Sweetkind, et al., 1997). The summary provides estimates about fracture frequencies, orientations, and connectivities in the Topopah Spring Tuff, fracture frequencies from borehole measurements, permeabilities from air-injection tests, fracture apertures, van Genuchten parameters, fracture porosity, and heterogeneity of fracture distributions. The summary also includes pneumatic responses of faults and provided estimates of fault hydrologic properties, such as pneumatic permeability and porosity of the fracture continuum. The data are organized into a consistent set to be used with the UZ hydrostratigraphic model Table 7.7 of Sonnenthal, et al. (1997a)), including mean values for fracture spacing, frequency, trace length, intensity, and the proportion longer than 1 m for 16 zones in the upper 12 sublayers of the UZ model. These are 12 hydrostratigraphic sublayers from the ground surface to the repository horizon.

A brief discussion of fracture properties as related to hydrologic properties by hydrostratigraphic unit is included below. A detailed discussion of the fracture properties can be found in the SDS IRSR (NRC, 1998a). The nonwelded PTn sublayers generally have larger fracture spacing (i.e., lower density), lower frequency, and larger trace lengths than the overlying and underlying welded tuffs of TCw and TSw, although on a sublayer basis, there is considerable overlap between the units. There are as yet few data for the CHn nonwelded unit. However, the Busted Butte test facility should provide the needed information.

In the TCw, fracture spacing is significantly smaller than the fracture length thus implying the likelihood of connectivity of fractures. Geometric connectivity is an important criterion for fracture flow capability. Air injection tests performed on the drift-scale in the ESF demonstrated the connectivity and showed that the fracture network generally behaves as a continuum, with the mean fracture permeability generally increasing as the scale of the system increases (Sonnenthal, et al., 1997a). Pneumatic responses supported by gas chemistry data led Thorstenson, et al. (1998) to conclude that vertical permeability to air of the PTn was 1 to 3 orders of magnitude less than in the TCw or TSw. Thorstenson, et al. (1998) correctly noted that the gravity force acting on water percolating through the PTn is orders of magnitude greater than the buoyant forces acting on air, hence, the "gas permeability contrast does not preclude a high rate of water percolation through the PTn."

Because the repository will be in the TSw, a more detailed reporting of fractures in the TSw was organized by Sonnenthal, et al. (1997a). In looking at all of the fractures in the TSw (down to a length of 0.3 m) and over a 100-m scale, the middle nonlithophysal unit has higher fracture densities than the other layers. The vertical air permeabilities of the other TSw units measured from boreholes in the ESF are about 2 to 3.5 times the horizontal air permeabilities, while the ratio for the nonlithophysal layer is only about 1.3 (uniform over a distance of over 1,200 m in the ESF). However, the water permeability could be underestimated if it is based directly on air permeability, especially for horizontal water permeability where blockage by wat could impact air permeability testing. Also for the TSw, the number of fractures was found to be inverse proportional to fracture size, and over half of the fractures are found in the 0.3- to 1.0-m range. This would indicate that the earlier cutoff length of 1.0 m used for the average values in the different zones of the UZ model probably skewed the data input to the model (Sonnenthal, et al., 1997a).

Two important features of the model layer properties in Sonnenthal, et al. (1997a) are worth underscoring here. One, for most of the sixteen zones (in the upper 12 hydrostratigraphic sublayers), the standard deviations for fracture spacing and fracture intensity are greater than the mean values. Therefore, use of mean values in flow models will underestimate the lateral and vertical variability of permeability in the UZ. Two, more than a third of all the fractures are eliminated from the analysis due to use of a 1 m fracture-length cutoff (fractures shorter than 1 m were not measured and counted). Elimination of short fractures from nonwelded, lithophysal, or densely fractured units could lead to an underestimation of hydrologic properties, such as porosity, permeability, and fracture connectivity. Elimination of fractures less than 1 m also may modify fracture intensity interpretations near faults such as for the GDF in the ESF where the 1 m cutoff for trace length leads to extremely different fracture intensity estimates over a wide zone (Sweetkind, et al., 1997).

Major faults in the vicinity of the repository include the north-south trending GDF, SCF, Bow Ridge, and Dune Wash Faults, which are normal faults, and the northwest trending Sundance, Drill Hole, and Tea Cup Faults, which are strike-slip faults. Hydraulic properties of fault zones are impacted by the degree of associated fracturing, the geometric character of the fracturing, and the nature of the fault gouge, all of which can vary vertically and laterally. The limited pneumatic monitoring and air-injection testing on fault zones at YM is summarized in Sonnenthal, et al. (1997a). The geologic characterization of faults at YM is analyzed in detail in the SDS IRSR (NRC, 1998a).

Sonnenthal, et al. (1997a) made several recommendations for additional data collection that are worth restating here. First, that fracture mapping data should be obtained from the east-west drift to compare and combine with data from the ESF. The proposed emplacement zones all lie west of the ESF loop. Second, additional borehole testing data are needed for units below the proposed repository horizon to better constrain the fracture distribution and permeability structure of zeolitic units. And finally, if faults are expected to play a large role in formulating UZ waste isolation strategy, then additional investigations are needed to better define fault widths, frequencies, interconnectedness, and gouge properties.

It should be noted that the current NRC/CNWRA modeling approach emphasizes relatively rapid fracture flow in the UZ. Our approach places little emphasis on retardation of radionuclides in the UZ, with repository performance being much more affected by properties of the SZ. Under this approach, bounding values are probably acceptable for hydraulic properties of fractures, reducing the need for extensive characterization of UZ fracture networks. One exception to this would be the need for ESF data on fractures within the TSw. A reasonable understanding of general fracture patterns in the ESF is needed to refine conceptualizations of conditions under which water may enter emplacement drifts and drip onto waste packages. Data from the ESF and the east-west drift should provide an acceptable reference base.

- **Model Formulations**

There are two main approaches to modeling flow in unsaturated fractured tuffs: continuum methods and discrete-fracture methods (Evans and Nicholson, 1987). Continuum methods treat the matrix and fracture systems with various levels of interaction [e.g., methods using an equivalent continuum model (ECM), a lual-porosity model, a dual-permeability model (DKM), and a multiple interacting continua (MINC) model]. Discrete-fracture models may either account for or ignore interactions with the matrix. The models are discussed by Altman, et al. (1996). The continuum models are evaluated to investigate prediction differences by Doughty and Bodvarsson (1996, 1997). The observations of fast-path bomb-pulse ^{36}Cl detected in the ESF, coupled with newer estimates of MAI that exceed matrix permeabilities, have required a shift from matrix-dominated flow models (such as the ECM approach) toward fracture-dominated methods (such as the DKM approach), to enable some portion of percolation fluxes to occur in fast pathways.

Model dimensionality is another factor that may have a large impact on transport times. One dimension simulations cannot find fast pathways through lateral flow, thereby, magnifying the impact of low-permeability zones, while 2D and 3D simulations provide increasingly greater latitude for lateral flow.

The ECM formulation, developed by Klavetter and Peters (1986), merges matrix and fracture continua into a single equivalent continuum by assuming that the pressure in the matrix and fracture continua are in hydraulic equilibrium at each spatial location, resulting in considerable computational efficiency. In general, the fracture system only carries flow when the matrix system is essentially saturated. Early versions of the 3D UZ site-scale model developed by LBNL used the ECM formulation (Bodvarsson and Bandurraga, 1996), but subsequent analyses have largely abandoned the approach in favor of the DKM approach (Bodvarsson, et al., 1997a). The GWTT-94 analyses performed by SNL used the ECM approach, but the GWTT-95 analyses used the DKM approach. A modified ECM approach was used in TSPA-95 (Andrews, et al., 1994), with a heuristic disequilibrium assumed between matrix and fractures, but DOE intends to use a DKM approach for TSPA-VA (S. Sevougian, presentation at DOE/NRC Technical Exchange on Total System Performance Assessment, March 17, 1998). The NRC staff supports the use of the DKM approach relative to the ECM approach for site-scale flow modeling as long as DOE demonstrates that the results bound the effect of episodic pulses.

Doughty and Bodvarsson (1997) conclude that the ECM is most appropriate for steady state conditions and gas-flow problems at YM, as the assumption of matrix/fracture pressure equilibrium is best met under these conditions. Doughty and Bodvarsson (1997) and Tsang (1997) find that the DKM predictions significantly differ from the ECM predictions under transient conditions, with transport times significantly slower in the ECM. The DKM provides prediction more consistent with simulations of a ponded-infiltration experiment examining flow processes in TSw bedrock at Fran Ridge (Eaton, et al., 1996) than the ECM predictions. Doughty and Bodvarsson (1997) further conclude that the additional complexity of the MINC approach is most necessary near faults.

Discrete-fracture approaches have not been used frequently at YM but have not been ignored completely. The WEEPS model (Gauthier, et al., 1992; Sandia National Laboratories, 1994), used to assess fluxes onto a WP for TSPA, assumes that all percolation is within fractures and is gravity-driven. The model uses geometric arguments to map the intersection between flowing fractures and WPs in order to arrive at total flux onto WPs. The model apportions the available flux into flowing fractures, with a primary uncertainty being the aperture distribution of the flowing fractures.

Individual fracture segments within a fracture network are explicitly represented in a discrete-fracture formulation, with each segment having individual hydraulic and pneumatic properties. The explicit-fracture method is attractive at scales where continuum behavior is not observed (i.e., at scales small relative to fracture density) but becomes intractable once many fractures are considered. Discrete-fracture methods are not practical for use at a YM-site scale as there are an estimated 10^9 significant fractures at YM (Doughty and Bodvarsson, 1997). Anna (1996) attempted to model a portion of the North Ramp using discrete-fracture formulation with limited success. The generated network of fractures was based on E... observations and had generally low connectivity, but pneumatic testing suggested that fracture connectivity should have been much larger. The discrepancy between simulated and inferred connectivities may be due to those fractures not considered in the discrete-fracture model (i.e., fractures less than 1 m in trace) or to the partial pneumatic connection through the matrix not included in the formulation.

The most appropriate application at YM for discrete-fracture methods may be drift-scale modeling, as there are few enough fractures that discrete-fracture discretization requirements may be tractable, and continuum approaches may be invalid. Nevertheless, DOE drift-scale studies for isothermal flow have invariably used continuum approaches: (1) matrix continuum, with fractures included as heterogeneous pathways (Wang, presentation to Site-Scale Unsaturated Zone Expert Elicitation Panel, 1997); (2) fracture continuum, with no consideration of matrix interaction (Birkholzer, et al., 1997a); (3) equivalent continuum (Nitao, 1997); and (4) DKM (Tsang, 1997). The DOE conceptual model for seepage into drifts is not well enough defined, nor is the uncertainty reasonably enough constrained to determine, a single appropriate model at this time (TRW Environmental Safety Systems, Inc., 1997a). However, seepage and moisture studies are ongoing at YM to better evaluate the drift seepage processes, percolation fluxes, and the capillary barrier system. These investigations are titled "Percolation in the Unsaturated Zone - Exploratory Studies Facility." The objective is to conduct *in-situ* ambient cross-hole pneumatic and liquid-release niche seepage studies and alcove surface infiltration studies.

Wang, et al. (1998) presented the Phase 1 preliminary test results and numerical model analysis of seepage into drifts. This included test results of the first seepage tests at Niche 3650 and sensitivity analysis of drift seepage with two and three-dimensional numerical models. The numerical models were then tested to predict the wetting-front arrival time of the planned infiltration test for Alcove 1. This report is the third technical report for the drift seepage testing and moisture analysis.

According to the Master Scientific Notebook YMP-LBNL-JSW-6.0, ongoing field studies include: (1) the Phase 2 drift scale seepage test; (2) field tests of flow propagation through the heterogeneous and fractured Paintbrush nonwelded tuff (PTn); (3) investigation of fracture flow and storage effects in the PTn; (4) horizontal diversion of flow along interfaces between different subunits, (5) fracture flow, fracture-matrix interaction, and matrix imbibition tests of the middle nonlithophysal unit of Topopah Spring welded hydrogeological unit; and (6) Alcoves 1 and 7 testing. The results of these field investigations will feed the site-scale and drift-scale models calibrated against on-going field test results to support the TSPA for YM.

4.4.2.7 Past Evidence and Impact of Future Climate Changes on Deep Percolation

The primary sources of information for future predictions of climatic change are the paleo records. Local data include the isotopic record from Devils Hole, pack rat middens, paleospring deposits, and water table fluctuations recorded by isotopic data, while the global data include information such as the integrated marine record (see NRC, 1997a; Forester, et al., 1996).

The single most important data set for predicting deep percolation under pluvial conditions is net shallow infiltration. According to Forester, et al. (1996), shallow infiltration may increase by a factor of 2 to 3 as a consequence of 5 to 10 °C drops in temperature, so that significant changes in vegetation may occur (NRC, 1997b). The factor for the increase in infiltration due to climatic change (pluvial) may be larger due to the nonlinear response of infiltration to increased precipitation and cooler temperatures. The staff is currently evaluating climate analog sites to incorporate in infiltration estimates the effects of soil characteristics, vegetation, and surface water runoff phenomena.

Tyler, et al. (1996) interpreted chemical and isotopic data below about 50 m deep at the NTS as representing two Pleistocene superpluvial recharge periods. Isotopic enrichment for pore-water samples of δD and $\delta^{18}O$ above 50 m was due to evapotranspiration. Phillips (1994) states that the soil moisture flux decreased by 20 times in the U.S. desert southwest over the past 15 kyr and that Holocene infiltration has been largely consumed by vegetation.

For deep percolation, the effect of climatic changes would be expected to impact the magnitude and pattern of percolation rates, including seepage into the drifts and flow below the repository. Increased percolation through the TSw is expected to be through the fracture system as the low matrix permeabilities will not take a significantly larger magnitude of the flow. The seepage-to- percolation ratio for seepage into drifts increases (Birkholzer, et al., 1997a) due to the fractures taking up a higher fraction of the flow as percolation increases. The spatial pattern of percolation might be expected to change as different portions of the fracture system begin to carry more flow as percolation increases. Below the repository, both the perched water and water table levels might be expected to change.

Site-scale modeling of potential future climatic impacts by Ritcey, et al. (1997b) using the ECM formulation suggests increased fluxes over the northwestern portion of the repository, though there is little significant change in pattern for other areas at the repository horizon or below the repository. Ritcey, et al. (1997b) noted that modest increases, less than 10 m, in the elevation of perched water tables resulted from doubling the shallow infiltration rates.

The question of how much to increase percolation rate to account for possible climatic changes requires a linkage of paleoclimatic conditions to the shallow infiltration. Linkage of the top boundary condition of shallow infiltration to both general and local paleoclimate information led Gauthier (1998) to use precipitation multipliers of 1 for the current dry conditions, 2 for the long-term average conditions, and 3 for the super pluvial conditions. Over the past four hundred thousand years, the long-term average conditions occurred about 80 percent of the time (Forester, et al., 1996). A constraint on the conditions is the paleo position of the maximum 100-m rise of the water table as indicated by the strontium data from calcite fracture filling and paleosprings deposits in Crater Flats (Forester, et al., 1996).

4.4.2.8 Pneumatic Responses at YM

A major topic of study at YM has been the movement of unsaturated zone gases, mainly water vapor, in response to barometric pressure changes. There have also been concerns about the possible interference of exploratory shafts and tunnels on testing in the UZ. The NRC staff developed an open item on pneumatic issues during our review of the Site Characterization Plan (see SCA, 1989, p. 4-92). Our comment (no. 123) stated that:

> The effects of ventilation of the exploratory shafts and the underground testing rooms may have been underestimated in the evaluation of the potential interference with testing and the potential for irreversible changes to baseline site conditions; also, there is not an adequate analysis of the effects of ventilation in the ESF on the ability of the site to isolate waste.

DOE (1990) responded that the exploratory shaft would be lined with poured concrete that would isolate the rock from the ventilation air. The staff did not close the open item at that time because it was not c whether the shaft would be lined, and secondary effects of ventilation on baseline conditions were not addressed. Since that time, DOE has chosen to construct the underground exploratory facility and the east-west drift using a tunnel boring machine (TBM) rather than build vertical access shafts.

Another open item had been raised by the staff regarding possible interference by the ESF on gas chemistry sampling. This item was closed in a 1994 letter from NRC to DOE (NRC, 1994). The staff's remaining concern was with pneumatic pathways.

Early in 1993, the State of Nevada wrote to NRC questioning whether DOE could adequately characterize pneumatic pathways before the UZ was disturbed by construction of the ESF. The State felt that the potential loss of data could prevent the NRC from making a licensing finding on the issue of the fastest pathway for radionuclide release. The State's letter was forwarded to DOE by NRC staff along with a reminder that the staff also had related concerns. The topic was discussed at a meeting of the NWTRB on October 19, 1993. Then, during January 26-27, 1994 a forum was convened by the YM Affected Units of Local Government (AULG). Proceedings of this roundtable have been published (AULG, 1994).

The concern that characterization of pneumatic pathways could be precluded by penetrating the PTn with a TBM was a valid one. It was thought that if the PTn was an effective pneumatic barrier, distinction between the pneumatic system above, in, and below the PTn could be determined by responses to changes in barometric pressure. If, however, the PTn were breached by the large diameter ESF, the distinction might have been masked. Knowledge of the effectiveness of a pneumatic barrier above a hot nuclear waste repository could be important to performance assessment.

DOE, in its Accelerated Surface-Based Testing Program, committed to collect data on ambient pneumatic conditions and perturbations caused by ESF excavation. DOE installed pressure monitoring systems in boreholes NRG-6 and NRG-7a in October and November, 1994. These holes were located along the north ramp portion of the planned ESF. Data were collected from these holes for over two years, ending in December 1996. The staff had no objections to DOE's decision to discontinue monitoring in these holes because, by that time, the TBM was almost two miles away constructing the south ramp of the ESF. The TBM was no longer within the repository horizon and, therefore, NRG-6 and NRG-7a were no longer yielding new information.

Pneumatic information was also obtained from boreholes UZ-4, UZ-5, UZ-7a, NRG-4, NRG-5, SD-7, SD-9, SD-12, and ONC-1. NRG-4 and ONC-1 were instrumented by the Nye County cooperative study program. Locations of pneumatic testing and monitoring boreholes had been sited based on the ESF layout, allowing large-scale seasonal barometric responses to be monitored along with responses to ESF construction. To give a time perspective to progress of the TBM, the front of the TBM passed closest to NRG-4 on June 16, 1995 and penetrated through the PTn into the Topopah Spring unit on June 20, 1995. The TBM passed closest to UZ-4 and UZ-5 on September 2, 1995, and closest to SD-9 on November 16, 1995. It passed SD-12 on April 4, 1996, and SD-7 on June 5, 1996 (Ahlers, et al., 1996).

Summaries of the pneumatic response data are provided by Ahlers, et al. (1996; 1997). They reported that the ESF can affect pneumatic pressures from a large distance where faults are involved. They recommended that any new pneumatic monitoring boreholes be located far enough from the ESF that the data would not be affected by the tunnel. If additional drifts are planned (such as the east-west drift), boreholes along the drift alignments should be considered. Faults were identified as fast pneumatic pathways in the PTn and the TSw. Ahlers, et al. (1997, p. 10-28) concluded that:

> Overall, simulation of pneumatic conditions at Yucca Mountain using the three-dimensional site-scale UZ model has been successful. Though some minor modifications to the model are warranted by the simulation results, the technique for pneumatic calibration produces reasonable pneumatic parameter sets. These parameter sets should be acceptable for simulation of future scenarios and predictions at Yucca Mountain.

As noted in Section 5, and based on the above discussion, the staff now considers SCP open item Comment 123 to be resolved. Sufficient data on baseline conditions have been obtained and data were collected during the construction of the ESF. Pneumatic monitoring and testing is continuing at various locations in the ESF. As of June 1998, recording of pneumatic data continues at boreholes UZ-4, UZ-5, UZ-7a, SD-12, NRG-7a, and SD-7. Nye County, Nevada, continues to record pneumatic data in NRG-4 and ONC-1.

4.4.2.9 Evidence for Fast Pathways

Early conceptualizations of flow processes at YM discounted the possibility of significant fast-pathway flows below the TCw unit, based on low infiltration rates and the large capacity of the PTn to dampen wetting pulses. The associated concept, that the TSw matrix conducted all percolation fluxes at a steady state with little or no fracture flow, was strongly challenged by observations of bomb-pulse ^{36}Cl and other radionuclides far below the PTn. It is difficult to provide strong limits on fluxes using bomb-pulse evidence, as mixing of waters distorts interpretations, so that bomb-pulse observations are only evidence of fast pathways and not necessarily focused-flow pathways. However, additional evidence that significant flux occurs in fast pathways at YM has been mounting steadily, forcing revision of conceptual models for both infiltration and subsurface flow processes.

Isotopes arising from nuclear testing worldwide in the 1950s provide the strongest evidence that fast-flow pathways exist in the subsurface of YM. Although ^{36}Cl is the bomb-pulse isotope providing the most unambiguous indication of fast water flow paths, since ^{36}Cl moves only with liquid-phase water, ^{3}H and ^{14}C (despite moving both in the air and the liquid phases) also provide supporting evidence for fast flow (Yang, et al., 1996a; Fabryka-Martin, et al., 1997). Elevated isotope levels are found in the fracture systems in the ESF and in perched water bodies. Elevated isotope levels are also found in the boreholes in the TCw (fracture-dominated flow) and at the top of the PTn. Detection limits for tritium often were 8 TU ± 4 TU, and therefore a value up to 12 TU may be background. Tritium has been shown to move faster than groundwater due to vapor transport (Phillips, 1994). Measured values of ^{36}Cl for boreholes were found to be lower than in the ESF due to collection techniques (Fabryka-Martin, et al., 1997). Tritium data and interpretations suggesting bomb-pulse should be reconsidered due to high detection limits (8 TU), large uncertainty in the measurements (± 4 TU), and the issue of vapor transport.

Geochemical data from UZ matrix waters, perched waters, and the saturated zone suggest that fast pathways, having little interaction with the matrix, exist through the UZ. Ca^{2+}, Mg^{2+}, and Cl^{-} are up to 10 times more concentrated in the matrix pore water than either the perched water or the saturated zone water (Yang, et al., 1996b). The Cl^{-} concentrations are indicative of percolating water bypassing pore water in units above the perched water. Chloride concentrations in some portions of the CHn range from 4 to 8 mg/L (Yang et al., 1996b), which is closer to the near-surface estimate of 0.6 mg/L than to the matrix concentrations of 60 to 228 mg/L in the PTn (Fabryka-Martin, et al., 1997). Indicative of little mixing in the UZ, dissolved SiO_2 levels are consistently 50 percent higher in the matrix pore water than in perched or [illegible] waters.

Hydrogen and oxygen isotope ratios in perched waters are similar to the current winter-precipitation meteoric ratios, indicating that there is little evaporative loss before recharge (Wu, et al., 1996), or stable isotopic compositions in perched water may represent colder climates during the Pleistocene. Lateral flow from Solitario Canyon or vertical fast-pathway percolation may explain the isotope-ratio data. The similarity to current meteoric water and dissimilarity to waters north of the repository is evidence that perched water is not formed from fluids migrating from the north. Preliminary ^{14}C dates show a trend of younger water to the south (Wu, et al., 1996), providing further evidence that perched water near the repository may not be related to the zone of large hydraulic gradient to the north. Preliminary data from WT-24 suggest that the gradient is less steep than previously thought. Lateral flow from Solitario Canyon or vertical fast-pathway percolation may explain a portion of the water in perched zones of the CHn.

In a study of transport and water-rock interaction by Johnson and DePaolo (1994), strontium isotope data in water, whole rock, and calcite fracture fillings in the TSw were found to be consistent with fast pathway movement of water.

Studies at Rainier Mesa support the possibility of fast-pathway flow through fractured nonwelded tuffs. A sequence of lithologies similar to YM is present at Rainier Mesa, including alternating welded and nonwelded tuffs capped by a moderate-to-densely-welded tuff. However, the sequence at Rainier Mesa is primarily nonwelded with a thick sequence of zeolite-altered tuffs (Wang, et al., 1993). Percolation estimates from seepage into the tunnels, based on discharge at the portal and vapor flow, are approximately 24 mm/yr with a mean annual precipitation of 320 mm (Russell, et al., 1987; Wang, et al., 1993), or about 8 percent of the precipitation. Suggestive of fracture or fault flow, there is a distinct difference between the geochemistry of the matrix pore water and the water in the seeps (Murphy and Pabalan, 1994). The saturated zone water geochemistry is similar to that of the seeps. Residence times estimated from tritium data suggest travel times less than 6 yr from ground surface to the observation tunnels at a depth of 350 m (Wang, et al., 1993). Bomb-pulse ^{36}Cl observations in the seeps provide additional evidence for fast-path movement of water. Using the precipitation record, seep discharge rates, gross water chemistry, stable isotope composition, and two tracer tests, Russell, et al. (1987) concluded that: (1) the seep water was meteoric in origin with winter as the principal period of recharge based on hydrogen and oxygen isotope ratios; (2) the period of hydrologic response was at least 4 months; and (3) the travel time from surface to tunnel was at least 1 yr and less than 6 yr (Wang, et al., 1993). The period of hydrologic response is the time it takes for a given recharge event to cause a corresponding increase in discharge at the seeps in the tunnels. In spite of the large matrix permeabilities of the nonwelded tuffs, fault systems intercepted by the tunnels within the zeolitic horizons provide the bulk of the discharge. An estimate of 10 percent of the total percolation is from 2 seeps in the U12n tunnel while 50 to 60 percent of the 112 mapped faults in the U12e tunnel supplied most of the total discharge from the tunnel system (aqueous discharge through the portal and vapor discharge through the air ventilation system). The analogy to YM is weakened by the observation that nuclear testing probably altered the flow system, but the extent of alteration is unknown.

Observations at the Apache Leap Test Site (ALTS) featuring a sequence of fractured tuffs also suggest fast pathway flow along fractures, although the fracture system at ALTS has far wider apertures than exist at YM; mean aperture is 760 μm at ALTS (Bassett, et al., 1994) and the range of mean apertures is 131 to 497 μm for all units at YM (Sonnenthal, et al., 1997a). At ALTS, intermittent recharge from a stream penetrates to a tunnel 150 m below the ground within days to weeks (National Research Council, 1996). Infiltration tests by Rasmussen and Evans (1993) demonstrated the possibility of high water intake rates on exposed fractured rock surfaces at the Apache Leap site.

The portion of flow that occurs through fast pathways is an important consideration for repository performance. Seepage into the repository is dependent on the partitioning of percolation flux into matrix, dispersed fractures, and fast-pathway fractures or faults. Transmission capacity for matrix flow in the welded units is about 1 mm/yr assuming, that percolation is gravity-dominated, based on effective conductivities and typical water saturations provided by Flint (1997). Any additional percolation flux is carried in discrete pathways, typically in small-aperture (capillary-dominated) fractures appropriate for continuum approaches or large-aperture (gravity-dominated) fractures or faults that may not be appropriate for continuum approaches. Partitioning between the two fast-pathway alternatives, in part, is related to the physics of flow through small-aperture fractures versus large-aperture fractures, but it is also controlled by focusing mechanisms at the ground surface and at depth. Despite the evidence presented in this section demonstrating that fast pathways occur at YM, it is difficult, however, to estimate the portion of the repository that might be contacted by fast pathways.

The discussion of mass balance of ^{36}Cl in Section 4.4.3.1 looked at the fraction of the perched water having the bomb pulse signature, with roughly 1 to 50 percent ascribable to water infiltrating in the past 50 yr. Murphy (1998) estimated that the bomb-pulse ^{36}Cl signature was primarily evident in three ESF zones, comprising 23 percent of the tunnel, which implies that roughly a quarter of the repository may experience fracture flow if the ESF is representative of the remainder of the repository footprint. Note that Murphy (1998) used a lower threshold to identify bomb pulse ^{36}Cl than was used by Fabryka-Martin, et al. (1997) in order to account for bomb-pulse dilution through mixing.

4.4.2.10 Calculated Distribution of Percolation at the Repository Horizon

A map of estimated spatial distribution of shallow infiltration, on a mean annual basis, was presented in NRC (1997b). The distribution was in qualitative agreement with the map of Flint, et al. (1996a). Using the presumption that flow above the repository is predominantly vertical, the magnitude and distribution of percolation flux at the repository horizon is equal to that of the shallow infiltration. The assumption of vertical flow means that no lateral flow at the PTn is recognized. Current efforts by the NRC staff are focused on further refining percolation estimates by adding the impact of plants and lateral flow at the bedrock interface with the alluvium, colluvium, or atmosphere.

4.4.3 Summary of Deep Percolation Topics That Warrant Further Analysis

Significant variability of flow and transport pathways and travel times is expected to occur at YM due to the natural heterogeneity, stratification, alteration, fracturing, and other characteristics of the site. The extent to which such heterogeneities of the flow system should be incorporated into the DOE site-scale UZ flow model depends on their importance for estimating seepage into the repository and flow below the repository. Conceptualizations of flow in the UZ at YM have ranged from single-continuum models, to equivalent continuum models, to dual- and multiple-continuum models, to discrete-fracture models, as the importance of particular components of the flow system was examined. Given the matrix permeability values (Flint, 1997) and assuming a unit hydraulic gradient, groundwater flowing only in the matrix would move sufficiently slowly that it would take many tens of thousands of years for shallow infiltration to go through the repository horizon and arrive at the SZ. In contrast, both geochemical evidence and transient-flow modeling have suggested that a significant amount of groundwater flux occurs in the fracture system, and that these fluxes can travel at much faster rates than in the matrix. Fluxes in the fracture systems may move sufficiently fast that some component of shallow infiltration reaches the water table in tens to hundreds of years. Differing conceptualizations of the link between the matrix and fracture systems and flow processes in the fractures cause important differences between alternative conceptual models. The differences in the conceptualizations can have a strong impact on PA modeling and, as such, are the focus of the discussion in this section.

The development of both the repository-scale and drift-scale conceptual models at YM may be partitioned into:

- Percolation processes above the repository, which affect the spatial and temporal distribution of water moving through the repository horizon
- Percolation processes at the drift scale, which affect the release of radionuclides from the repository
- Percolation processes below the repository, which affect the transport of radionuclides from the repository to the SZ

An assessment of current understanding of these three parts of the conceptual model is summarized below for flow above, at, and below the repository.

1.4.3.1 Percolation Processes Above the Repository

Percolation processes above the repository have a direct impact on flow processes at the drifts, by affecting the amount of water that arrives at the repository horizon and the partitioning of that water between matrix and fractures. As discussed in the IRSR related to shallow infiltration (NRC, 1997b), water infiltrates into the subsurface in pulses following precipitation events. Some portion of this infiltrating water (net infiltration) eventually escapes downward from the root zone to become deep percolation. Both within wash channels above the repository and where bedrock cover is shallow (i.e., less than 0.5 m), the magnitude of the infiltration pulse can be much larger than the permeability of underlying moderately to densely welded tuff. As there is typically a plentitude of fractures within the Tiva Canyon bedrock, it is anticipated that infiltration pulses below the root zone primarily enter the bedrock fracture system and move under the dominant influence of gravity. There may be some fracture/matrix transfer within the TCw unit, but the percolating water should generally move vertically downward until a zone is reached with increased matrix permeability or reduced fracture permeability. If the fracture system exhibits numerous subhorizontal cooling joints, significant lateral flow may occur within the fractures leading to either a spreading or a coalescing of flow.

Available evidence supports the interpretation of rapid penetration of infiltration pulses into the TCw unit where bedrock alluvial or colluvial cover is shallow (i.e., less than 2 m, which corresponds to all of the repository footprint except for some wash bottoms). Neutron-probe data have been obtained for a network of 99 boreholes, with records extending nearly 10 yr for some boreholes (Flint and Flint, 1995). As discussed by Flint and Flint (1995), the average wetting-pulse penetration depth in the years 1990 through 1993 that was detected by the neutron-probe apparatus was at least 5 m for 12 of the 14 ridgetop and sideslope boreholes considered, with average wetting pulses penetration greater than 10 m in 8 of the boreholes. The neutron-probe methodology is relatively insensitive to fracture flow, so that deeper wetting pulses may have occurred without having been detected.

Further corroboration of rapid penetration of infiltration pulses is indicated by bomb-pulse ^{36}Cl found within borehole ream-bit cuttings. As discussed by Fabryka-Martin, et al. (1997), bomb-pulse ^{36}Cl has been transmitted well into the fractured bedrock (e.g., 20 to 80 m) at all but one of the shallow boreholes examined that has alluvial cover less than 2 m (most have less than 1 m of cover). Bomb-pulse ^{36}Cl was found within the PTn unit in several of the boreholes, penetrating to the TSw unit in one borehole. Bomb-pulse ^{36}Cl evidence (Fabryka-Martin, et al., 1996b) suggests that lateral flow may occur in the TCw and PTn units, based on the existence of multiple peaks in several of the boreholes.

Aside from the lower portion of the west flank of YM, which exhibits outcrops of the TSw unit, the bedded tuffs within the PTn unit form the first barrier to fracture-dominated flow within the repository footprint. These bedded tuffs have relatively large primary permeability and relatively few fractures, and the fracture system tends to be strata-bound (i.e., fractures within the PTn unit are poorly connected to those within the overlying TCw unit and the underlying TSw unit). Montazer and Wilson (1984) hypothesized that the PTn has the potential to significantly attenuate infiltration pulses due to these factors. Simulations (Buscheck, et al., 1991; Nitao, et al., 1992) suggest that an infiltration pulse penetrating to the PTn unit, either in the matrix or in fractures, should end up entirely within the PTn matrix by the time the pulse reaches the bottom of the PTn unless the fracture and the flow rates are quite large, due to strong capillary uptake from the fractures to the matrix. Furthermore, the large storage capacity of the PTn is thought to provide a strong buffer, almost completely damping out the pulse by the time it reaches the bottom of the PTn. If the PTn does damp out infiltration pulses both spatially and temporally, fluxes in the underlying TSw unit may be nearly steady state and total fracture flux would be significantly smaller than in the TCw unit, although the flow in the fractures may still be widespread. However, if the PTn causes lateral diversion and, thereby, focuses flow, fracture flow may be spatially infrequent, but those areas with fracture flow may have large fluxes. As the PTn unit thins from north (roughly 80 m) to south (roughly 20 m) within the repository block (Moyer, et al., 1996), the effects of the PTn unit should diminish from north to south.

The perched water at the base of the TSw unit does not carry a strong geochemical signature of having passed through the PTn matrix, suggesting that the bulk of the perched water may have bypassed the PTn matrix (Bodvarsson and Bandurraga, 1997; Striffler, et al., 1996; Yang, et al., 1996a,b). In particular, the chloride concentration is far larger in the PTn unit than in the perched water. The perched water may be largely the result of lateral flow from Solitario Canyon directly entering the TSw, thereby bypassing the PTn, or from lateral flow from the area of the so-called large hydraulic gradient to the north of the repository footprint. If the perched water primarily results from net infiltration occurring above the repository, the discrepancy between the signatures of the PTn matrix and the perched water suggests that a large component of deep percolation does not pass through the PTn matrix. Flow starting above the PTn unit may bypass the PTn matrix in several ways:

- Connected fracture pathways with fracture coatings that reduce matrix/fracture interaction
- Fine-scale matrix pathways formed by heterogeneity and/or fingering
- Systematic down-dip movement within the fractures above the PTn until a fast pathway, such as a fault, is encountered that focuses flow

The different mechanisms for water moving through the PTn have different influences on flux distributions at the repository horizon within the underlying TSw unit. The TSw unit is similar to the TCw unit: densely welded, with low permeability and extensive fracturing. Matrix fluxes within the PTn unit would tend to preferentially move into the more fine-pored TSw matrix through capillarity, to the extent possible, with excess perhaps moving downdip until sufficient pressure builds up to overcome the matrix/fracture capillary barrier. Flux pulses bypassing the PTn matrix via fractures may tend to remain within fractures in the TSw if the fracture sets are connected. As bypass fluxes become large, it becomes increasingly unlikely that the TSw matrix can conduct all percolation flux and more likely that fracture flow is initiated where the bypass fluxes contact the TSw unit.

The chloride mass balance technique, as applied by Fabryka-Martin, et al. (1996b), assumes that average chloride concentration multiplied by total flux is conserved, and flows are approximately steady state. To roughly estimate the relative components of PTn matrix flux and bypass flux, assume that:

- $C_m\, Q_m + C_b\, Q_b = C_p\, (Q_m + Q_b)$, where C represents concentration, Q represents flux, and the m, b, and p subscripts represent matrix, bypass, and perched components, respectively.
- Bypass fluxes arrive at the perched water body with the chloride concentration of rainfall (0.62 mg/L) that was used by Fabryka-Martin, et al. (1996b)
- PTn fluxes arrive with an average chloride concentration of 62 mg/L [a number near the middle of the range of observed PTn values reported by Fabryka-Martin, et al. (1996b)]
- Chloride concentration in perched waters is 6.2 mg/L [a typical value from Yang, et al. (1996a)]

'sing these chloride concentrations in a simple mass-balance calculation, which requires that chloride ,om both matrix and bypass fluxes fully mix in the perched waters, suggests that bypass fluxes are roughly ten times as great as PTn matrix fluxes. As the chloride concentration in the bypass fluxes increases (indicating evaporation within the subsurface), the ratio of bypass flux to matrix flux also increases.

Using a similar mass balance technique for ^{36}Cl, the ^{36}Cl signatures from both perched water and pore waters can be used to roughly estimate flux rates for the bomb-pulse portion of the perched waters. Based on Table 4-16 by Fabryka-Martin, et al. (1997), the ratio of ^{36}Cl to chloride in perched waters obtained from boreholes NRG-7a, SD-7, SD-9, UZ-1, and UZ-14 ranges from 449×10^{-15} to 999×10^{-15}, with a mean of 590×10^{-15}. Comparable ratios from 5 samples from the TSw unit [SD-12 and ONC boreholes in Table 4-11 of Fabryka-Martin, et al. (1997)] are 235×10^{-15}, while the deepest non-bombpulse sample obtained from the PTn unit in boreholes N37, N53, N54, UZ-14, and UZ-16 average 345×10^{-15} [Table 4-10 of Fabryka-Martin, et al. (1997)]. Seven borehole observations within the PTn unit were greater than $10,000 \times 10^{-15}$, with a peak value of $32,400 \times 10^{-15}$. Within the ESF, 21 of the 141 samples obtained from formations in or below the upper lithophysal zone of the TSw unit (station 18+00 to 69+00) were above $1,250 \times 10^{-15}$, with a maximum of $4,100 \times 10^{-15}$. Several calculations can be made:

- Assuming that the perched-water ratio is 590×10^{-15}, pore waters have the TSw ratio (235×10^{-15}); and fast-path ratio is $4,100 \times 10^{-15}$, about 10 percent of perched water has a bomb-pulse signature.

- Assuming that pore waters have the PTn ratio (345×10^{-15}), and the fast-path ratio is the largest observed at YM ($32,400 \times 10^{-15}$), about 0.8 percent of perched water has a bomb-pulse signature.

- Assuming that pore waters have the TSw ratio (235×10^{-15}), and the mean fast-path ratio is $1,250 \times 10^{-15}$, more than 50 percent of perched water has a bomb-pulse signature.

- Assuming that fast-path fluxes are 10 times greater than matrix fluxes, and pore waters have the PTn or the TSw ratio, the fast-path ratio is 626×10^{-15} and 615×10^{-15}, respectively.

From these considerations, it is likely that at least one percent, and perhaps more than half, of the perched water infiltrated in the past 50 yr. However, flux information derived from the chloride calculations yields an estimated ratio so low that it is unlikely that all of the bypass fluxes are younger than 50 yr unless a significant portion of the perched waters come from post-bomb-pulse waters. The magnitude and spatial distribution of fracture fluxes within the TSw are likely to have a profound impact on repository performance. As discussed in Section 4.4.2.4, capillary effects tend to preclude entry of liquid into open cavities in unsaturated porous media, particularly when the medium is as fine-grained as is the TSw matrix, so that flows in the matrix will tend to divert around the drifts rather than entering the drifts. Capillary-exclusion effects are less important for fractures, especially larger fractures, so that flows in fractures are less likely to divert around drifts. The larger the flow in a fracture, the less important capillary forces are relative to gravity and the less likely that diversion will occur around a drift intercepted by the fracture. If the fracture supports film flow, only viscous and gravity forces significantly affect the flow (Kapoor, 1994) so that capillary forces are unlikely to prevent entry into the drift.

As with the TCw unit, matrix/fracture interactions are likely to be relatively limited within the densely welded TSw unit, and flows are likely to be predominantly vertical. Hence, the distribution of fracture flows initiated in the TSw at the bottom of the PTn is likely to be propagated vertically downward to the repository horizon with some spreading or coalescing of flow paths possibly occurring.

- **Modification of Percolation Due to the Paintbrush Nonwelded Unit**

The possibility that the PTn unit may cause lateral diversion due to capillary effects (at the TCw/PTn interface) or permeability effects (at the PTn/TSw interface) has long been recognized (Montazer and Wilson, 1984). The effectiveness of the PTn unit in attenuating pulses or causing lateral diversion has been examined by numerous researchers (Prindle and Hopkins, 1989; Ross, 1990; Buscheck, et al., 1991; Nitao, et al., 1992; Brown, et al., 1993; Altman, et al., 1996; Bodvarsson and Bandurraga, 1996; Fabryka-Martin, et al., 1996a, b, 1997; Moyer, et al., 1996; Robinson, et al., 1996, 1997; Rousseau, et al., 1998; Wilson, 1996; Wolfsberg, et al., 1996; Fairley and Wu, 1997; Wu, et al., 1997; Ofoegbu, et al., 1997). In general, the PTn matrix is considered to have the potential to strongly attenuate pulses, due to large storage capacity, high matrix permeability, and capillary effects that strongly imbibe fracture waters into the matrix. The strong attenuation potential within the PTn, which would tend to reduce fluxes below the PTn to nearly steady, is often used to justify the modeling assumption that fluxes are at a steady state throughout YM. Depending on model assumptions and model parameters, however, disparate results for lateral diversion are obtained. For example, Prindle and Hopkins (1989) and Ross (1990) suggest lateral diversion increases as net infiltration increases while modeling studies reported by Bodvarsson and Bandurraga (1996) suggest that the capillary barrier effect decreases with increasing net infiltration.

Several factors appear to play a major role in determining the role of the PTn unit in attenuating and diverting infiltration pulses:

- Fracture/fault interaction with the PTn matrix
- Infiltration model
- Hydraulic properties
- Stratigraphy

Early models generally assumed that infiltration was quite small (less than 1 mm/yr) and at steady state; the PTn unit did not have significant fractures or fractures were included using the ECM conceptual model; hydraulic properties were based on early measurements reported by Peters, et al. (1984) and Klavetter and Peters (1986); hydraulic properties within layers were homogeneous; and microstratigraphy was usually not considered (e.g., several bedded-tuff layers were consolidated into the PTn unit). With such small and steady infiltration rates, the (assumed-homogeneous) matrix is sufficiently permeable to carry all percolation fluxes and fracture flow is inhibited due to capillary effects. These early models tend to indicate that significant lateral flow may occur. Significant lateral flow may be generated in the PTn in the absence of vertical discontinuities even when detailed microstratigraphy and updated hydraulic properties are considered (Moyer, et al., 1996).

Sampling from within the ESF and in deep boreholes has revealed bomb-pulse ^{36}Cl and ^{3}H in numerous locations (Fabryka-Martin, et al., 1996a, 1997; Yang, et al., 1996b), which requires that for at least some flow paths travel times are less than 50 yr to the repository horizon and the base of the TSw unit. In addition, calcite and opal fillings (their origins may be associated with fracture-flow paths) have been observed in numerous fractures within the ESF, and the portions of the PTn penetrated by the ESF exhibit numerous small-offset (slump) faults. Spurred by these observations, conceptual models have been modified to emphasize the role of fractures and faults and to consider the role of transient infiltration pulses. Recent models tend to exhibit predominantly vertical flow, less lateral diversion, and a small component of the flow bypassing the PTn matrix in fast pathways. However, significant systematic lateral flow (e.g., 500 m) is still produced with some calibration parameter sets (Bodvarsson, et al., 1997a).

Sweetkind, et al. (1995) conclude that observations of fractures in the PTn unit at 22 outcrop locations do not support interpretations of significant fracture flow within the PTn unit, due to the generally stratabound nature of the observed fractures and lack of alteration products within the fractures (although calcite fillings were observed in some of the fractures). If correct, this conclusion implies that fast pathways within the PTn, if they exist, are fault-derived or due to heterogeneity-derived channels in the matrix.

Field evidence for lateral flow within the PTn unit is derived primarily from geochemical data, such as inversions in concentration as depth increases. Kwicklis (1996) suggests that at least limited lateral redistribution may be indicated by inversions of aqueous ^{14}C data with depth in borehole UZ-14, although these inversions may also be due to fracture flow. Fabryka-Martin, et al. (1997) suggest that a model postulated by Paces, et al. (1997), in which percolating waters with two distinct strontium isotopes (resulting from areas with ridge crests and sideslopes without thick calcretes, and areas with thick calcite- and Sr-rich soils) requires mixing through lateral flow in the PTn unit to explain observed profiles within borehole SD-7.

The UZ expert elicitation panel had based its conclusions on available evidence for infiltration and deep percolation as of the end of 1996. The panel noted that lateral diversion might be expected at the TCw/PTn and PTn/TSw interfaces, and perhaps within the PTn itself, if textural differences alone were considered (Geomatrix, 1997). However, the panel generally agreed that the series of small slump faults observed in the ESF within the PTn would serve to capture flow moving laterally, diverting the flow vertically down the faults. Thus, the expert panel concluded that lateral diversion might occur over a few meters to tens of meters, but lateral diversion would not be expected to occur over a much larger scale. Most of the experts, accordingly, expected that the spatial distribution of percolation flux at the repository level is similar to the spatial distribution of net infiltration, although perhaps smoothed. One expert believed that there may be focusing processes as well as smoothing process, perhaps funneling flow into locally high-flux zones.

Two mechanisms that promote bypassing of the PTn matrix apparently have not been quantified to date: (1) potential lateral fluxes, in response to large infiltration pulses, in a TCw fracture system that is strata-bound (i.e., that terminates above the PTn); and (2) vertical fluxes in localized pathways within the PTn matrix. In the first case, large pulses of water may proceed rapidly down to the base of the fracture system. If the fractures are strata-bound or are filled with alteration products that drastically reduce fracture permeabilities, the infiltration pulse may tend to rapidly redistribute downdip until a fast pathway is encountered. If faults are not ubiquitous or if the moist conditions at the bottom of the TCw have caused widespread alteration, lateral redistribution within the TCw fracture system may be significant. In the second case, heterogeneity within the PTn matrix may cause local fast pathways within the matrix, which may not be captured by current estimates of grid-block-scale parameters. Potential causes and effects of misrepresenting heterogeneity are discussed in Section 4.4.2.3.

The NRC staff concludes that systematic lateral flow within the PTn may not occur in the vicinity of the ESF observations and would be similarly unlikely if the PTn is generally faulted over the repository block. The PTn unit is observed only in a relatively small portion of the ESF east of the GDF, and it is possible that the observed faulting is not typical of the relatively less distorted areas west of the GDF. If small-scale PTn faulting is much less frequent over the repository block, lateral flow diverting into faults may serve to localize flow rather than to prevent localized flow. In the absence of evidence to the contrary, however, the

NRC staff endorses use, in PA, of the assumption that general lateral diversion does not occur above repository, as this conservatively passes all net infiltration generated within the repository footprint to the repository horizon.

- **Focusing of Flow Due to Faults**

There is solid evidence that faults have large permeabilities, based on observations of barometric attenuation and phase lag during the excavation of the ESF (Ahlers, et al., 1996; Nilson, et al., 1991; Patterson, et al., 1996). The character of barometric response was altered kilometers from the ESF (e.g., in borehole ONC-1), apparently due to the interaction of faults with the ESF. Faults therefore represent potential fast pathways providing water to the deep subsurface. If water is diverted laterally into the fault, these potential fast pathways may carry substantial quantities of flow. However, if no waste is emplaced close to the faults, then this water is not intercepted by those waste packages. Fault-permeability estimates presented by Sonnenthal, et al. (1997a) (their figure 7.7) range from 3×10^{-13} to 6×10^{-10} m^2. Sonnenthal, et al. (1997a) further categorize faults into normal faults (large- and small-displacement) and strike-slip faults, all with different deformation features (fracturing gouge) resulting from different formation processes.

Observations of bomb-pulse ^{36}Cl in the ESF have prompted LANL and USGS researchers to hypothesize that three conditions are required for observations of flowing water to occur within the ESF (Fabryka-Martin, et al., 1997):

- A continuous fracture path must extend from the surface to the sampled depth (implying that a fault must cut through the PTn)
- Values of MAI at the surface must be at least 1 mm/yr (in order to initiate and sustain fracture flow)
- The residence time of water in alluvium must be less than 50 yr (alluvial thickness must be less than 3 m)

As noted by Fabryka-Martin, et al. (1997), predictions based on these conditions appear to be reasonably consistent with observations in the northern half of the ESF but are inconsistent with the paucity of bomb-pulse ^{36}Cl observations in moist fractures in the southern half of the ESF. Fabryka-Martin et al. (1997) suggest that, if the conceptual model for observations of bomb-pulse ^{36}Cl in the ESF is correct, requiring that the PTn be cut by a fault, then there may be significant connection between the fault and fractures in the welded unit. This suggestion is based on observations of bomb-pulse ^{36}Cl spread laterally downdip from the Sundance Fault (SDF) in a swath 300 m wide within the ESF (Levy, et al., 1997), which appears to travel laterally as much as 200 m within subhorizontal cooling joints in the middle nonlithophysal zone. An important implication of these observations is that significant downdip redistribution may occur within the fractures of at least some densely welded units, although fracture permeabilities are inferred to be as much as ten times greater in the vertical than the horizontal direction (Sonnenthal, et al., 1997a). Nicholl and Glass (1995) offer further evidence that considerable spreading can occur within the TSw fracture system, demonstrated with a ponded infiltration experiment at Fran Ridge where the TSw unit crops out. Thus, even if systematic lateral redistribution in and above the PTn unit does focus flow into faults, these locally concentrated fluxes may be significantly smoothed through lateral spreading before reaching the repository horizon.

Water will not enter a fault in the UZ unless the matrix is sufficiently saturated to overcome the capillary barrier represented by the fault. Other barriers, such as low permeability fracture coatings, may also be present. In order to focus flow within a fault possessing a significant capillary or other barrier, it is necessary for water to collect updip of the fault. This collected water will tend to make the updip side of the fault, where water is entering the fault, wetter than areas further updip from the fault, and thereby may cause enhanced vertical flows below the wetter region. As the main drift of the ESF parallels the GDF on the updip side, inferences drawn from observations within the ESF may be unrepresentatively wetter than the repository block as a whole if vertical fluxes are enhanced through significant collected water above the ESF. Note that waters within the GDF are likely to exit through gravity, so that the matrix in the immediate vicinity of the west-dipping fault is likely to increase in wetness as the fault is traversed from west to east at the ESF elevation.

The impact of a fault is likely to be most significant when the fault is perpendicular to the stratigraphic dip. From geometric arguments (all else being equal), north-trending faults at YM (e.g., the GDF) may tend to have a greater impact on UZ flow than north-west-trending faults (e.g., the SDF) as flows can divert around north-west-trending faults, to some extent. On the other hand, different fault-forming mechanisms may yield significantly different hydraulic properties, which may override the geometric arguments.

The focusing or spreading of flow, and the flow pathways in general, under current conditions does not necessarily reflect that under future conditions. A change in the amount and distribution of infiltration may lead to a change in the predominant flow pathways, or at least change the proportions of flow in various pathways. Also, active tectonic stresses on the YM block may alter the flow pathways by modifying the hydrologic properties along the fault or by creating new pathways. It is likely that reductions in fault and fracture apertures in one area may be accompanied by the dilation of other discontinuities. The NRC staff review of DOE methods may need to consider the potential impact of structural changes to the fault system. One approach would be to analyze the sensitivity of repository performance to altered patterns of percolation.

- **Influx on the West Flank**

Solitario Canyon may provide sources of infiltrating water with potential for impacting repository performance. These sources include infiltration from numerous small channels incised into the bedrock of the west flank of YM, distributed infiltration from the shallow colluvial cover and bedrock exposures on the west flank of YM, and percolation along the SCF. The potential for these sources to impact repository performance has not been quantitatively evaluated to date.

Portions of the west flank of YM lie above the repository footprint but below the PTn outcrop, so that infiltration in these areas may reach the western edge of the repository with none of the PTn buffering discussed in Section 4.4.2.3. Although the west flank of YM is steep, fractured bedrock has minimal surface cover in many locations, which may enable significant infiltration. Any waters infiltrating below the PTn outcrop may flow directly to the repository or may continue to the TSw/CHn interface and flow laterally to form part of the perched water bodies observed at this interface. The possibility of direct recharge within the TSw outcrop was noted by the State of Nevada (Lehman, 1992; L. Lehman, letter to E. Smistad and A. Van Luik, November 14, 1994).

The main Solitario Canyon channel is west of the SCF and does not lie above the footprint. Based on geometric arguments and the predominance of vertical flow, it does not appear likely that flow from the main channel during large runoff events will move laterally towards the repository. However, the SCF offsets sufficiently near the repository block to juxtapose the PTn unit, to the west of the fault, with the TSw unit, to the east of the fault. Under these conditions, it is plausible to expect that any lateral diversion occurring in Solitario Canyon will intercept the SCF (Lehman, 1992). Since there is no evidence for or against flow moving across the fault zone in the UZ, and there is little evidence for lateral flow in the P↓ above the repository footprint, it is considered unlikely that groundwater flow from beneath the channel during runoff events will laterally move towards the repository along stratigraphic boundaries.

However, any laterally diverted percolation fluxes from Solitario Canyon may pass across the steeply west-dipping SCF and proceed vertically to the CHn unit. The diverted waters from Solitario Canyon may then form a significant portion of the perched water bodies observed at the TSw/CHn interface. This scenario has implications for the formation of the perched water beneath the repository as well as implications for dilution of radionuclides below the repository.

The potential for influx from Solitario Canyon was considered briefly and dismissed by two expert panels (Unsaturated Zone Hydrology Peer Review Team, 1991; Geomatrix, 1997) without quantitative justification. Nevertheless, there is potential for significant inflow arising from along the west flank of YM in Solitario Canyon to pass through the repository footprint. The SCF impacts repository design in terms of standoff distance from fault zones and flow in along the fault may contribute to the perched water bodies.

4.4.3.2 Percolation Processes at the Drift Scale

An understanding of the nature of water flow into drifts is important for two reasons: first, water in the vicinity of WP may elevate relative humidity, thereby, accelerating corrosion and WP failure; second, almost all radionuclides are expected to have a dominant release pathway of water traveling through drifts, contacting waste, and transporting dissolved or colloidal waste through the geologic setting.

- **Nature of Flow into Drifts (Drift Seepage)**

The conceptual model developed for unsaturated flow through repository drifts depends, to a large exte on whether drifts will be backfilled after waste emplacement and, if so, on the type of backfill material used. If backfill is to be used, it is necessary to take into consideration the moisture retention and permeability properties of the backfill before an effective assessment of the effects on flow can be considered. For example, a coarse, well-sorted backfill would allow water to pass easily through the drift; it would have a very low residual water content; and it would not produce enough capillary suction to imbibe water from drift walls. Conversely, a fine or poorly-sorted backfill would have a lower permeability, a higher residual water content than the well-sorted backfill, and could imbibe water out of drift walls toward the WP, depending on the saturation of the ESF wallrock. Although the higher capillary suction of a fine, poorly-sorted backfill can result in more uniform contact of water with the WP surface, the same capillary suction could prevent water from entering the WP. Shotcrete coatings on walls of tunnels or emplacement drifts, if applied, would have an effect on dripping patterns. This would have to be independently evaluated by the staff. The USGS (1998) has submitted to DOE a level 4 milestone report, SPH261M4, regarding the hydraulic properties of backfill materials. The staff have not yet evaluated this report.

In the absence of backfill, water dripping from the drift crown is the only mechanism for water to directly contact the WP. In this case, there are several factors that should be considered in estimating the amount of water that could potentially drip onto a WP. For example, the angle that a fracture intersects a drift will affect the potential for fracture flow to divert laterally around the drift. The dip angle will also affect the amount of water required to overcome any capillary barrier to dripping. The hydraulic properties of a fracture affect the fluxes within the fracture and the degree to which a capillary barrier between fractures and the open drift will act to divert flow around the drift. Several other factors, such as fracture frequency, 'acture intersections, fracture coatings, and degree of heterogeneity, should also be considered. Long-erm dripping from fractures is also likely to result in stalactite formation—especially in the high-evaporation environment that could result from WP heating. Formation of stalactites tends to focus fracture dripping on constant locations.

The case of partial filling of the drifts with backfill will exhibit features of both the full backfill and no backfill scenarios. Diversion of matrix flow and dripping from fractures may occur at the crown of the drift. The dripping water plus water imbibed from sidewalls of the drift will be somewhat distributed around the WP, although vertical flow through the backfill from a dripping crown would concentrate some of the moisture.

A conservative approach to incorporating drift seepage into PA models is to assume that 100 percent of the percolation flux that intersects a drift will enter the drift opening and contact a WP. Only a fraction of percolating waters is likely to enter drifts based on geometric arguments, i.e., the relatively small percentage of repository area that will contain waste packages. Also, because of the capillary barrier imposed by the drift opening, some percolation flux is expected to be diverted around the drift. Presumably, there is a percolation threshold, below which no seepage into the drift will occur. The DOE PA model currently takes credit for diversion of flow around drifts; their characterization of drift seepage is based on both modeling and field studies. A more conservative approach than 100 percent of the percolation flux intersecting the drift may be envisioned if focusing or funneling of flow incorporates flow from a larger area than the repository into the repository. Given the intensity of fracturing in the TSw, NRC staff believe that, on the average, the amount of flow funneled to the repository will be the same as the amount funneled away from the repository. New information on the fracture system in the TSw may change the NRC staff views on seepage into drifts.

Wang, et al. (1997) reported preliminary results of field seepage tests conducted in two niches in the ESF. Of the five tests conducted, one did not result in flow into the niche; another induced flow to reach the eiling and migrate along the mined surface as film flow, but water did not drip into the niche; and dripping rrom fractures into the niches was observed in the remaining three tests. Of the three tests where dripping was observed, the mass of water collected in the fluid collection system ranged from 9.5 to 27 percent of injected mass. The NRC believes that the niche and alcove tests are extremely useful for corroborating drift-scale numerical model and that measurements and experiments in the east-west drift will similarly provide useful information.

Birkholzer, et al. (1997a,b) used a 3D fracture continuum model to simulate seepage into drifts under both isotropic conditions and anisotropic permeability conditions. Heterogeneity was applied to the permeability field with no consideration of possible correlation between permeability and fracture α values. The modeled steady-state percolation fluxes ranged from 5 mm/yr to 1,000 mm/yr. Seepage into drifts was found to start when steady-state percolation fluxes were on the order of tens of millimeters per year, with heterogeneity in the fracture continuum being a key factor controlling the rate of seepage. The same fracture continuum model was used to simulate the niche studies, with generally good agreement between the model and observations, reportedly occurring with no calibration or fitting (Birkholzer, 1998).

A similar modeling effort was conducted using 2D and 3D dual-permeability models with a fracture-matrix interface factor to allow for a reduced wetted contact area between fractures and matrix. Results of this effort, reported by Tsang (1997), indicate that the inclusion of fracture-matrix interaction is only important when percolation flux occurs as transient pulses.

A continuum model requires definition of a representative elementary volume (REV). This requires th any heterogeneities should be incorporated at a scale either much smaller than the grid scale (i.e., sub heterogeneity) or much larger than the grid scale (i.e., parameter variability within the model). Accordingly, the assumption of a fracture continuum requires that the fractures either be numerous relative to the grid scale (subgrid) or be explicitly accounted for (parameter variability within the model). Sonnenthal, et al. (1997a) report that measured fracture frequencies in the TSw unit (counting only fractures at least 1 m in length) range from 0.48 to 4.45 m^{-1}. If the continuum approximation requires numerous fractures, a continuum approximation for fractures of this size and larger may require tens of meters to achieve a representative elementary volume, which is larger than the drift diameter. Using an *ad hoc* criterion of 5 fractures per grid block length to enable the fracture-continuum assumption, drift-scale simulations with 0.5-m grid blocks (fairly coarse) would require fracture frequencies of roughly 10 m^{-1}, implying that the assumption of a fracture continuum may be violated at the drift scale and models assuming a fracture continuum may misrepresent important fracture/drift interactions.

The assumption of uniform, steady-state infiltration in the fracture continuum model does not take into account potential episodic fracture flow. Modeling results that indicate that the PTn unit has a large capacity to attenuate large infiltration pulses, together with the presence of the PTn over almost all of the repository footprint, support the assumption of steady-state conditions at the repository horizon. However, given the existence of perched water at the base of the TSw that shows geochemical evidence of having partially bypassed the PTn (e.g., Striffler, et al., 1996; Yang, et al., 1996a,b), the potential for episodic infiltration pulses should not be discounted entirely.

In a fracture continuum model, diversion of percolation flux around the drift is possible at all spatial locations, due to the continuum assumption, and diversion is controlled by random heterogeneities. In reality, the diversion path of fracture flow around a drift is controlled by geometric factors, particularly, fracture orientation: fractures that intersect the drift at highly oblique angles require a longer flow path f diversion and, thus, are more likely to result in dripping. NRC staff believe that correlation structures u in the DOE fracture continuum model do not appear to capture this effect of increased diversion path length caused by oblique fractures. Moreover, continuum models do not account for fracture intersections, which may form highly permeable linear pathways that can focus flow toward drifts. Furthermore, it is assumed in the fracture continuum model that all water in fractures is influenced by capillarity; the possibility of sheet-type flow in large-aperture fractures is not considered. Because sheet flow along surfaces of large-aperture fractures is not held by capillary forces, it is more likely to result in dripping where such flows intersect drifts. The predominance of sheet-type flow in fractures at the ESF horizon may be supported by the predominance of fracture coatings (Paces, et al., 1998b) occurring on only one side of the fractures.

Fracture permeability distributions used in the DOE fracture continuum model are based on drift-scale air permeability measurements, analysis of cores, and ESF fracture mapping. Estimations of fracture α values are based on calibration of the Site-Scale UZ Model (Bodvarsson and Bandurraga, 1997a). In general, narrow-aperture fractures are expected to have lower permeability and more capillary suction (lower α values), with the opposite being true for wide-aperture fractures. Inclusion of such a correlation in seepage models would cause low-permeability fractures to have higher saturations than high-permeability fractures, which may affect both seepage into, and diversion around, drifts. Correlation between fracture permeability and fracture α value is not considered in the DOE model, although it is recognized that both fracture frequency and fracture aperture affect fracture permeability, while only fracture aperture affects fracture α. Dual-permeability drift scale-model results, reported by Tsang (1997), predict a reduction in drift seepage, when fracture α values are correlated to fracture permeability. Based on this result, a lack f correlation between these parameters in a seepage model can be considered a conservative assumption.

An additional caution regards the use of air-permeability testing to infer fracture hydraulic permeability. There is a possibility that water-bearing fractures could exhibit low air permeability because of water filling the fracture voids. This would be especially true for narrow-aperture horizontal fractures with high capillary suction, which can wick away significant quantities of water. In areas where the horizontal fractures have smaller apertures than the vertical apertures, capillary suction may generate a moisture-dependent anisotropy for water that is primarily horizontal rather than vertical at low saturations.

- **Distribution of Drifts with Potential for Seepage**

The quantity and distribution of water that seeps into drifts depends on the amount and spatial variability of deep percolation that reaches the repository horizon, and on the variability in hydraulic properties of fractures that intersect drifts. Two quantities are used to parameterize seepage into drifts for the DOE model: the seepage fraction and the seep flow rate. The seepage fraction is defined as the fraction of WP contacted by seeps while the seep flow rate is the flow rate onto those packages that are contacted by seeps. Ranges for these parameters are estimated stochastically, using the 3D heterogenous fracture continuum model described in the previous section; they are based on weighted distributions of fracture permeabilities and α values, and a broad range of percolation fluxes are used in this estimation method. It is assumed that there is no correlation between these model input parameters. Based on the distribution of fracture properties, a distribution of seepage threshold fluxes is calculated, and the seepage fraction is the fraction of drifts that receive percolation flux above their respective seepage thresholds while the seep flow rate is the portion of percolation flux in excess of the seepage threshold. In the DOE PA model, seepage is calculated for six repository regions under present climate conditions, long-term average climate, and a super-pluvial climate. It is presently assumed by DOE that all seepage that enters the upper half of a drift will contact a WP.

The NRC approach to incorporating seeping drifts into a PA model is currently based on the approach used in TSPA-95 (TRW Environmental Safety Systems, Inc., 1995), assuming that the matrix will carry all fluxes up to the matrix K_{sat} with any excess flows occurring in the fractures. Matrix fluxes are assumed to divert around the drift, while fracture flows enter the drift, with both the matrix K_{sat} and the percolation fluxes assumed to be independent and lognormally distributed.

An option under consideration by DOE for emplacement of canisters is to create a stand-off distance from fault systems that have been recently active on a geologic time scale. An active fault is one that has indications of movement over the last 2 million yrs (Elater and Nolting, 1996). Stand-off of 60 m is limited to the active faults, such as the SCF, the Drill Hole Fault, and the Abandoned Wash Fault. However, for the GDF, the distance that canisters should be shifted away from the fault is 120 m due to the large air permeability values and large fracture zone width (Elater and Nolting, 1996). The NRC staff review of methods used for determination of stand-off distance should consider variability along fault systems, both the dip of the fault and the strike of the fault relative to the drift, and the geochemical evidence suggestive of spreading laterally away from faults. In the ESF, ^{36}Cl appears to have spread laterally away from the main fault trace of the SDF over 200 m along the cooling joint system (Levy, et al., 1997).

4.4.3.3 Percolation Processes Below the Repository

The nature of percolation below the repository horizon affects the formation of perched water, the spatial distribution of flux to the water table, groundwater velocities, and radionuclide advection, dispersion, sorption, and decay. If percolation is dominated by matrix flow through the CHn rather than fast pathways, slow travel times, increased adsorption (with resulting augmentation of retardation and decay), and mixing with the relatively large volume of water in the matrix pores are expected to occur. The potential for adsorption is particularly great in zeolitic horizons.

Flow paths from the repository horizon to the base of the TSw unit are expected to be predominantly vertical within the TSw fracture system. At the base of the TSw unit and below, flow paths are more uncertain. In nonwelded vitric units, flows are expected to be predominantly vertical within the matrix, but fracture flow may occur as well. In areas with significant zeolitization, there may be complex combinations of matrix and fracture flows, with strong possibilities of lateral flow. The nature of flow through the CHn is the primary source of uncertainty in flow paths and travel times from the repository to the water table.

- **Flow Through Non-Welded Vitric and Zeolitic Horizons**

Percolation in the TSw unit is expected to occur primarily in the fracture system. The highly fractured TSw basal vitrophyre overlies the porous nonwelded CHn, leading to the possibility of lateral flow and perched water in areas where the vertical transmission rate of the CHn is exceeded. The presence of perched water above altered units in the CHn signifies slow vertical percolation within the altered units, providing the potential for lateral flow to bypass the altered zones and enter faults or unaltered zones. The absence of perched water above the vitric portions of the CHn suggests that percolation is rapid enough to conduct fluxes under current climatic conditions.

The vitric zones are sufficiently permeable that percolation may be primarily within the matrix. Zeolitic alteration of glassy tuffaceous material has been shown to drastically reduce permeability without significantly affecting porosity (Loeven, 1993). Measured permeabilities in the vitrified and de-vitrified horizons are generally 1 to 2 orders of magnitude higher than in the altered zones. Hydraulic conductivity measurements of 5 vitric samples from the CHn range from about 1×10^{-5} to 5×10^{-6} m/s, whereas, zeolite-altered core measurements ranged from about 3×10^{-7} to less than 1×10^{-12} m/s [the lower limit of the measurement technique (Flint, 1997)]. The saturations in vitric units are generally lower than those in altered units, indicating greater drainage properties for the vitric versus the altered (zeolitic).

Flow in the vitric portions of the CHn may also be through fractures. The characteristics of fractures and fast pathways in the vitric portion of the CHn are not well known. However, there are indications that water moved quickly into the vitric zones. Major element chemistry and ^{14}C data suggest that matrix water below the perched water is distinct from the perched water (Fabryka-Martin, et al., 1997; Rousseau, et al., 1998). The underlying matrix water appears to be younger, and to have bypassed the perched water in the CHn layers. This could be explained either by fracture flow through the vitric or matrix flow through a small thickness of the vitric layers followed by lateral flow beneath the perched zone. Where the vitric overlies the zeolitic alteration, the transitional contact in the north is less than 20 m below the basal TSw vitrophyre in the north and 460 m below in the southwest (Rousseau, et al., 1998).

The impact of large structural features on travel times could be significant. According to Ritcey, et al. (1997a), the fastest travel times are expected for paths in the center of the repository block where a greater amount of fracture flow would occur or where flow might be along stratigraphic contacts to tructural features such as the GDF and Dune Wash Fault. The hydraulic properties of the faults dictate whether perching or drainage down the fault to the saturated zone will occur. Wu, et al. (1996) hypothesized that travel paths south of Dune Wash divert to the east, and, if the GDF is neither a barrier nor a conduit, continue eastward in the fractured TSw to meet the water table near the Bow Ridge Fault. However, the perched water noted in boreholes SD-7, SD-12, SD-9, NRG-7, UZ-1, UZ-14, G-2, and WT-6 is an indication that the GDF is likely (at least locally) to be a barrier with relatively low permeability, and possibly altered near the perched water. There are insufficient data on the lateral characteristics of the GDF to determine the continuity of perched zones at YM.

The CHn mineralogy is highly variable, with both lateral and vertical gradational variations, due to nonuniform alteration of parent tuffs. The general distribution of zeolitic alteration in the repository block is described by Moyer and Geslin (1995) and Carey, et al. (1997). Based on the interpretations of Moyer and Geslin (1995) and Hinds, et al. (1997), there is a gap in the zeolite alteration in the southwestern portion of the repository area (Figure 4). The LBNL model (Hinds, et al. 1997) is based on four layers in the geologic stratigraphy from the basal TSw, through the CHn, to the upper Prow Pass unit. Each sublayer is divided into a homogeneous layer of vitric or zeolitic portions as delineated by a threshold of ten weight percent zeolite alteration. In the LBNL model, appropriate hydrologic properties for each zone are assigned, but are kept uniform throughout each zone. However, given the limited data available to support this generalized description of the zeolite distribution, new information may significantly change the interpretation.

In contrast to the LBNL interpretation, the LANL site-scale flow and transport modeling (Robinson, et al., 1997) used the ISM2.0 geologic framework and adds a mineralogic module that modifies the CHn sublayer properties based on the amount of zeolite alteration; hence, heterogeneous properties are incorporated into the numerical model for flow and transport. The mineralogic model is based on the work of Chipera, et al. (1997) and Carey, et al. (1997), where the x-ray data from boreholes were interpolated into the geologic section using a program called STRATAMODEL. In their conceptual model, Robinson, et al. (1997) assumed that flow would more readily occur in the vitric and the slightly altered zones. Zones of heavy zeolite alteration would have low permeability, thus, promoting lateral flow around, rather than vertical flow through, the zeolites. However, a small amount of zeolites may not impact the permeability of the vitric zone. Hence, the predominance of sorption of radionuclides would be postulated to occur in the slightly altered zones rather than the heavily altered zones. The wide range, from 10 to 10,000 yr, in the particle tracking results of Robinson, et al. (1997) captures the uncertainty in flow paths through the CHn unit, with short times reflective of fast pathways through faults and long times reflective of flow through zeolitic matrix. Thus, understanding the detailed distribution of the mineralogy in the Calico Hills Unit is of utmost importance for flow and transport below the repository.

A total of 1503 records from 20 boreholes in the YM block extend into or cross the CHn; 18 of the boreholes fall in the area outlined in Figure 4. Typically, there are 10 to 35 analyses in the zone from the basal TSw unit to the upper Prow Pass units. The area below the western portion of the repository is poorly constrained (Carey, et al., 1997) due to data available in only three boreholes of which only one is considered reliable (G-3, one mile south of repository). Chipera, et al. (1997) report thinly intercalated layering of the vitric and zeolitic zones that would have been easily missed by the previous sampling intervals of 15 to 40 m. They also contend that there are no data to support the "misconception" of holes in the zeolite layers, indicating instead, that there are intercalated vitric and zeolitic layers at each borehole.

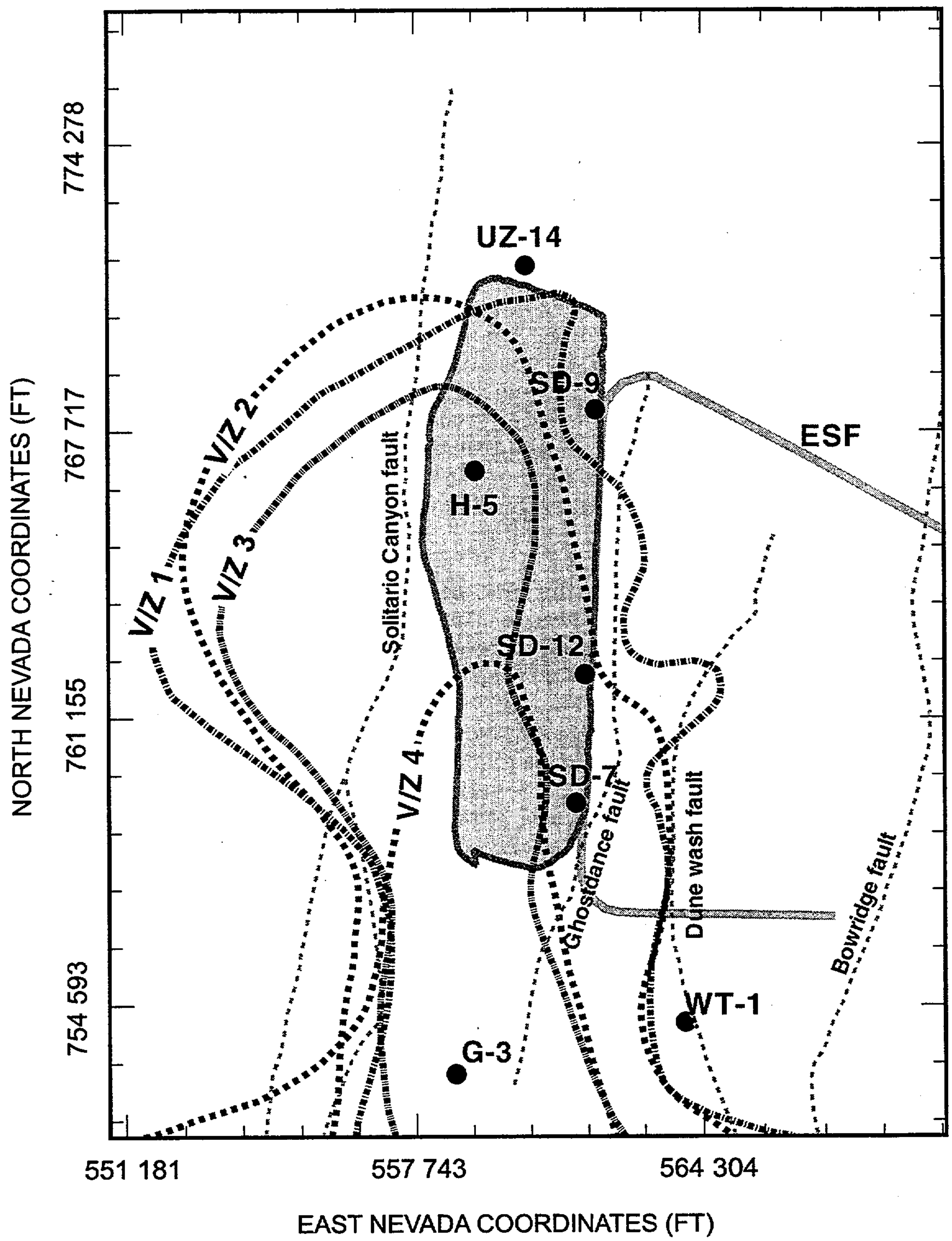

Figure 4. Transitions from zeolitic to vitric zones in the basal vitrophyre of the Topopah Springs Tuff, the Calico Hills Unit, and upper Prow Pass Tuff used by Lawrence Berkeley Laboratory in the site-scale unsaturated zone flow model. The model accounts for four layers, all of which include a transition (V/Z) from vitric to zeolitic. This figure is a modified version of Figure 4-8 (page 4-12) of Bodvarsson, et al. (1997a).

Figures 5 and 6 represent the interpolated data from the LANL STRATAMODEL program conformally mapped onto the GFM3.0 geologic section (Geologic Framework Model; documentation not yet released). The geologic portion of ISM2.0 and the GFM3.0 models do not differ in the region around the zeolites. In the figures, the zeolite weight percent is conformally mapped to the Tac and the Tacbt (basal part of Thtbt) units using 0.1 as a vertical factor to support the lateral continuity of the altered zones. Figure 5 represents the distribution in the vicinity of the contact between the Tac and the Tacbt. Figure 6 represents the distribution on a plane that is a slice at the elevation of 826 m msl. Figures 5 and 6 would be expected to illustrate the V/Z 4 transition in Figure 4. These figures are presented not as a more accurate representation of the zeolite distribution but rather indicative of the lack of data to constrain the distribution of zeolites in the CHn and the representative hydrologic properties for those zones. The purported hole in the zeolite alteration in the southwestern portion of the repository is based on a borehole 1 mile south of the repository that has zeolite alteration (>50 weight percent) in the units immediately below the Calico Hills Formation.

Since the primary pathways for flow and transport of radionuclides through the Calico Hills hydrostratigraphic unit would appear to be through the highly fractured welded units and the nonwelded vitric units, the focus on characterizing the heavily altered zones of the zeolites should be directed towards characterization of the slightly to non-altered vitric units. The work planned at Busted Butte (Bussod, et al., 1998) should reduce some of the uncertainty of flow through and near the vitric and zeolitic zones. The section at Busted Butted is a thin, distal portion of the Calico Hills Formation with a thin layer of up to 10 weight percent zeolite alteration. Hence, the Busted Butte work would be expected to address flow through slightly altered to unaltered vitric horizons; little lateral flow would be expected, since there are no zones strongly altered to zeolite.

There are two implications for lateral diversion above the zeolitic horizons in the vicinity of the repository. Significant amounts of adsorption of radionuclides by the zeolites cannot occur if a majority of the flow is laterally diverted away. Adsorption would increase the retardation of RT, and hence allow for longer periods of time for decay of radionuclides to occur. Travel times to the water table may be shortened by lateral diversion to structural or lithologic features that are more permeable than vertical pathways through the zeolitic horizons.

The NRC staff considers that significant matrix flow through the zeolitic horizons of the CHn is unlikely, given the presence of perched water as well as the geochemical and thermal data supporting lateral flow without complete mixing in the CHn. The heterogeneity of the CHn as well as the characteristics of the fractures are poorly known, yet they are extremely important for travel time and pathway analysis of radionuclides to the water table. Ongoing DOE characterization studies and planned percolation experiments at the Busted Butte experiment should contribute significantly to the understanding of flow in the CHn.

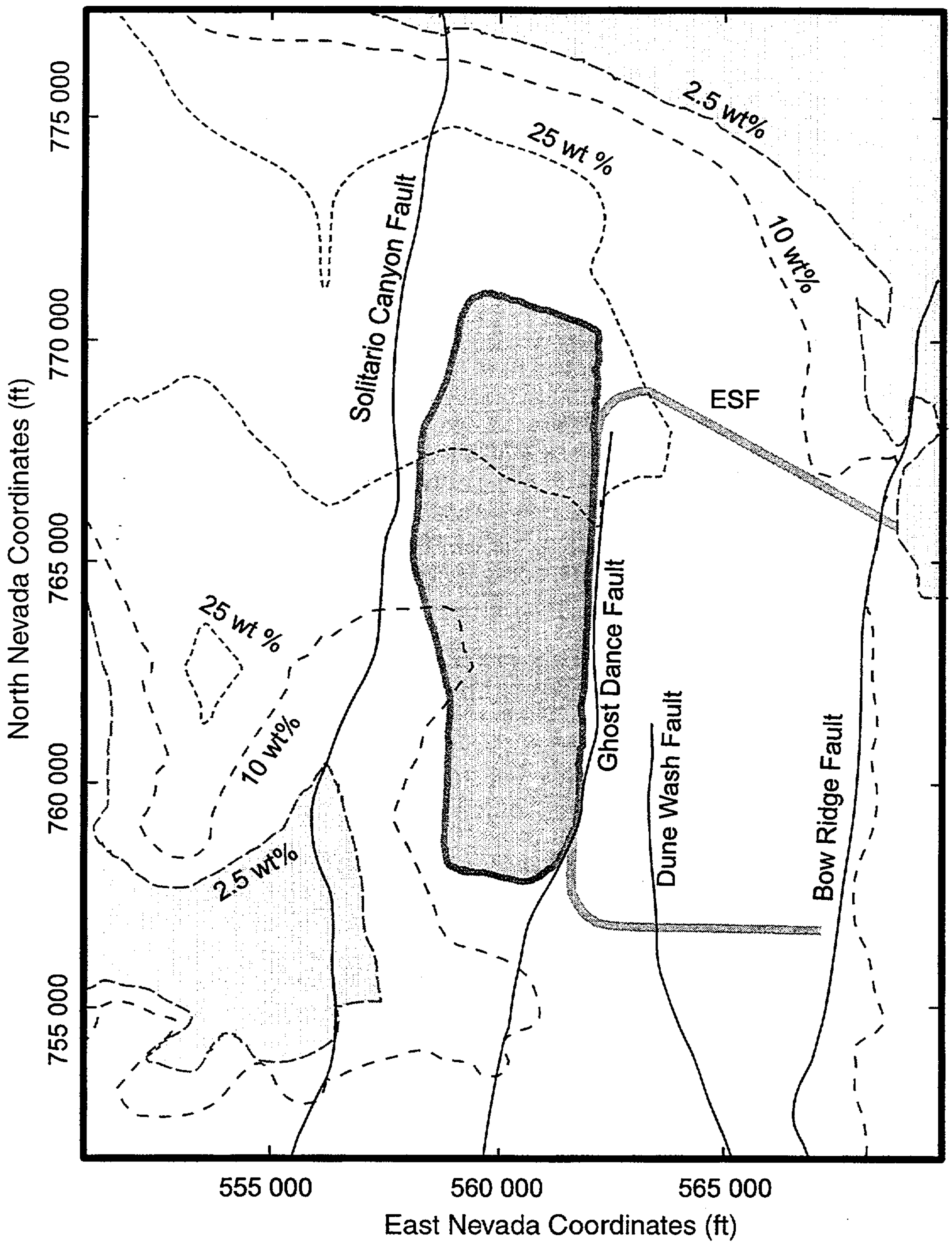

Figure 5. Zeolite weight percent contours over the same area as Figure 4 using interpolated data referenced in Carey, et al. (1997) in the lower portion of the Calico Hills Formation.

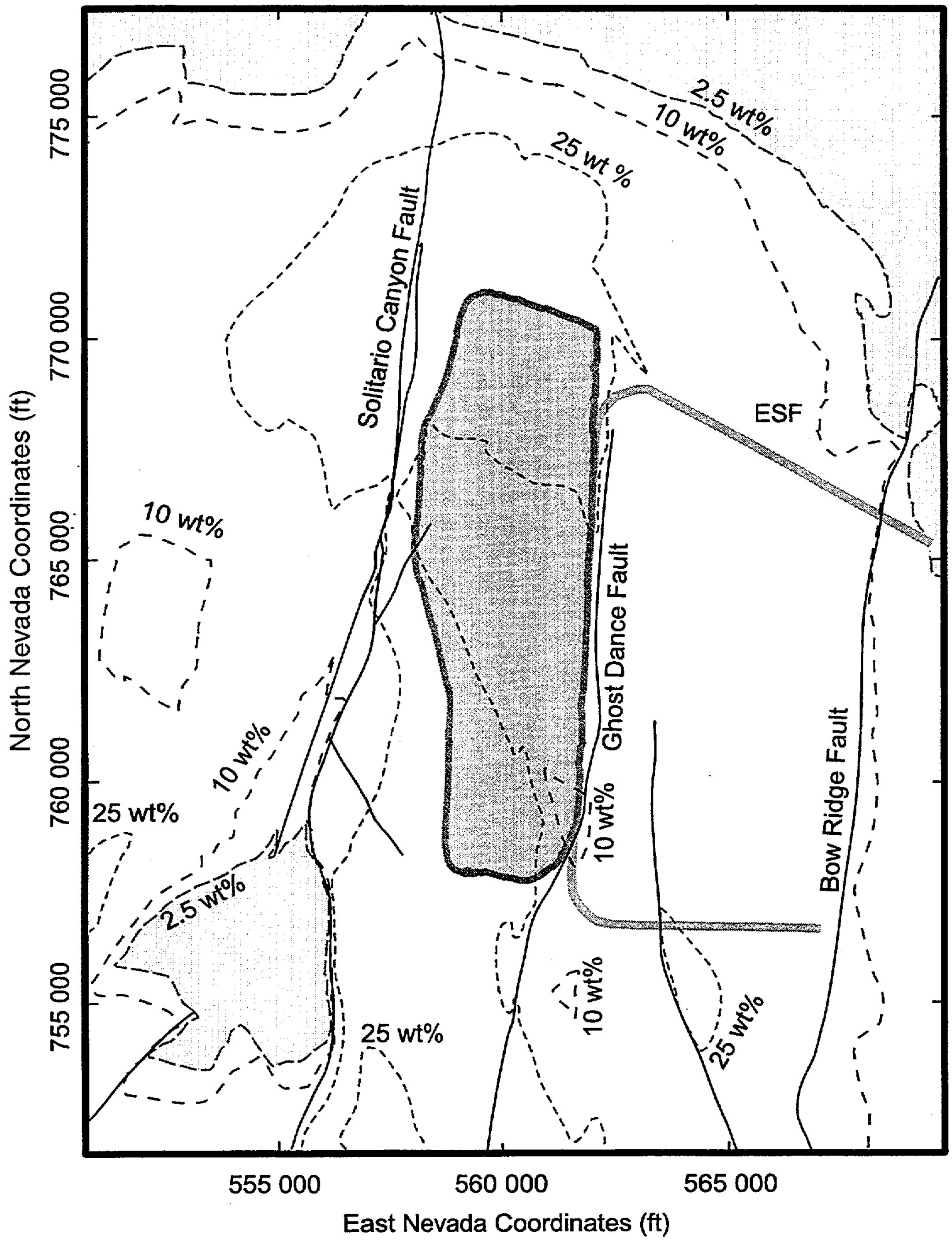

Figure 6. Zeolite weight percent contours over the same area as Figure 4 using the interpolated data referenced in Carey, et al. (1997) at the 2709 foot elevation (above mean sea level).

4.5 SATURATED ZONE AMBIENT FLOW CONDITIONS AND DILUTION PROCESSES

The staff's technical review of DOE's treatment of the saturated zone will be based on an evaluation of the completeness and applicability of the data and evaluations presented by DOE. It is expected that DOE will summarize or document the results of all significant related studies that have been conducted in the YM vicinity. The staff will determine whether DOE has reasonably complied with the acceptance criteria listed below.

4.5.1 Acceptance Criteria

(1) DOE has considered conceptual flow and data uncertainties. Uncertainties due to sparse data or low confidence in the data interpretations have been considered by analyzing reasonable conceptual flow models that are supported by site data, or by demonstrating through sensitivity studies that the uncertainties have little impact on repository performance.

(2) DOE has reasonably delineated possible flow paths from beneath the repository to potential receptor locations based on data that is sufficient to elucidate (i) the relative travel distances through aquifers of differing hydrologic and geochemical properties; (ii) in fractured-rock aquifers, the portions of flow through rock matrix and fractures; (iii) flow directions with respect to the hydraulic gradient, considering the potential effects of horizontal anisotropy; (iv) approximate volume fluxes and pore velocities; and (v) vertical hydraulic gradients, including the potential for flow between the Paleozoic carbonate aquifer and the volcanic tuff aquifer. A sufficient number of wells and exploratory holes should be drilled, and an adequate number of tests conducted, to reasonably bound the hydraulic and transport properties of the units downgradient from the proposed repository.

(3) DOE has provided a hydrologic assessment to describe likely causes of the "moderate hydraulic gradient" and the "large hydraulic gradients."

(4) DOE has provided maps of approximate potentiometric contours of the regional uppermost aquifer for an area that, at a minimum, includes wells J-11 on the east, VH-1, VH-2, and the GEXA Well on the west, UE-29a #2 to the north, and domestic and irrigation wells south of Amargosa Valley (aka Lathrop Wells). Maps of regional and site-scale recharge and discharge should be provided, along with site-scale hydrostratigraphic cross sections constructed along the paths to the accessible environment, and site-scale flow-net analysis of the SZ.

(5) DOE estimates of key hydrologic parameters are described in the form of either probability distributions or deterministic bounding values that are reasonably consistent with site data. These parameters should include transmissivity, hydraulic gradient, effective flow porosity, effective immobile porosity, and effective aquifer thickness.

(6) DOE has used mathematical groundwater model(s) that incorporate site-specific climatic and subsurface information. The models were reasonably calibrated and reasonably represent the physical system. Fitted aquifer parameters compare reasonably well with observed site data. Implicitly- or explicitly-simulated fracturing and faulting are consistent with the data in the 3D geologic model. Abstractions are based on initial and boundary conditions consistent with site-scale modeling and the regional models of the Death Valley groundwater flow system. Abstractions of the groundwater models for use in PA simulations should use appropriate spatial- and temporal-averaging techniques.

(7) If credit for wellbore dilution is taken, a demonstration has been provided that reasonable assumptions have been made about well design, aquifer characteristics, plume geometry, withdrawal rates, and capture zone analysis for the receptor location.

(8) If credit is taken for dilution due to either dispersion, groundwater mixing below the repository footprint, or mixing of the YM water with water from the north in Fortymile Wash, reasonable assumptions have been made about spatial and temporal variations of aquifer properties and groundwater volumetric fluxes.

(9) DOE has incorporated key conclusions regarding potential geothermal and seismic effects on the ambient SZ flow system (e.g., National Research Council, 1992; NWTRB, 1998; memorandum from R. Craig to S. Brocoum, October 8, 1997).

(10) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

(11) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

4.5.2 Technical Basis for Review Methods and Acceptance Criteria

Evaluation of the following topics provided key support for review methods and acceptance criteria for saturated zone ambient flow conditions and dilution processes.

Regional geology (DOE, 1988; Luckey, et al., 1996)
Regional hydrologic setting (Plume, 1996; D'Agnese, et al., 1997a; DOE, 1988)
Regional groundwater use patterns (Buqo, 1996)
Stratigraphy and lithology of rocks and surficial deposits at YM (DOE, 1988)
Hydrostratigraphy (Luckey, et al., 1996; Czarnecki, et al., 1997)
Hydraulic head data (Graves and Goemaat, 1997)
Perched zones (Striffler, et al., 1996)
Hydraulic properties of aquifers (Czarnecki, et al., 1997; Luckey, et al., 1996; Geldon, et al., 1997)
Inferences about groundwater fluxes from inter-well pumping tests (Geldon, et al., 1997)
Inferences about effective porosity from field tests (Geldon, et al., 1997)
Groundwater chemistry (Oliver and Root, 1997)
Dating of YM groundwaters (Kwicklis, 1997; Thomas, 1996)
Seismic and natural thermal effects on the saturated flow regime (NWTRB, 1998)
Summary of regional and site scale groundwater modeling (D'Agnese, et al., 1997a; DOE, 1997b)
Dilution processes in the saturated zone (Geomatrix, 1998; Fedors and Wittmeyer, 1998, Attachment B)
Uncertainties in the data and conceptual model flow system (Luckey, et al., 1996; Czarnecki, et al., 1997)

4.5.2.1 Regional Geology

YM, located in southern Nevada, is proposed as the site for the U.S. HLW repository (Figure 7). YM lies within the southern portion of the Great Basin section of the Basin and Range physiographic province, which is defined exclusively on the basis of internal drainage of surface and subsurface water of shallower depth. The physiography of this region is comprised of generally linear, north-trending mountain ranges separated by intervening basins (Luckey, et al., 1996). YM is in the southern part of the southwestern Nevada volcanic field of Miocene age. The geology of YM consists of a group of north-trending block-faulted ridges that are composed of volcanic rocks of Tertiary age that may be several kilometers thick (Snyder and Carr, 1984). The topography of YM resulted from faulting and erosion of an extensive volcanic plateau that was created by the deposition of a thick sequence of pyroclastic rocks of Miocene age. Extensional tectonics occurring between 17 million years ago (Ma) and 11 Ma formed the Basin and Range topography that characterizes the surrounding area (Luckey, et al., 1996).

YM extends northward to Pinnacles Ridge and southward to the northern edge of the Amargosa Desert. Just east of YM lies Jackass Flats, which is separated from YM by Fortymile Wash. The Crater Flat basin, on the west of YM, is a thick sequence of Tertiary volcanic rocks, valley fill, and small basaltic lava flows of Quaternary age (Luckey, et al., 1996). Crater Flat is separated from YM by Solitario Canyon, which is formed along the trace of a steeply dipping normal-fault feature known as Solitario Canyon Fault (Luckey et al, 1996). North of YM lies Timber Mountain, about 40 km further north of YM is Pahute Mesa, and about 35 km north-northeast is Rainier Mesa. Further south, i.e., south of the Amargosa Desert, lies Alkali Flat (Franklin Lake Playa)[1].

Snyder and Carr (1982) defined the stratigraphy (Table 5) of YM as a thick sequence of Tertiary pyroclastic rocks overlying sedimentary and possibly igneous intrusive rocks of Paleozoic age. The Tertiary volcanic rocks consist of pyroclastic flow and fallout deposits, lava flows, and volcanic breccias Miocene age (Luckey, et al., 1996). The tuffs at YM are primarily nonwelded to densely welded, vitric t devitrified pyroclastic flow deposits separated by nonwelded, vitric fallout deposits; the flow deposits are laterally continuous and fairly homogeneous throughout the YM area (Luckey, et al., 1996). Rhyolitic to dacitic lava flows, in addition to tuffs, are not laterally extensive throughout the area (Luckey, et al., 1996).

The rocks exposed at the surface consist of formations of the Paintbrush Group with minor outcrops of the Rainier Mesa Tuff of the Timber Mountain Group (Scott and Bonk, 1984; Sawyer, et al., 1994). The formations of the Paintbrush Group, in descending order, are the Tiva Canyon Tuff, the YM Tuff, the Pah Canyon Tuff, and the Topopah Spring Tuff. The Tiva Canyon Tuff is a compositionally zoned ash-flow tuff as defined by Ross and Smith (1961). The Calico Hills Formation underlies the Paintbrush Group and overlies the tuffs of the Crater Flat Group (Prow Pass, Bullfrog, and Tram Tuffs). Below the Crater Flat Group lie the Lithic Ridge Tuff, older unnamed ash-flow tuffs, lavas, and breccias (Carr, et al., 1986; Luckey, et al., 1996).

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[1] Both names, Alkali Flat and Franklin Lake Playa, are used to describe this geologic feature since various reports are not consistent in using either name. Most modern maps call this feature Alkali Flat, however, the term Franklin Lake Playa was used in some very old reports. Both terms are used together throughout this IRSR to avoid confusion.

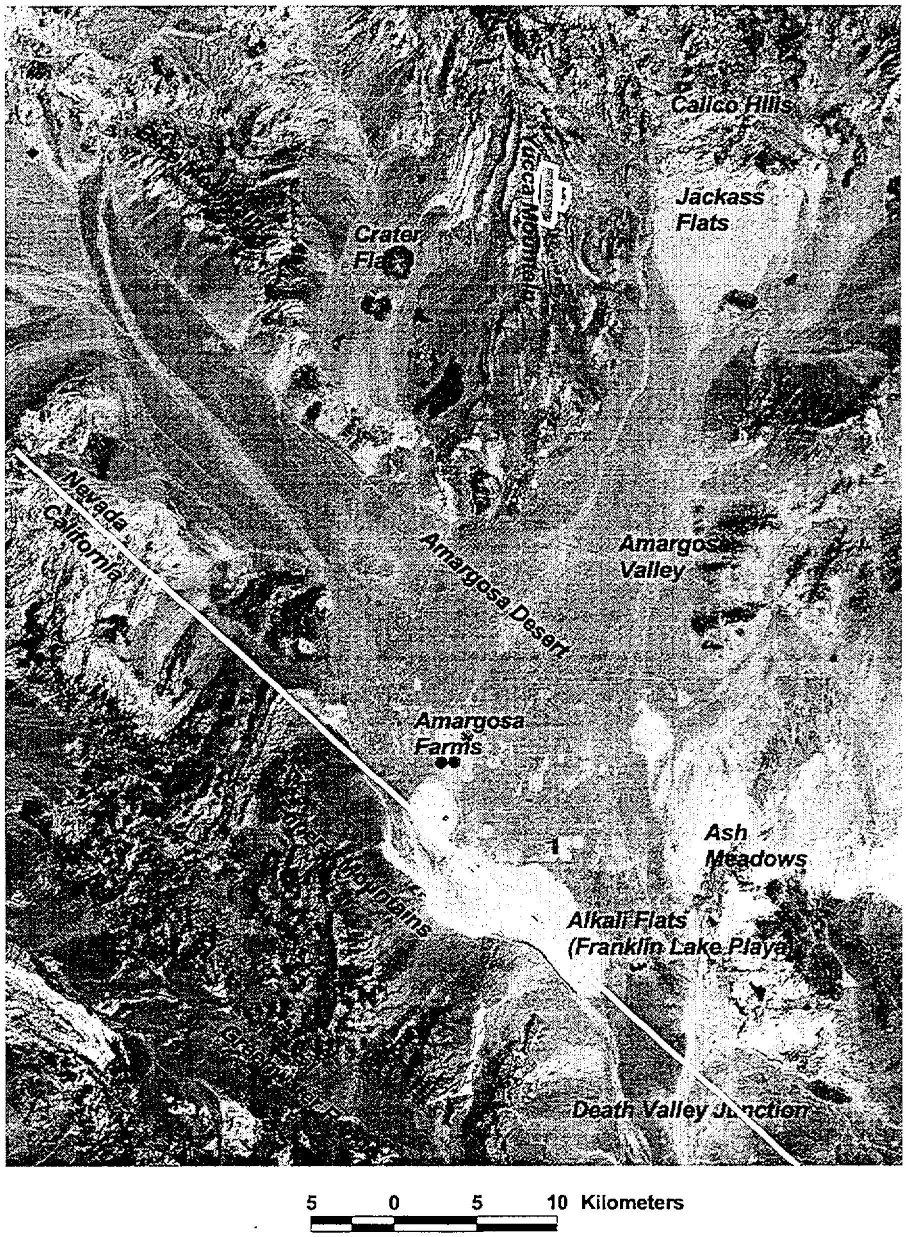

Figure 7. Map showing geographic features in the Yucca Mountain region.

Table 5. Selected stratigraphic units in the vicinity of Yucca Mountain (Snyder and Carr, 1982; Luckey, et al., 1996).

Period	Stratigraphic Unit	
Quaternary	Valley fill and alluvium	
Tertiary	Timber Mountain Group	Rainier Mesa Tuff
	Paintbrush Group	Tiva Canyon Tuff
		Yucca Mountain Tuff
		Pah Canyon Tuff
		Topopah Spring Tuff
	Calico Hills Formation	
	Crater Flat Group	Prow Pass Tuff
		Bullfrog Tuff
		Tram Tuff
	Lithic Ridge Tuff	
	Older tuffs, lavas, and breccias	
Early Permian and Pennsylvanian	Tippipah Limestone	
Mississippian and Late Devonian	Eleana Formation	
Devonian to Cambrian	Undifferentiated, primarily carbonate rocks	
Cambrian	Undifferentiated, primarily clastic rocks	

The surface expressions of Cenozoic era at YM can be broadly classified as normal faults, strike-slip faults, and volcano-tectonic structures (Scott, et al., 1983). The normal faults at YM dip steeply to the west. The geometry of the normal faults and of the strike-slip faults controls much of the topography and drainage development at YM (Luckey, et al, 1996). Strike-slip faulting has been linked to tectonic activity in the Walker Lane Belt, which is a large northwest-trending structural zone that parallels most of the southwest border of Nevada (Luckey, et al., 1996). Major washes and drainage patterns, such as Yucca Wash and Pagany Wash, developed parallel to the strike-slip faults (Scott, et al., 1984). Volcano-tectonic features are related to caldera formation and volcanic activity. Generally, circular or semicircular faults are coincident with the surficial expression of the boundary of a caldera. Near YM, these types of faults are located to the north in the vicinity of the boundary of the Timber Mountain caldera complex (Luckey, et al., 1996). In addition to these Cenozoic era faults, surface expression of principal units composing the volcanic stratigraphy beneath the Paintbrush Group at YM are, in descending order, the Calico Hills Formation (principally nonwelded tuffs), the Prow Pass, older low-angle faults have been identified near YM primarily east in the Calico Hills and west at Bare Mountain (Maldonado, 1985).

4.5.2.2 Regional Hydrologic Setting

The Death Valley flow system occupies a subregion within the Great Basin regional aquifer system (Plume, 1996). The SZ hydrologic system at YM is part of the Death Valley Groundwater Flow System (Bedinger, et al., 1989; D'Agnese, 1994). The Death Valley groundwater basin as defined by Bedinger, et al. (1989) includes several sub-basins, each of which has a particular discharge area and generally is named after its discharge area. YM is centrally located in the Death Valley groundwater basin and also is centrally located in the Alkali Flat (Franklin Lake Playa)-Furnace Creek sub-basin, as described by Waddell (1982) and others (see DOE, 1988, Vol. II, Part A, Figure 3-2, p. 3-3). Inflow to the system, in this sub-basin, is provided by recharge within its boundaries and as underflow from adjoining sub-basins, whereas, the discharge from the sub-basin is in the form of evapotranspiration, spring outflows, groundwater pumpage, and interbasinal outflow (Luckey, et al., 1996). Infiltration from surface-water runoff events in Fortymile Wash also contributes as recharge.

Most recharge in the Death Valley regional system probably occurs at higher altitude features like Timber Mountain, Pahute Mesa, Rainier Mesa, Shoshone Mountain, and the Spring Mountains due to greater precipitation and less evapotranspiration. Interbasinal inflow to Death Valley basin probably comes from Pahranagat Valley (Winograd and Thordarson, 1975). The discharge areas for the Death Valley groundwater basin include, among others, Ash Meadows, Alkali Flat (Franklin Lake Playa), and Oasis Valley. Death Valley is the ultimate groundwater discharge area and is a closed basin (Luckey, et al., 1996).

It appears that the direction of groundwater flow in the YM region is generally east-southeast near the repository site. The groundwater is mostly southward in the Amargosa Desert area. Some local variations from this general trend do exist; however, these variations are not important in a regional context. This direction of groundwater flow is supported by existing potentiometric data in the YM region and is consistent with numerical modeling results (Waddell, 1982; D'Agnese, et al., 1997a). The lowest hydraulic heads and relatively high aquifer transmissivities are found along Fortymile Wash southeast of the site (wells J-13, J-12, and JF-3). For the shallower groundwater system, potentiometric data also indicate that a groundwater divide may exist south of the Funeral Mountains in the Greenwater Range, between the Amargosa Desert and Death Valley (Czarnecki and Wilson, 1991). The groundwater flows from Pahute Mesa and Rainier Mesa to YM, southward to the Amargosa Desert, and then to Alkali Flat (Franklin Lake Playa) and Death Valley. Discharge at Alkali Flat (Franklin Lake Playa) occurs primarily through evapotranspiration. Some groundwater also may flow in a southwesterly direction from the Amargosa Desert beneath the Funeral Mountains to discharge as spring flow and evapotranspiration in the vicinity of Furnace Creek Ranch (Luckey, et al., 1996). Based on the hydrochemical data, it was suggested by Winograd and Thordarson (1975) that a deep hydraulic connection through the carbonate aquifer may connect the Ash Meadows area on the east side of the Amargosa Desert to the Furnace Creek Ranch area of Death Valley (Luckey, et al., 1996). In addition, a recent investigation of rare earth elements and stable isotope data for groundwater by Johannesson, et al. (1997) "...did not support an origin in the valley-fill aquifer at the Amargosa Desert for the Furnace Creek ground waters." The contribution of the shallow groundwater from the Amargosa Desert to the Furnace Creek springs is believed to be minor.

Faults and fractures play an important role in groundwater occurrence and flow in the YM area. It is believed that the majority of groundwater flow in the YM area is predominantly through interconnected networks of fractures, joints, and faults at varying scales. Faunt (1997) examined the hydrogeologic significance of faults in the YM vicinity. This involved examining faults and structures as well as the regional stress field. According to Faunt (1997), geologic structures have affected the regional hydro' in the general area of YM by: (1) large-scale folding and block faulting, forming the major topographic features and sedimentary basins; (2) faulting and intense folding in the hard limestone and dolomites, causing fracturing and creating highly permeable channels that are enhanced by dissolution in the carbonate aquifer; and (3) faulting and folding in other rock types, creating low permeability barriers to water movement due to displacements juxtaposing unlike strata and the creation of reduced permeability materials within fractured rock-units and these resulting in the emergence of springs. As used in this report, the NRC staff define the term "barrier" as a zone of reduced hydraulic conductivity or permeability. A "barrier" is not an impermeable boundary. We define an impermeable boundary as an idealized no-flow zone through which no or negligible groundwater flow occurs. Naturally occurring formations or barriers that are truly impermeable are rare (e.g., thick bedded salt deposits, permafrost, fresh lava flows, etc.) and often represent conditions in which water cannot exist as a liquid. In addition, the report discusses evidence of the effect of faults and their relationship to the orientation of the principal stress axes on groundwater movement.

The Death Valley regional groundwater system can be divided into three regional aquifer systems in the area of YM: (1) volcanic aquifer complex; (2) Paleozoic carbonate aquifer system; and (3) basin fill aquifers (also known as alluvial or valley-fill aquifers). These aquifer systems have been further divided into layers of aquifers and confining units.

4.5.2.3 Regional Groundwater Use Patterns

For the Amargosa Desert, designated as Hydrographic Basin 230, the state has estimated the perennial yield to be 29,592,000 m^3/yr (24,000 acre-ft/yr) (Buqo, 1996), which appears to incorporate the discharge from Ash Meadows. Committed water use, which includes both certificated and permitted water use, is estimated to be more than 50,553,000 m^3/yr (41,000 acre-ft/yr). This situation makes it unlikely that ne permits will be granted by the State Engineer, given that groundwater "mining" is presently prohibited . Nevada. In the past few years, requirements for water users to demonstrate beneficial use have led to thousands of acre-feet of forfeiture for well permits. These proceedings may have had an impact on the number of water users reported in the basin during the mid-1990s (Buqo, 1996).

LaCamera and Westenburg (1994) estimated the average pumping in the Amargosa Desert during 1985–1992 as 8.1×10^6 m^3/yr with a range of 4.8×10^6 to 11.9×10^6 m^3/yr. The water pumped in the YM area from wells J-12 and J-13 is about 2.5 percent of the average yearly pumping of the Amargosa Desert (Luckey, et al., 1996). Water pumped in the Amargosa Desert region is predominantly used for irrigation and mining. The bulk of the mining-related water use is in the playa area, which lies south of the farming area. Groundwater pumping for irrigation increased significantly in the late 1950s (D'Agnese, 1994; and Buqo, 1996). Irrigation use was 3,699,000 m^3 (3,000 acre-ft) in 1962, 11,466,900 m^3 (9,300 acre-ft) in 1967, and 9,000,900 m^3 (7,300 acre-ft) in 1973. Kilroy (1991) reported rapid declines in the water table during the 1970s and less severe declines in the 1980s. The declines are 6 to 9 m in three different areas of Amargosa Farms with the largest being a northeast-trending trough near the Nevada-California border.

Since 1983, the Nevada State Engineer has tabulated water use for individual users and summarized annual use by category, although data for 1984 were not recorded. The annual summary of water use with both the Amargosa Desert total and the Amargosa Farms portion total is provided in Appendix A of Attachment B to this report. The annual totals increased significantly from 1993 to 1996 due to large increases in irrigation use, with the largest volume being 16,330,000 m^3 (13,244 acre-ft) in 1995.

Individual domestic water use is not recorded in the State Engineer's tables, and individual records for quasi-municipal water users did not start until 1996. Annual estimates were grouped together for the domestic and quasi-municipal/commercial use for each year, although some re-categorization occurred in 1996. Annual usage of 3.4 m^3/d (1 acre-ft/yr) is assumed for every household, although this may be an over-estimate (Buqo, 1996). However, DOE (DOE, 1988) states that the annual household usage estimate is 6.81 m^3/d (2 acre-ft/yr).

Individual records for each irrigation user are tabulated for the years 1983 and 1985–1996, and are summarized in Appendix A of Attachment B to this report. For individual users, the maximum annual pump volume for any particular user is 1,443,000 m^3 (1,170 acre-ft). The average for all years for an individual irrigation user is 828 m^3/d and the range in any particular year is 348 to 1,300 m^3/d. The number of irrigation users for any year ranged from 15 in 1991 to a high of 55 in 1996.

There are 508 wells recorded in the State of Nevada's well driller's log, which dates back at least to 1921. Many of these wells are no longer in operation. The groundwater site inventory (GWSI) database contains 224 well records for approximately the same area in the central Amargosa Desert. The well permit database contained 153 certificated or permitted water rights entries. The estimated water use tables from the Nevada State Engineer tracked as many as 72 entries in a single year (1996) and a total of 126 different entries over the span 1983–1996. For hydrographic Basin 230, the state water use tables have no record for any individual domestic wells or any quasi-municipal wells prior to 1996. The water use category may have changed over the years on permitted or certificated water rights. The DOE (1988) identifies nine quasi-municipal wells, five commercial wells, and three industrial wells that were active.

D'Agnese, et al. (1997a) estimated the average water use for their regional model area. The wells were divided into four categories: commercial, municipal, industrial, and agricultural. The overall average pumping rates used in the model were 50 percent of water-use rates. The total pumpage within the regional model boundary was 64.75×10^6 m^3/yr from 208 wells, whereas the pumpage in the Amargosa Farms area was only 8.41×10^6 m^3/yr from 61 wells. There is no comprehensive survey that provides the actual pumpage data year after year.

It is suggested in DOE (1997) that the typical drawdown caused by an individual well has historically been less than 10 m and, therefore, is not a significant factor when compared to a large radionuclide plume. If the radionuclide plume is too large compared to the capture zone of the well, the pumping will have little or no effect in changing the extent or direction of migration of the plume. However, if the extent of capture zone of a well or well field is greater than the plume, the pumping will significantly affect the direction of migration of the plume.

4.5.2.4 Stratigraphy and Lithology of Rocks and Surficial Deposits at Yucca Mountain

Volcanic rocks of Tertiary/Miocene age are the most predominant rocks in the upper stratigraphic sequence at YM. These rocks consist of a series of gently-dipping, welded and nonwelded ash-flow and ash-fall tuffs and lavas, and volcanic breccias of Cenozoic (Tertiary/Miocene) age. They have a thickness of more than 1,800 m, and they are intercalated with relatively thin units of volcaniclastic rocks and flanked by younger Quaternary alluvial, colluvial, and Eolian deposits. The volcanic sequence is underlain by pre-Cenozoic rocks, including Paleozoic clastic and carbonate rocks, and Cambrian and Precambrian clastic and crystalline rocks. The lithology of the lower part of the Cenozoic volcanic sequence and all pre-Cenozoic rocks is poorly known because of limited deep borehole data. Only one borehole in the YM area (borehole UE-25p #1) penetrates pre-Cenozoic rocks. The character of rocks below about 1,800 m is mainly inferred from geophysical data and the interpolation and extrapolation of data from the surroun region. Estimates based on borehole and geophysical data indicate that the depth to the contact betw Cenozoic and pre-Cenozoic units ranges from 1,300 m (Luckey, et al., 1996) beneath the southeastern part of YM (borehole UE-25p #1) to more than 3,500 m beneath the northwestern part (U.S. Geological Survey, 1984).

An excellent description of the surficial deposits and individual stratigraphic or lithologic units has been provided by DOE (1988).

4.5.2.5 Hydrostratigraphy

Site-scale and regional-scale investigations of the SZ to determine the suitability of YM for the disposal of radioactive waste have been conducted by DOE, USGS, National Laboratories, and other parties. The latest and possibly most comprehensive work to date was carried out by the USGS under contracts with DOE. The results of these investigations have been reported by Luckey, et al. (1996), Laczniak, et al. (1996), Czarnecki, et al. (1997), Zyvolosky, et al. (1997), D'Agnese, et al. (1997a,b), Faunt (1997), and Geomatrix (1998). Unless stated otherwise, the following characterization of the hydrostratigraphy and groundwater flow conditions in the SZ in the area of YM is based on the data and interpretations provided in the USGS reports cited above, and in the site characterization plan by DOE (DOE, 1988).

Three regional aquifer systems have been identified in the area of YM. These are the volcanic aquifer complex; the Paleozoic carbonate aquifer system; and the basin fill aquifers. These aquifers are separated by widespread confining units of low hydraulic conductivity. The relation of the hydrostratigraphic units described in this section to the stratigraphic units that were described in the previous section is provided in Table 6. The volcanic and carbonate aquifer systems underlie the proposed repository site; the basin fill aquifers occupy sediment filled basins in Crater Flat, Jackass Fla and the Amargosa Valley. The thicknesses and hydraulic properties of aquifers and confining units in t area are not uniform, and the hydraulic properties of formations can vary greatly from one location to another. Furthermore, there are some uncertainties about the degree of hydraulic linkage among these aquifers in the YM area. A schematic section showing the relative position of major aquifers and confining units in the YM area is provided in Figure 8.

Luckey, et al. (1996) characterized the hydrostratigraphy in the area of YM as consisting of three aquifers and two confining units, based on the relative permeability of the stratigraphic units (see Figure 8). The upper two aquifers and both confining units lie in the Tertiary volcanic rocks; the third aquifer is a Paleozoic carbonate aquifer that underlies the volcanic rock sequence. But based on previous work by Winograd and Thordarson (1975) and Laczniak, et al. (1996), Czarnecki, et al. (1997) have developed a numerical simulation site-scale model that included three volcanic aquifers and three volcanic confining units (see Table 6). The upper and middle volcanic aquifers correspond to the upper and lower volcanic aquifers in Luckey, et al. (1996) and the lower volcanic aquifer lies in the lower volcanic sequence below the Crater Flat group. In addition, Czarnecki, et al. (1997) have also recognized and included in their site-scale model two carbonate aquifers and two Paleozoic clastic confining units of Paleozoic age, as well as a valley fill aquifer and a valley fill confining unit of Quaternary age.

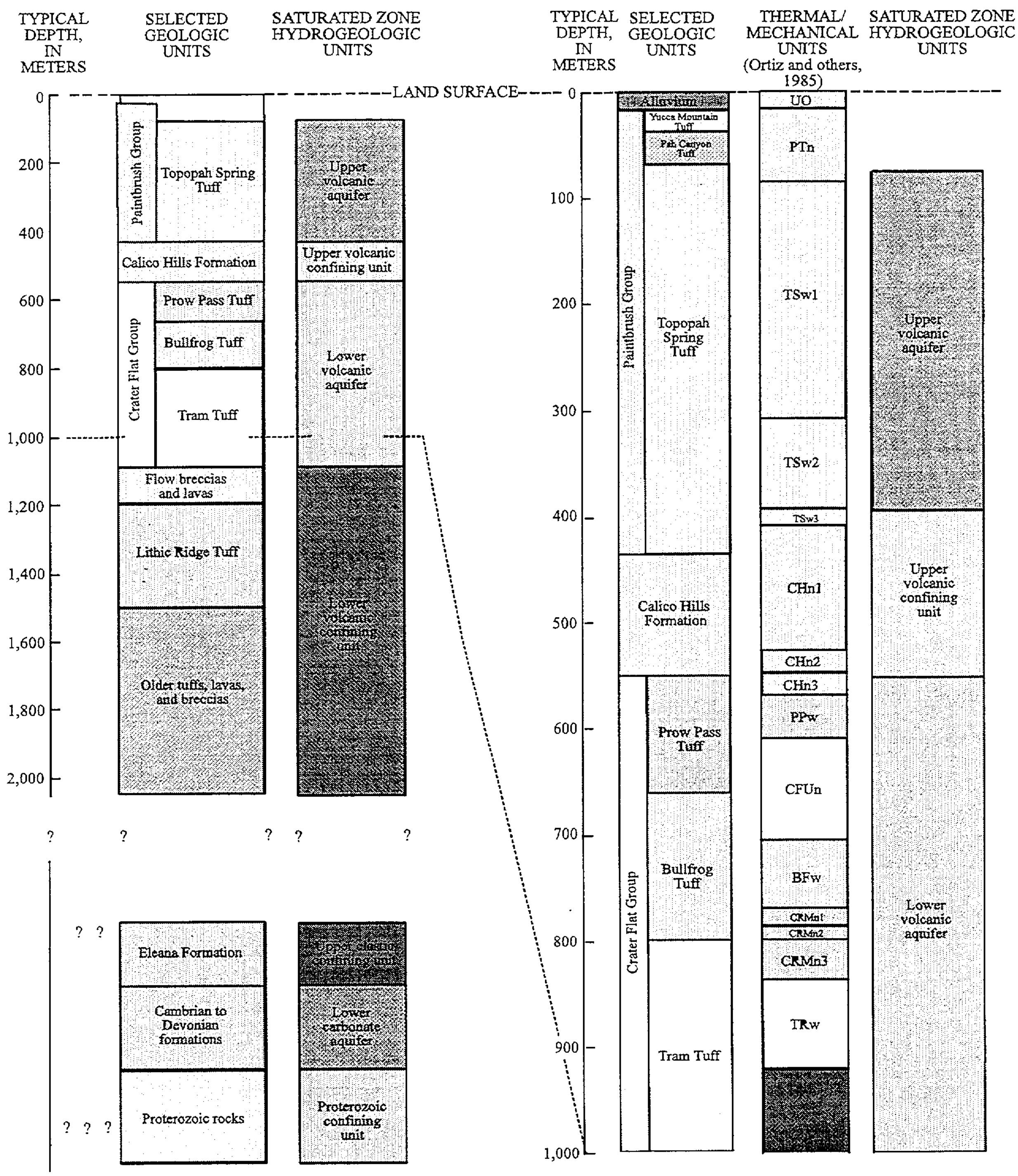

Figure 8. Hydrostratigraphy at Yucca Mountain (Luckey, et al., 1996).

Table 6. Hydrogeologic units and corresponding stratigraphic units (modified from Czarnecki, al., 1997).

Hydrogeologic Unit Czarnecki, et al. (1997)	Equivalent Unit		
	Winograd and Thordarson (1975)	**Laczniak, et al. (1996)**	**Luckey, et al. (1996)**
Valley-fill aquifer	Valley Fill (Valley-fill aquifer)	Alluvial deposits (Valley-fill aquifer)	Alluvium
Valley-fill confining units	Valley Fill (Valley-fill aquifer)	Alluvial deposits (Valley-fill aquifer)	Alluvium
Limestone aquifer	NA	NA	NA
Lava-flow aquifer	Basalt of Kiwi Mesa Basalt of Skull Mountain (Lava-flow aquifer)	Basalt	NA
Upper volcanic aquifer	Timber Mountain Tuff Paintbrush Tuff (Welded-tuff aquifer)	Thirsty Canyon Group Timber Mountain Group (Welded-tuff and lava-flow aquifers)	Paintbrush Group (Upper volcanic aquifer)
Upper volcanic confining unit	Wahmonie Formation Salyer Formation Rhyolitic flows and tuffaceous beds of Calico Hills (Lava-flow aquitard- Tuff aquitard)	Volcanics of Area 20 Wahmonie Formation (Lava-flow aquifers)	Calico Hills Formation (Upper volcanic confining units)
Middle volcanic aquifer	Grouse Canyon Member Tuff of Crater Flat (Tuff aquitard)	Crater Flat Group Belted range Group (Welded-tuff and lava-flow aquifers)	Crater Flat Group (Lower Volcanic Aquifer)
Middle volcanic confining unit	Local informal units of Indian Trail Formation (Tuff aquitard)	Tunnel Formation (Tuff confining unit)	Flow Breccia Lithic Ridge Tuff (Lower Volcanic Confining Unit)
Lower Volcanic Aquifer	Tub Spring Member	Volcanics of Big Dome (Lava-flow and welded-tuff aquifers)	NA
Lower volcanic confining unit	? (Tuff aquitard)	Older Volcanics (Tuff confining unit)	NA

Table 6. Hydrogeologic units and corresponding stratigraphic units (modified from Czarnecki, et al., 1997) (cont'd)

Hydrogeologic Unit Czarnecki, et al. (1997)	Equivalent Unit		
	Winograd and Thordarson (1975)	Laczniak, et al. (1996)	Luckey, et al. (1996)
Undifferentiated valley fill	Rocks of Pavits Spring Horse Spring Formation (Tuff aquitard)	Pavits Spring Formation Horse Spring Formation Paleocolluvium	NA
Upper carbonate aquifer	Tippipah Limestone (Upper carbonate aquifer)	Bird Spring Formation (Upper carbonate aquifer)	NA
Upper clastic confining unit	Eleana Formation (Upper clastic aquitard)	Eleana Formation (Eleana confining unit)	NA
Lower carbonate aquifer	Devils Gate Limestone Nevada Formation Ely Springs Dolomite Eureka Quartzite Pogonip Group Nopah Formation Dunderberg Shale Bonanza King Upper Carrara Formation (Lower carbonate aquifer)	Guilmette Formation Simonson Dolomite Sevy, Laketown, and Lone Mountain Dolomite Roberts Mountain Formation Dolomite of the Spotted Range Ely Springs Dolomite Eureka Quartzite Pogonip Group Nopah Formation Bonanza King Formation Upper Carrara Formation (Lower carbonate aquifer)	Lone Mt. Dolomite Roberts Mt. Dolomite (Carbonate Aquifer)
Lower clastic confining unit	Lower Carrara Formation Zabriskie Quartzite Wood Canyon Formation Stirling Quartzite Johnnie Formation (Lower clastic aquitard)	Lower Carrara Formation Zabriskie Quartzite Wood Canyon Formation Stirling Quartzite Johnnie Formation Noonday(?) Dolomite (Quartzite confining unit)	NA
Granitic confining unit	Granitic Stocks (A minor aquitard)	Granite	NA

The following description of individual aquifers and confining units is based on the classification by Czarnecki, et al. (1997), and characterizations by Czarnecki, et al. (1997) and Luckey, et al. (1996).

- **Basin Fill Aquifer:** The basin fill aquifer that has significance to the proposed repository is the valley fill aquifer that underlies most of the Amargosa Desert area, to the east and south of

YM. This aquifer is of Tertiary and Quaternary age. It is composed of alluvial fan, fanglomerate, lakebed, and mudflow deposits, and has a thickness of several hundred me. This aquifer is important in that it constitutes a main water supply source for domestic and irrigation water use in the Amargosa Valley. In addition, the valley fill aquifer may receive lateral flow and recharge from the volcanic tuffs. There is no conclusive evidence that the valley fill aquifer is hydraulically connected to the carbonate aquifer, although the occurrence of springs in some localities in the YM area has been attributed to upward flow from the carbonate aquifer.

- **Upper Volcanic Aquifer:** The Topopah Spring unit of the Paintbrush Tuff is the uppermost water bearing unit of the SZ and constitutes the upper volcanic aquifer in the YM area. It consists of variably welded ash-flow tuffs and rhyolite lavas (nonwelded tuffs). It is noted that the Topopah Spring unit is not saturated below the repository, but it becomes saturated to the east and south of YM and in Crater Flat.

- **Upper Volcanic Confining Unit:** The upper volcanic confining unit consists of rhyolite lavas, volcanic breccias, nonwelded to welded tuffs, and is commonly argillaceous or zeolitic. It includes the lowermost part of the Topopah Spring Tuff, Calico Hills Formation, and the uppermost part of the Crater Flat Group.

- **Middle Volcanic Aquifer:** The middle volcanic aquifer consists of variably welded ash-flow tuffs and rhyolite lava. It includes most of the Prow Pass tuff, and the underlying Bullfrog and Tram tuffs of the Crater Flat Group. This aquifer underlies YM, but tends to be less productive than the upper volcanic aquifer.

- **Middle Volcanic Confining Unit:** The middle volcanic confining unit consists of nonwelde and commonly zeolitized units of the Lithic Ridge Tuff.

- **Lower Volcanic Aquifer:** The lower volcanic aquifer consists of variably welded ash flow tuffs and rhyolite lavas below the Lithic Ridge Tuff, which correspond to the Tub Spring member (Winograd and Thordarson, 1975) and the lava flow and welded tuff aquifer (Laczniak, et al., 1996). It has a moderate permeability that is comparable to the permeability of the middle volcanic aquifer.

- **Lower Confining Unit:** In areas where the upper carbonate aquifer is missing, such as the YM area, the lower confining unit consists of the lowermost part of the volcanic sequence and the uppermost part of the pre-Cenozoic sequence. The lowermost part of the volcanic sequence includes nonwelded and commonly zeolitized units of older volcanics, at the lowermost interval of the volcanic sequence. The upper part of the pre-Cenozoic is the Eleana Formation of Devonian/Mississippian age, which has been characterized as the upper clastic aquitard. In areas where the upper carbonate aquifer is not missing, such as western Yucca Flat and northern Jackass Flats, it would occupy the interval between the lowermost part of the volcanic sequence and the Eleana formation.

- **Carbonate Aquifer:** Although both an upper and a lower carbonate aquifer have been identified regionally, the upper carbonate aquifer, which is a limestone aquifer, may be missing at YM. It is absent from the one drillhole at YM that penetrates the Paleozoic rocks (i.e., UE-25 p#1). The upper carbonate aquifer is underlain by the upper clastic confining unit represented by the Eleana formation, which consists of siliceous siltstone, sandstone, quartzite, conglomerate, and limestone that have a low permeability. The lower carbonate aquifer, designated in this report as the carbonate aquifer, underlies the Eleana Formation; it consists of Paleozoic dolomite and limestone, and is locally cherty and silty. The lower carbonate aquifer does occur in UE-25 p#1.

4.5.2.6 Hydraulic Head Data

This section provides information about the monitoring well network and patterns that have been observed in the potentiometric data, including vertical hydraulic gradients and zones that have been characterized as having large, moderate, and small hydraulic gradients. Subsections include the following, with reference to key citations.

Monitoring Well Network and Measurement Procedures (Graves and Goemaat, 1997)
Potentiometric Heads and Flow Patterns (Graves and Goemaat, 1997; Czarnecki, et al., 1997)
Large Hydraulic Gradient (Luckey, et al., 1996; Czarnecki, et al., 1997; Geomatrix, 1998)
Moderate Hydraulic Gradient (Luckey, et al., 1996; Geomatrix, 1998)
Small Hydraulic Gradient (Luckey, et al., 1996; Ervin, et al., 1993)
Vertical Hydraulic Gradients (Graves and Goemaat, 1997)

- **Monitoring Well Network and Measurement Procedures**

The water levels have been monitored in the YM area by the USGS since 1981 (Tucci, et al, 1996). The monitoring network included a total of 28 wells in 1995 (Graves and Goemaat, 1997). Seventeen wells representing 18 discrete depth intervals were monitored periodically (i.e., usually monthly); 9 wells representing 15 depth intervals were monitored both periodically and hourly; and 2 wells representing 3 depth intervals were monitored hourly. In addition, continuous water level and fluid pressure data were also collected in three of the monitoring wells, using analog-chart recorders to allow monitoring of fluctuations caused by earthquakes (Tucci, et al. 1996). All of the monitored wells were completed in the Tertiary volcanic system, except for one well (UE-25p#1), which was completed in the Paleozoic carbonate aquifer. A list and pertinent information about the monitoring wells are provided in Table 7, and the locations of the wells are shown in Figure 9.

According to published USGS reports (e.g., Tucci, et al., 1996), periodic water level measurements are made using calibrated steel tapes or a multi conductor cable. Steel tape measurements are corrected for mechanical stretch, thermal expansion, equipment calibration, and borehole deviation. Hourly measurements are made using pressure transducers and electronic data loggers. The transducer/data-logger systems are calibrated by recording transducer output at known depths of submergence. Specific procedures followed in equipment calibration and data correction are discussed by pertinent USGS reports (i.e., Tucci, et al., 1996; Graves and Goemaat, 1997). The water level altitudes are computed based on calibrated water level measurements, and surveyed elevations of the measurement reference points. According to the USGS (Tucci, et al., 1996; Graves and Goemaat, 1997), all the water level data were acquired in accordance with the quality-assurance program to support the data reliability.

Table 7. **Summary of wells monitored for water levels, 1995 (Graves and Goemaat, 1997).**

(p & h, well measured periodically and hourly during 1995; p. well measured periodically during 1995; h, well measured hourly during 1995; —, data not available)

				Water Level		
Well name	Drilled depth (meters)	Depth below land surface of bottom of monitoring tube (meters)	Date completed (month/year)	Approximate mean, 1995, depth below reference point (meters)	Approximate mean, 1995, altitude (meters)	Frequency monitored
USW WT-1	515	507.5	5/83	471	730	p & h
USW WT-2	628	622.0	7/83	571	731	p
UE-25 WT#3	348	343.0	5/83	300	730	p & h
UE-25 WT#4	482	477.6	6/83	438	731	p & h
UE-25 WT#6	383	372.0	6/83	280	1,034	p
USW WT-7	491	481.3	7/83	421	776	p
USW WT-10	431	402.6	8/83	347	776	p & h
USW WT-11	441	416.0	8/83	363	731	p
UE-25 WT#12	399	388.9	8/83	345	729	p
UE-25 WT#13	354	346.0	7/83	303	729	p
UE-25 WT#14	399	397.2	9/83	346	730	p & h
UE-25 WT#15	415	406.9	11/83	354	729	p
UE-25 WT#16	521	514.0	11/83	472	738	p
UE-25 WT#17	443	419.4	10/83	394	730	p
UE-25 WT#18	623	609.0	5/84	606	731	p
UE-25 b#1	1,220	—	9/81	—	—	—
upper interval	—	488.0	—	470	731	p
lower interval	—	1,199.0	—	471	730	p
UE-25 p#1	1,805	[1]418.0	5/83	362	753	h
USW G-2	1,831	[2]597.0	10/81	534	1,020	p
USW G-3	1,533	792.0	3/82	750	731	p
USW H-1	1,829	—	1/81	—	—	—
Tube 1	—	1,806.0	—	517	786	p
Tube 2	—	1,115.0	—	567	736	p
Tube 3	—	741.0	—	572	731	p & h
USW H-3	1,219	—	3/82	—	—	—
USW H-4	1,219	—	6/82	—	—	—

				Water Level		
Well name	Drilled depth (meters)	Depth below land surface of bottom of monitoring tube (meters)	Date completed (month/year)	Approximate mean, 1995, depth below reference point (meters)	Approximate mean, 1995, altitude (meters)	Frequency monitored
lower interval	—	1,188.0	—	518	730	p & h
USW H-5	1,219	—	8/82	—	—	—
upper interval	—	709.0	—	704	775	h
USW H-6	1,220	—	10/82	—	—	—
lower interval	—	752.0	—	526	776	p & h
USW VH-1	762	205.4	2/81	184	779	p
J-11	405	(4)	7/57	317	732	p
J-12	[5]347	—	8/68	227	728	p
J-13	1,063	—	1/63	283	728	p

[1]Well is constructed so that the hydraulic head in the Paleozoic carbonate rocks located 1,244 meters below land surface is monitored.
[2]Before October 1, 1995, well measured through open casing. Well is open hole from 242 meters below land surface to the bottom of the well. After October 1, 1995, well monitored through monitoring tube which was placed to a depth of 597.0 meters.
[3]Transducer removed from well USW H-3, lower interval on September 21, 1995, and a manual water-level measurement was attempted in the well on the same date. While making the measurement the steel tape broke off in the well and was unrecoverable. No further water-level measurements were made in USW H-3 lower interval during 1995.
[4]Well measured through open casing. Well is cased to bottom of well. Casing is perforated from 328.3 to 334.4 meters below land surface and from 379.2 to 396.2 meters below land surface.
[5]Original drilled depth 271 meters in 1957; well deepened to present depth in 1968.

Water levels in the Yucca Mountain Area, Nevada, 1995

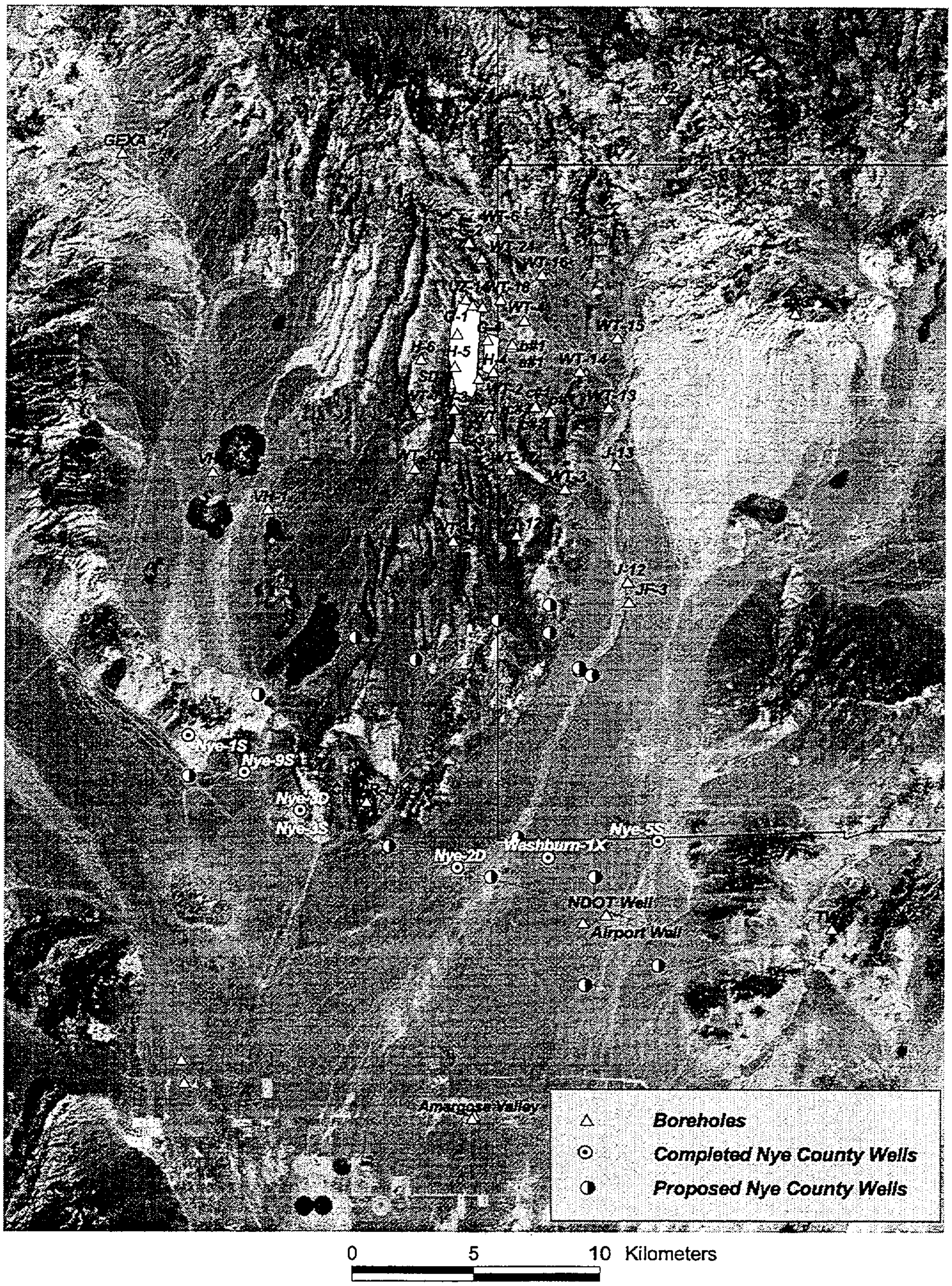

Figure 9. Map showing boreholes in Yucca Mountain region.

- **Potentiometric Heads and Flow Patterns**

Water level and potentiometric head data and well hydrographs for individual wells are provided in pertinent USGS publications (e.g., Tucci, et al., 1996; Graves and Goemaat, 1997). The available data indicate that the regional water level at the repository is about 700 m below the ground surface and 300 m or more below the repository level.

Robison (1984) developed a preliminary potentiometric-surface map for the YM area based on the 1983 potentiometric data. The general downgradient direction based on this map is east-southeast in the immediate vicinity of YM. The map clearly shows three distinct regions: (1) a large hydraulic gradient just north of YM, with a southward gradient of 0.12–0.13; (2) a moderate hydraulic gradient at or west of YM, with an eastward gradient of 0.05; and (3) a small hydraulic gradient, in most of the area beneath YM and further south, with a south-southeast gradient. Each of these distinct gradient areas are discussed in detail below. There is also a section on vertical hydraulic gradients. The data used for this map resulted in a poor resolution of potentiometric surface in the area of the small hydraulic gradient. Ervin, et al. (1993, 1994) refined this map primarily by using the mean 1988 potentiometric data. The area of small hydraulic gradient is represented by a 0.25-m contour interval. Based on this map, the predominant groundwater flow direction is to the east-southeast near YM.

A recent potentiometric surface map was developed by Czarnecki, et al. (1997). They stated (p. 25) that "...water levels in most of the wells appear to represent a laterally continuous aquifer system." Czarnecki, et al. (1997) pointed out that, at YM, water levels from most wells are obtained from the uppermost part of the SZ. South of YM, wells penetrate a significant thickness of the SZ, but, in this area, horizontal flow is predominant and vertical gradient is negligible. For wells with multiple piezometers, only the data from the uppermost saturated interval was used. This potentiometric surface map, as shown in Figure 10, also represents the three distinct zones of large, moderate, and small gradients. The inferred groundwater flow direction, as shown in Figure 10, is east-southeast near the YM and predominantly south further downgradient in Amargosa Valley. But this is based on an assumption of isotropic transmissivity. A high degree of anisotropy would tend to deflect flowlines more to the south. As discussed in Section 5, we believe that all reasonable horizontal flowpaths can be bounded within a narrow arc of azimuth that assumes a full range of conditions from isotropic to highly anisotropic. Figure 11 shows the effect of including data from the new Nye County wells (compare with Figure 10). The contours are significantly changed in the region south and southwest of YM.

Figure 12 provides the potentiometric head contours in the immediate area of YM, which were constructed based on the average water level measurements by the USGS in 1995. The potentiometric contours are based on the uppermost water levels in the measured wells. To the extent that the water levels represent different depth intervals and hydrostratigraphic units in the measured wells, the potentiometric head contours reflect composite averages that may represent the potentiometric head in more than one hydrostratigraphic unit. The potentiometric contours include preliminary water-level elevation data from wells WT-24 (839.5 m) and SD-6 (731.5) [personal communication with Chad Glenn, NRC Onsite Representative, July 1998]. The discovery of perched water in the upper Calico Hills Tuffs in WT-24 makes it possible that water-level elevations previously reported for wells G-2 and WT-6 may be overestimated. The potentiometric map will be revised in the future to reflect any interpreted changes in water levels for site wells. The uppermost water level data indicate that, in general, the potentiometric head in the Tertiary volcanic rocks declines from north to south and from west to east.

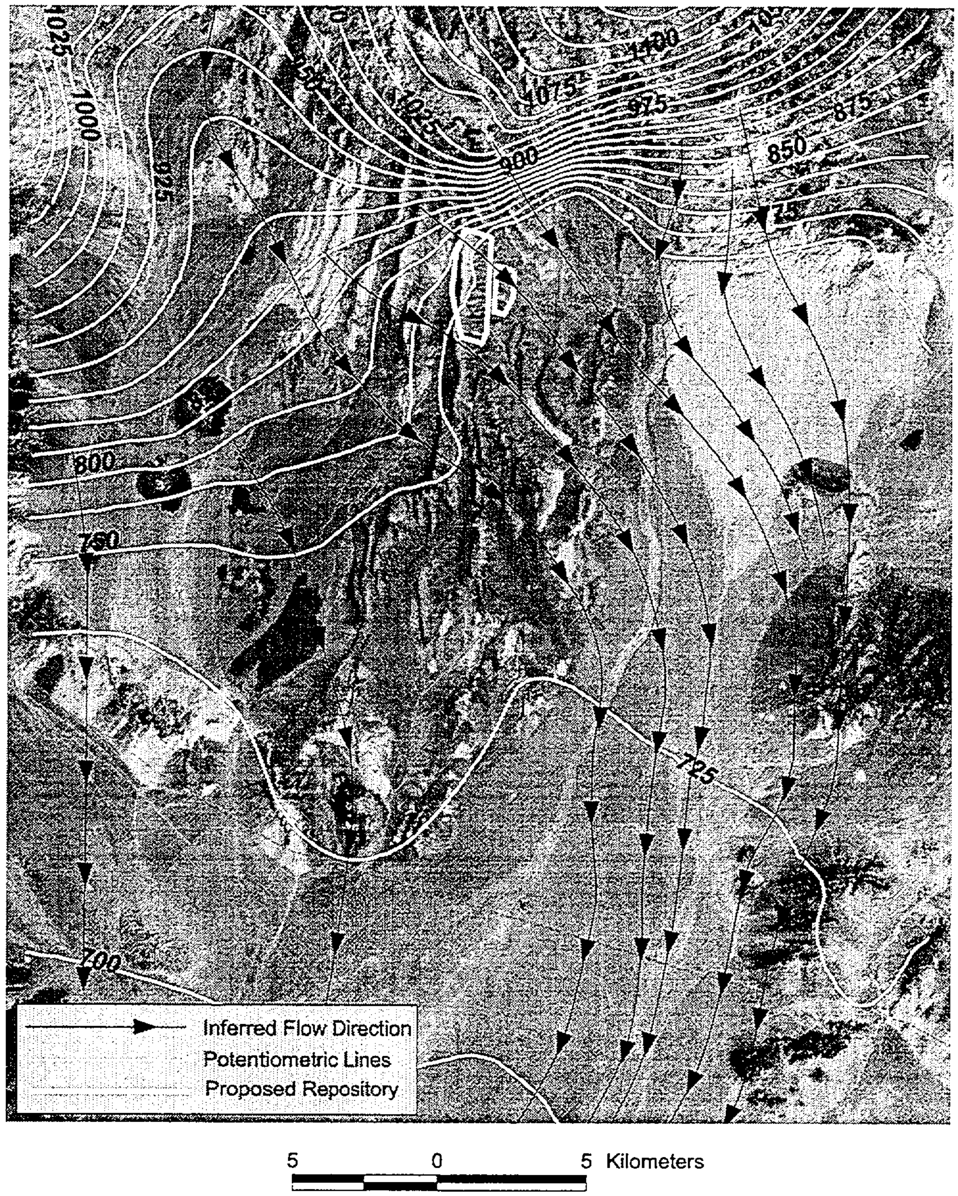

Figure 10. Preliminary inferred groundwater flow direction based on potentiometric surface map by Czarnecki, et al. (1997).

(contour interval 25 m, datum is sea level)

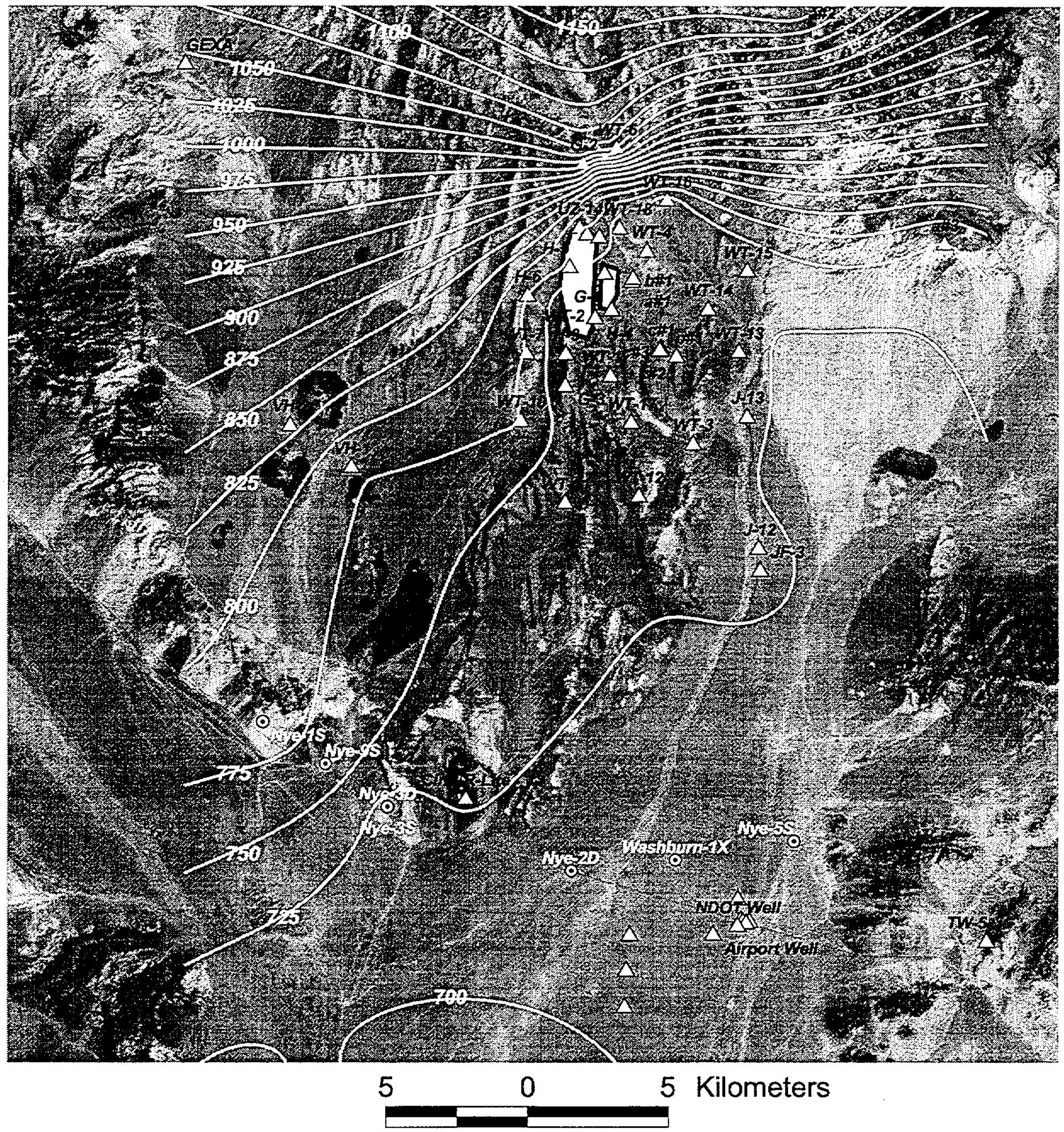

Figure 11. Potentiometric surface map for Yucca Mountain region with all available data.

(contour interval 25 m, datum is sea level)

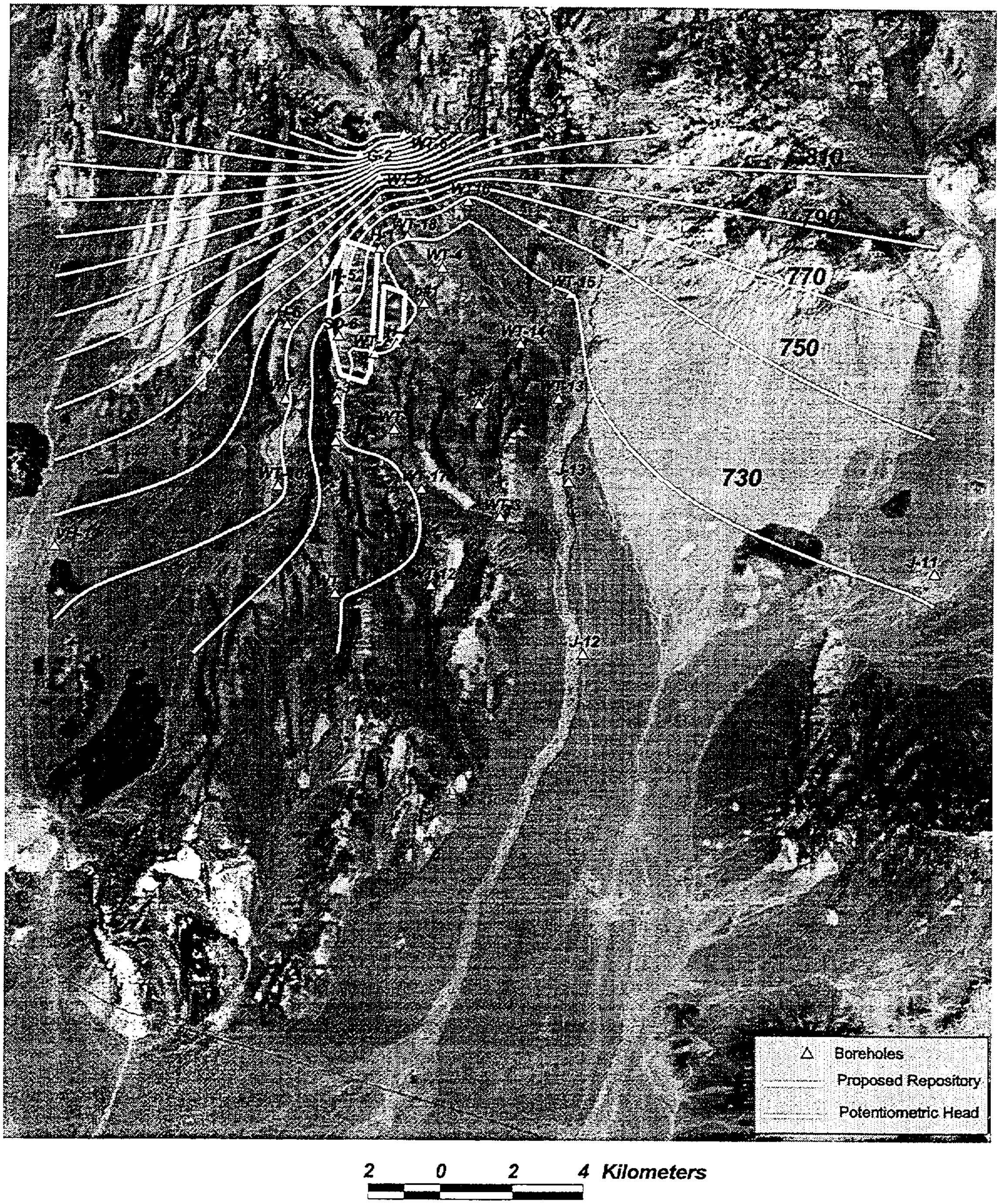

Figure 12. Potentiometric head contours in the immediate area of YM based on water level measurements for 1995 (Graves and Goemaat, 1997).

(contour interval 20 m, datum is sea level)

The water level data indicate further that the uppermost potentiometric head gradients are not uniform and can vary significantly along the apparent flow path, both across the repository footprint and away from the repository. West of the repository, all wells are completed in the Tertiary volcanic rocks and have a potentiometric head of 775 m or more above sea level. The highest potentiometric head west of the repository is about 833 m above sea level, which was measured in well USW VH-2, about 9 km west of Solitario Canyon.

East and south of the repository, all of the measured wells are completed in the Tertiary volcanic rocks, except well UE-25p#1, which is completed in the carbonate aquifer. They have a potentiometric head of about 731 m or less above sea level. The lowest potentiometric head is about 728 m above sea level, which was measured along Fortymile Wash in wells J-12 and J-13, about 10 and 6 km, respectively, southeast of the repository footprint (Graves and Goemaat, 1997).

The average west-east potentiometric head gradient is about 7 m/km between wells USW VH-2 and J-13. However, this gradient is not uniformly distributed along the apparent flow path from west to east. The average head gradient is about 7 m/km between well USW VH-2 (833 m altitude) and wells USW WT-10, USW WT-7, and USW H-6 (776 m altitude) west of the repository footprint. The head gradient increases abruptly across the repository footprint to: (1) about 22 m/km along the northern repository footprint boundary (i.e., between wells USW H-5, upper interval, 775 m altitude, and UE-25b#1, upper interval, 731 m altitude); and (2) about 40 m/km south of the repository footprint (i.e., between well USW WT-7, 776 m altitude and wells USW H-3, upper interval, and USW G-3, 731 m altitude). Further to the east, the potentiometric head declines sharply to only about 0.4 m/km (i.e., between well USW G-3 and well J-13).

North of the repository footprint, the uppermost water level declines from about 840 m above sea level in well USW WT-24 (based on June, 1998 measurement by DOE), to about 731 m above sea level in wells USW H-1, upper interval, and UE-25 WT#18. This corresponds to a north-south average potentiometric head gradient north of the repository footprint of about 50 m/km. However, the head gradient declines sharply to about 0.5 m/km to the south and southeast of wells USW H-1 and UE-25 WT-18, off the repository footprint.

The water level altitude in well UE-25p#1 is about 752 m. This is the only well completed in the carbonate aquifer in the YM area. Neither the horizontal potentiometric gradient nor local flow direction in the Paleozoic rocks can be determined from this well alone. Other wells in the region are completed in the Paleozoic aquifer system. They are not within the Alkali Flat Subbasin that includes YM, but do provide information about the regional carbonate aquifer system that underlies large areas of the Great Basin and other regions of the western United States. The carbonate rock province extends over most of southern and eastern Nevada and areas of adjoining states (Plume, 1996, Fig. 2). The USGS Amargosa Tracer Calibration Site is located 24 km southwest of Mercury, Nevada, and consists of five wells completed in the Bonanza King dolomite. One of these wells, AD-6 (Tracer Well 3), has a potentiometric elevation of 720 m (LaCamera and Locke, 1997) and is located 45 km south-southeast of YM. Seventeen wells are completed in the lower carbonate aquifer at Yucca Flat on the NTS, with water elevations ranging from 724 to 745 m (DOE, 1997b, Vol. II, Potentiometric Data Documentation Package). Well MV-1 (Army Well #1) is completed in carbonate rocks. It is located about 8 km southwest of Mercury, Nevada, and has a hydraulic head elevation of 722 m (LaCamera and Locke, 1997). This well is 50 km southeast of YM. Devils Hole, in the Ash Meadows area, has a potentiometric level of 719 m. Based on what is known about regional hydraulic heads in the Alkali Flat Subbasin and locations of recharge and discharge areas, it is expected that the general pattern of flow in the Paleozoic carbonate aquifer at YM is southerly toward the Amargosa Desert. DOE's cooperative well drilling program with Nye County, Nevada has intended to drill a number of wells into the deep carbonate aquifer south of YM and west of Amargosa Valley. However, the deep w drilled to date have terminated in volcanics or thick valley fill. If future wells reach the carbonates, they could considerably enhance understanding of flow conditions in the Paleozoic aquifer system. It should also be noted that two existing oil and gas exploration boreholes (Felderhoff Federal 5-1 and 25-1) penetrate the carbonate rocks south of the town of Amargosa Valley. These could be converted to monitoring wells at a fraction of the cost of drilling new holes. Carr, et al. (1995) summarized lithologic and geophysical data for these holes.

Some wells at YM display significant water-level change with time. Three wells located northeast of YM in Fortymile Canyon (UE-29 a#1, a#2, and UE-29 UZN #91) experienced fluctuations of up to 5 m in response to streamflow infiltration events (Savard, 1998). Well USW H-3 has two monitored intervals that are divided by an inflatable packer. This packer was moved in December of 1990. The lower interval monitors the Lithic Ridge Tuff, and since the packer was moved, the water level in this interval has steadily risen from 753 m in December 1991 (Luckey, et al., 1996) to over 759 m as of December 1995 (Graves and Goemaat, 1997). The water level is equilibrating to a new static level. For most other wells, the water-level change with time is not very significant, in either the uppermost part of the Tertiary aquifer or the carbonate aquifer of the Paleozoic. In the Tertiary, where the great majority of the monitoring wells are completed, the 1995 daily and monthly average water level fluctuated from a few centimeters to a few tenths of a meter. In the carbonate aquifer, where only one well (UE-25p#1) is completed, the daily water level altitude in 1995 fluctuated by 0.2 m, from 752.46 m to 752.66 m, and the monthly mean water level ranged from 752.52 in November to 752.59 m in April, May and August. The 1995 average water level altitude in well UE-25p#1 (752.57 m) is 0.02 m higher than the average water level for 1994 (752.55 m), and about 1 m above the water level measured at the time of well construction in 1983 (about 751.52 m, based on data from Craig and Robison, 1984).

- **Large Hydraulic Gradient**

The potentiometric surface at the north end of YM is characterized by a large hydraulic gradient (gradient 0.13–0.15) between altitudes of approximately 1,030 to 750 m; the surface is markedly steeper than the surface toward the south and east (Luckey, et al., 1996). Typically, large hydraulic gradients in Southern Nevada have been associated with known geologic and topographic features, such as a contact in the Paleozoic rocks between clastic rocks and regional carbonate aquifer. However, the large hydraulic gradient at the north end of YM cannot be associated with such a feature. This lack of an association with an obvious geologic cause can be due to the scarcity of data, since there are only a few wells completed in this area.

Several possible explanations have been extended for the cause and nature of the large hydraulic gradient: (1) faults that contain nontransmissive fault gouge (Czarnecki and Waddell, 1984); (2) faults that juxtapose transmissive tuff against nontransmissive tuff (Czarnecki and Waddell, 1984); (3) the presence of a different type of lithology that is less subject to fracturing (Czarnecki and Waddell, 1984); (4) a change in the direction of the regional stress field and a resultant change in the intensity, interconnectedness, and orientation of the fractures on either side of the area with large hydraulic gradient (Czarnecki and Waddell, 1984); (5) the apparent large gradient actually represents a disconnected, perched or semi-perched water body so that the high water level altitudes are caused by local hydraulic conditions and are not part of the SZ flow system (Czarnecki, et al., 1994; Ervin, et al., 1994); (6) a highly permeable buried fault that drains water from tuff units into a deeper regional carbonate aquifer (Fridrich, et al., 1994); (7) a buried fault that forms a spillway in the volcanic rocks (Fridrich, et al., 1994); (8) the result of flow through the upper volcanic confining unit (Luckey, et al., 1996); or (9) presence of the Eleana Formation (Luckey, et al., 1996).

Explanations (1)–(4) are based on geological and lithological reasons that cannot be supported without additional field data. However, they can first be tested using mathematical models to determine if they are theoretically reasonable. Ervin, et al. (1994) suggested Hypothesis (5), that the large hydraulic gradient represents a semiperched system. Semiperched systems are not uncommon in the vicinity of the Nevada Test Site (NTS) (Winograd and Thordarson, 1975). Under this hypothesis, the large hydraulic gradient may simply be an artifact of attempting to contour points from two different and widely separated aquifers. Water levels from boreholes completed in the confining unit between these two different aquifers (such as UE-25 WT #6), where flow is essentially vertical and water levels change dramatically with depth, would be difficult to interpret (Luckey, et al., 1996). At least some of the water levels measured north of YM represent composite heads that may be influenced by perched water. These northern boreholes that may be influenced by perched water include USW UZ-14, USW G-2, UE-25 WT #6, and UE-29a #2 (Czarnecki, et al., 1997).

Fridrich, et al. (1991, 1994) proposed Hypothesis (6), that the large hydraulic gradient represents a drain and is part of a large regional hydraulic gradient that extends many kilometers to the northeast of YM. Based on gravity surveys and stratigraphic data, it was surmised that a fault in the vicinity of the large hydraulic gradient is buried beneath the Calico Hills Formation and is the northern-bounding fault of a buried graben. There is no surface expression of the postulated fault (Luckey, et al.,1996). In this hypothesis, Fridrich, et al. (1994) suggested that this fault marks the northern extent of active flow in the carbonate aquifer and provides a drain that moves water from the volcanic aquifers into the carbonate aquifer. The drain removes most of the water from the volcanic aquifers and greatly decreases flow through the volcanic aquifers to the south, which accounts for the small hydraulic gradient to the south and east of YM. Part of the water returns to the lower volcanic aquifer south of the large hydraulic gradient through faults, most notably the Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults. This hypothesis is intriguing in that it also accounts for the anomalously low heat flow observed at YM (Sass, et al., 1988), but the hypothesis relies heavily on aeromagnetic and gravity data to define the buried graben, because other geologic data are sparse (Luckey, et al., 1996).

Fridrich, et al. (1994) also proposed (7), the spillway hypothesis, to explain the large hydraulic gradient. This explanation requires the same deeply buried fault; but, in this spillway hypothesis, the fault marks the effective northern limit of the lower volcanic aquifer. Fridrich, et al. (1994) speculated that, as a result of the fault, the Crater Flat Group is: (1) thinner to the north of the graben; (2) is more altered; and (3) is much less permeable than it is to the south. This explanation envisions very little flow from the north, and what little flow there is drops abruptly at the northern-bounding fault of the buried graben (Luckey, et al., 1996).

Luckey, et al. (1996) proposed Hypothesis (8) and suggested that a large hydraulic gradient could be expected in a thick confining unit. Based on the water-level data from borehole USW G-2 in the upper volcanic confining unit, located at the northern end of the large hydraulic gradient, the saturated thickness of the confining unit is almost 300 m. Because the unit that composes the upper volcanic confining unit is not saturated to its full thickness at borehole USW G-2, the large hydraulic gradient may persist somewhat north to the area where the potentiometric surface is in the upper volcanic aquifer. The lower volcanic aquifer in this area also could have decreased hydraulic conductivity, due to lithostatic pressure and hydrothermal alteration, and also would contribute to the large hydraulic gradient.

Luckey, et al. (1996) suggested Hypothesis (9), that the large hydraulic gradient is the result of the presence, at depth, of the Eleana Formation, which is part of the Paleozoic upper elastic confining unit described by Winograd and Thordarson (1975). Fridrich, et al. (1994) noted that the regional large hydraulic gradient appeared to follow the contact between the upper clastic confining unit and the carbonate aquifer. The Eleana Formation is responsible for a large hydraulic gradient on the west side Yucca Flat in the northeastern part of the NTS (Winograd and Thordarson, 1975). The Eleana Format. could be deeply buried beneath northern YM and could be affecting the flow system in that area in the same way it affects the flow system on the west side of Yucca Flat. Currently, there are no boreholes that can suggest the presence or absence of the Eleana Formation to the north of YM.

During a recent expert elicitation (Geomatrix, 1998), the experts had differing opinions about two questions: (1) whether the large hydraulic gradient is important to understanding the amount of inflow to YM from the north; and (2) whether the large hydraulic gradient is a perched system or is connected to the regional saturated system. One of the experts suggested that the large hydraulic gradient is important for knowing the amount of inflow coming beneath the YM from north. Whereas, other experts surmised that the resolution of the large hydraulic gradient, although important, is not critical to understand the hydrological system at the repository site. The connected saturated system model for the large hydraulic gradient suggested that it is fully in the saturated system and is related to topography, recharge patterns, and geology. Another panelist suggested that it can be attributed to geological features, such as a vertical low permeability feature, a horizontal low permeability feature, or a deep drain. The perched system consists of an upper SZ underlain by a wedge of UZ over the regional water table. It was agreed among the experts that the UZ between the two saturated layers is near saturation. The experts agreed that a very carefully drilled well can resolve the uncertainty associated with the large hydraulic gradient.

The NAS (1992) considered whether the cause of the large hydraulic gradient in the saturated zone, located just north of the YM site, could influence future water-table rise. They recommended (NAS, 1993, p. 140) that hydrologic data be measured and collected *in situ* in boreholes to identify the cause of the large hydraulic gradient. DOE originally planned to drill two holes for this purpose. One of these boreholes, WT-24, is currently being constructed, and data, to date, indicate that a perched water system exists near the top of the Calico Hills Formation. Preliminary hydraulic head data show that the regional potentiometric surface has been intersected and occurs more than 100 m above that found in wells to the south. In th recent expert elicitation (Geomatrix, 1998), the experts concluded that the probability of any large transi change in the configuration of the large hydraulic gradient due to disruptive events is extremely low.

The completion of well USW WT-24, just southeast of well G-2, provides new insight for the large hydraulic gradient. Preliminary data show the presence of a perched-water zone. A fairly conductive fracture was eventually encountered near the base of the Calico Hills tuff and the water level rose over 100 m, marking the location of the potentiometric surface. The water level was reported to be rising slowly as of early June of 1998. In June 1998, the water level altitude was reported at about 839.5 m, implying a lateral southerly hydraulic gradient of about 0.059 m/m between well WT-24 and wells WT-16 and H-1 (shallow zone). The preliminary data verify that heads are indeed higher north of the YM site, and that the relatively high heads in wells G-2 and WT-6 are not entirely the result of perched water.

The cause of the so-called large hydraulic gradient is still uncertain, but the evidence from WT-24 and USW G-2 points to a simple model with a thick, low-permeability confining unit that perches water above and within it. The Calico Hills tuff is relatively thicker to the north and occurs within the saturated zone, whereas, it is unsaturated at the YM site. The Calico Hills causes perched water at WT-24 and at numerous locations further south, demonstrating that vertical permeabilities are relatively low and that any fractures present are poorly conductive. Lateral permeabilities are also low, as demonstrated through testing at well USW G-2. This, combined with proximity to the water table, probably causes a lateral flow barrier that restricts flow and causes heads to build up to the north. The YM site appears to be bounded on both the north and west by zones of relatively low permeability. The high gradients across these features provide a driving force for groundwater to move laterally into the YM area. The staff will update this preliminary interpretation as needed in a future IRSR update.

- **Moderate Hydraulic Gradient**

The area of the moderate gradient is defined by at least eight wells. The uppermost potentiometric heads in the Tertiary volcanic aquifer depict a west-to-east head anomaly across the repository footprint. The moderate hydraulic gradient (~ 0.05 m/m) exists in the vicinity of the Solitario Canyon fault system, with the fault functioning as a reduced-permeability barrier to flow from west to east. This explanation of the moderate gradient was shared by DOE's expert elicitation panel that addressed saturated zone issues (Geomatrix, 1998). Offsets on the fault increase from north to south and range from ~100 to ~250 m at the YM site. These offsets place more permeable units against units of lower permeability, and fault gouge and mineralization may contribute to the permeability contrasts. Luckey, et al. (1996, p. 25) suggest that "Some flow undoubtedly crosses the Solitario Canyon Fault because there is a large difference of hydraulic potential (45 m) across it. However, most of the groundwater west of the Solitario Canyon Fault probably flows south, either along the fault or through an aquifer in Crater Flat." Major ion chemistry from well USW H-3 provides evidence, however, that a significant groundwater flux does cross the Solitario Canyon fault from west to east under the prevailing hydraulic gradient. This well occurs just east of the fault. Concentrations of Na^+ and Ca^{2+} in H-3 more closely resemble those found in wells west of the fault (H-6, WT-7, and WT-10) than those in wells to the east (data from Oliver and Root, 1997). Estimates of lateral groundwater flux east of the fault also provide evidence of the magnitude of lateral flow (see Section 4.5.2.11).

The boreholes located on the west side of the Solitario Canyon Fault, USW H-6, USW WT-7, and USW WT-10, have higher water level of about 776 m. The boreholes located to the east of the Solitario Canyon Fault, USW H-1, and USW H-3, have a lower water level of about 731 m in their uppermost monitoring ones, except for borehole USW H-5 which has a water-level of about 775 m. It was suggested by Ervin, et al. (1994) that borehole USW H-5 may be well connected hydraulically with the boreholes west of the fault. This apparent anomaly of borehole USW H-5 is explained by Luckey, et al. (1996, p. 25) who note that H-5 "...is located to the east of the Solitario Canyon Fault but on the downthrown (west) side of a major northeast-trending splay of the Solitario Canyon Fault." Most of the flow in H-5 originates from the part of the Bullfrog Tuff that is located between 720 to 780 m. Therefore, it is possible that most of the flow to the borehole comes from an interval that is above the interval where the fault splay probably intersects H-5. The fault splay may contain fault gouge and this low-permeability interval may tend to mound water against the fault splay of the Solitario Canyon fault causing a higher head in well USW H-5. The staff also note that the ability of the fault to restrict lateral flow likely diminishes to the north where its' displacement reaches a minimum just southwest of well G-2.

Fridrich, et al. (1994) suggested that there could be substantial upwelling of water from the carbonate aquifer along the Solitario Canyon Fault, as well as along other north-striking faults. However, this is not substantiated by hydrochemistry data (Oliver and Root, 1997) which show that (1) the lowest Ca^{+2} ion concentrations in the area occur in wells in Solitario Canyon; and (2) there are strong contrasts in chemistry between groundwater in the tuffs and in the Paleozoic carbonate aquifer. Therefore, any upwelling that occurs must be relatively small compared with the flux from lateral flow.

Well SD-6 has been drilled at the crest of YM south of well H-5, and preparations are underway to conduct aquifer testing. Preliminary data show that the potentiometric surface exists near an elevation of 731.5 m. The proposed hydrologic testing at well SD-6 will provide new insight for the moderate hydraulic gradient.

The east-west drift penetrated the main Solitario Canyon Fault, and found a zone of clay-rich fault goug about 1 m thick. This kind of low-permeability zone readily explains the head differences across the fa

- **Small Hydraulic Gradient**

The area of the small hydraulic gradient east of the Solitario Canyon fault is defined by more than 20 wells. The sharp decline in the head gradient south and southeast of well UE-25 WT-18 may reflect: (1) a sharp decrease in the groundwater flux (i.e., loss due either to downward inter-aquifer flow or local discharge); (2) an increase in SZ hydraulic conductivity; and/or (3) a sudden increase in SZ flow cross sectional area (i.e., aquifer thickness and/or width). The horizontal gradient varies through a range of 0.0001 to 0.0005. However, it is not certain that the small hydraulic gradient is actually a smooth potentiometric surface because the wells are separated by thousands of meters. The small hydraulic gradient is within the area bounded by boreholes UE-25 WT-18 and WT-16 to the north; boreholes USW H-1, SD-6 (preliminary data), USW H-3, USW G-4, and USW WT-11 to the west; borehole J-11 to the east; and appears to extend south of well J-12 through southern Jackass Flats to the Amargosa Desert. Ervin et al. (1993) suggested that the small hydraulic gradient could indicate highly transmissive rocks, limited groundwater flow through the system, or a combination of both phenomena. The potentiometric surface, in the area of the small hydraulic gradient, generally slopes east-southeast from YM toward Fortymile Wash with a smaller component sloping generally southward. Limited data east of Fortymile Wash indicates that the potentiometric surface in Jackass Flats is also relatively flat and probably slopes westward toward Fortymile Wash with a smaller component sloping to the south (Luckey, et al., 1996). The relatively highest gradient (0.00054) within the area of the small hydraulic gradient occurs south of YM between wells WT-11 and WT-12, demonstrating a potential for easterly or southeasterly flow.

Based on data currently available, the cause of the small hydraulic gradient is likely the combination of factors described by Ervin, et al., 1993. These include: (i) reduced lateral flux from the north and west caused by low permeability zones, and (ii) the presence of zones of relatively high permeability in the s gradient area, especially east of the C-wells complex where the potentiometric surface occurs within the strongly welded and highly fractured Topopah Spring tuff. Wells J-12 and J-13 are highly productive wells that are completed in the Topopah Spring tuffs. Well JF-3, located just south of J-12, has the highest transmissivities estimated for any site well, 13,000-15,000 m^2/day. The lowest hydraulic heads in the vicinity of YM occur at these wells along Fortymile Wash, and hydraulic head data demonstrate a potential for flow to converge on the vicinity of J-12 and J-13 from the west, north, and east.

- **Vertical Hydraulic Gradients**

Information about changes in potentiometric head with depth in the saturated zone in the area of YM are provided in the annual progress reports by the USGS concerning the results of water level monitoring (e.g., Graves and Goemaat, 1997; Tucci, et al., 1996), and other USGS reports (Bentley, 1984; Craig and Robison, 1984; Czarnecki, et al., 1997; Luckey, et al., 1996; Oliver and Root, 1997; Thordarson, 1983; Waddell, 1985).

The available water-level data indicate that the potentiometric head varied with well depth at some locations in the YM area, both within the Tertiary volcanic rock sequence and between the Tertiary and the underlying carbonate aquifer of the Paleozoic. Table 8 provides a list of ten wells where a change in potentiometric head with depth has been recorded; these include nine wells that are completed in the Tertiary volcanic rocks and one well that is completed in the Paleozoic carbonate rocks. Table 8 also provides information about the monitored intervals, measured potentiometric heads, and the direction and magnitude of the head change with depth.

Table 8. Water levels at different depth intervals in selected wells.

Well #	Interval #	Depth Interval (m Below Ground)	Strati-graphic Unit(s)	Potentio-metric Head (m Above Sea Level)	Potentio-metric Head Change with Depth (m)
UE-25b#1	Upper	WT-1199	CH; PP; BF; and Upper TR	730.61[a]	RH
	Lower	1199-1220	Lower TR	729.64[a]	- 0.97
UE-25c#3	Upper	692-753	Lower Volcanic Aquifer	730.22[b]	RH
	Lower	753-914	Lower Volcanic Aquifer	730.64[b]	+0.42
USW G-4	Upper	615-747	Lower Volcanic Aquifer	730.3[c]	RH
	Lower	747-915	Lower Volcanic Aquifer	729.8[c]	-0.5
USW H-1	Tube 4	572-673	PP	730.91[a]	RH
	Tube 3	716-765	BF	730.64[a]	- 0.27
	Tube 2	1097-1123	TR	735.74[a]	+ 4.83
	Tube 1	1783-1814	Older Flow Tuffs Below LET	785.97[a]	+ 55.06
USW H-3	Upper	WT-1114	Bedded Tuff and TR	731.29[a]	RH
	Lower	1114-1219	LET	759.23 & rising	+ 27.94, (Still Rising)

USW H-4	Upper	WT-1188	PP;BF;TR; Bedded Tuff; & Upper LET	730.37[a]	RH
	Lower	1188-1219	LET	730.50[a]	+ 0.13
USW H-5	Upper	WT-846	BF;TR;Bedded Tuff; Unnamed Lava Below TR	775.40[a]	RH
	Lower	846-1219	TR(?); Unnamed Lava Below TR	775.78[a]	+ 0.38
USW H-6	Upper	WT-533m	PP,BF,TR; Bedded Tuff	776.13[a]	RH
	Lower	752-1220	TR;Bedded Tuff; Unnamed Lava Between TR & LET; and LET.	776.01[a]	-0.12
J-13	Uppermost Interval	282.2-334.1	Topopah Spring	729.10[d]	RH
	Lowermost Interval	819.9-1063.1	TR;Bedded Tuff;& LET	728.00[d]	-1.10
UE-25p#1	Upper	384-500	Lower Volcanic Aquifer	729.90[b,e]	RH
	Lower	1110-1805	Older Tertiary Volcanics & Paleozoic	751.26[b,e] 752.57[a]	+21.36 +22.67

FOOTNOTES:

[a] Mean altitude, based on hourly measurements in 1995 (Graves and Goemaat, 1997).

[b] 1990 mean level (Luckey et al, 1996).

[c] Average value (Bentley, 1984; Luckey et al, 1996).

[d] Based on static water level measurements collected during hydraulic testing and construction of well (Thordarson, 1983).

[e] Average value (Craig and Robison, 1984; Luckey et al, 1996).

KEY:
PP: Prow Pass member of the Crater Flat Group
BF: Bullfrog member of the Crater Flat Group.
TR: Tram member of the Crater Flat Group.
LRT:Lithic Ridge Tuff.
CH: Calico Hills.
RH: Reference Head.
WT:Water Table

There are other wells near YM besides those listed in the above table that indicate a change in potentiometric head with depth. Wells UE-29a#1 and UE-29a#2 are located about 10 m apart at a site along the northern reaches of Fortymile Wash, about 15km north of well J-13. Both wells are located in the Calico Hills hydrostratigraphic unit. Well UE-29a#1 is 65.5 m deep, and well UE-29a#2 has a total depth of 421.5 m. Based on data provided by Waddell, 1985, and Oliver and Root, 1997, the potentiometric head at this location declines with depth, from about 1191 m above sea level in the depth interval between 24 and 65.5 m (in well UE-29a#1); to about 1187 m in the depth interval 87 to 213 m, and 1186 m in the depth interval between 250 and 355 m (in well UE-29a#2). The head data suggest that recharge is occurring at this location, and in fact water level rises have been observed in these wells due to runoff events in Fortymile Canyon that occurred in 1983, 1992, 1993, and 1995 (Savard, 1998). But these wells were not included in the table because it is unknown if the water levels measured at this location represent the regional saturated zone, or locally perched conditions.

The available potentiometric head data indicate that both downward and upward potentiometric head gradients occur in the Tertiary volcanic rocks in the area of YM. Downward head gradients, which are consistent with recharge conditions, have been observed in wells UE-25b#1, UE-25c#3, USW G-4, USW H-6, and J-13. Upward head gradients, which are consistent with discharge conditions, have been observed in wells USW H-3, USW H-4, and USW H-5.

In well USW H-1, the water level was measured at four depth intervals in the Tertiary volcanic rocks. These four depth intervals, representing four piezometer tubes, include (1) the depth interval from 1783 to 1814 m representing the older flow tuffs below the Lithic Ridge Tuff (Tube 1); (2) the interval from 1097 to 1123 m, representing the Tram member of the Crater Flat Group (Tube 2); (3) the interval from 716 to 765 m, representing the Bullfrog member (Tube 3); and (4) the interval from 562 to 673 m, representing the Prow Pass (Tube 4). The vertical gradient in this well was variable along the well depth. The gradient was slightly downward between the Prow Pass (Tube 4) and the Bullfrog (Tube 3); upward between the Tram (Tube 2) and the Bullfrog (Tube 3); and significantly upward between the older flow tuffs below the Lithic Ridge Tuff (Tube 1) and the Tram (Tube 2).

The highest potentiometric head change with depth in the Tertiary volcanic sequence was measured in wells USW H-1 and USW H-3. The head difference in H-1 is notably high because it is the largest known vertical head change with depth (55 m) in the YM area. The upward gradients were calculated by dividing the measured potentiometric head increase with depth by the corresponding formation thickness between the midpoints of the measured depth intervals. The upward gradient in well USW H-1 is as much as 0.07 m/m. The upward gradient in well USW H-3 (head difference 28 m) is about 0.11 m/m. The measured potentiometric head change with depth in the remaining Tertiary wells was relatively small (1.1 m or less).

A significant upward potentiometric head change of about 21 m has also been observed in well UE-25 which is completed in the Paleozoic carbonate aquifer that underlies the Tertiary volcanic rocks. The inferred upward hydraulic gradient is about 0.02 m/m. Most investigators have attributed the upward hydraulic gradient in this well to an increase in potentiometric head in the lower carbonate aquifer. For example, Bredehoeft (1997) presents an interesting analysis of fault permeability near YM, specifically focusing on the Fran Ridge fault which occurs at the top of the Paleozoic carbonates in borehole UE-25p#1. He noted (Bredehoeft, 1997, p. 2459) that "The hydraulic head in the deep carbonate aquifer is 20 m higher than the head in the overlying tuff aquifer. This indicates that the groundwater flow potential is upward out of the carbonate. This is a favorable condition for the repository. As long as this condition continues, groundwater will not move contaminants downward to the deep aquifer; the potential movement of groundwater is in the opposite direction." Bredehoeft analyzed the earth-tide response of the deep carbonates and concluded that a straightforward explanation was that the aquifer is highly permeable with good confinement. Using hydrologic data reported by Craig and Robison (1984), the good tidal response of the deep aquifer, and temperature anomalies at the site, Bredehoeft estimated the upward flow from the carbonate aquifer along 10-km long fault zones in Midway Valley and Solitario Canyon. His rough estimate was a total upward discharge of 1000 m^3/day, or about 300 acre-ft/yr, along the fault zones.

However, it has also been reported (Craig and Robison, 1984) that at the time of well construction, a potentiometric head increase (i.e., from 734.5 m to 752.2 m), was observed between depths of 1114 m and 1180 m. Thus the actual change in hydraulic heads occurs in the volcanics above the reported Tertiary/Paleozoic contact which occurs at a depth of 1244 m in this well (Carr, et al., 1986). Below the Tertiary/Paleozoic contact, the potentiometric head reportedly declined slightly to between 750.9 to 751.9 m altitude. This well apparently penetrates a fault zone, and it has been postulated that the fault zone may act as a hydraulic conduit between the Paleozoic and the Tertiary volcanic aquifer systems (Luckey, et al., 1996). This provides evidence that the lowermost volcanics and the lower carbonate aquifer are well-connected hydraulically and together may represent the regional aquifer system at well p#1. The present day upward flux from the regional aquifer through the lower volcanic confining units is unknown but is probably small because there are very distinct differences in groundwater chemistry between the lower carbonate aquifer and the lower volcanic aquifer. The flux may have been larger in the past given the existence of a highly calcified ash-flow tuff at depths of 1172 to 1205 m (Carr, et al., 1986, p. 73). One zone within this tuff reportedly contained more than 50 percent calcite.

Perhaps the key observation to be made about vertical hydraulic gradients at YM is that there appear to be widespread areas where there is a strong upward hydraulic potential from the lower volcanic confining units to the lower volcanic aquifer system. This upward potential would inhibit the migration of radionuclides downward from the volcanics to the regional aquifer. Wells that show this trend include USW H-1, USW H-3, and UE-25 p#1. A strong upward gradient may also exist in the vicinity of well J-11 in eastern Jackass Flats. This is the only nearby well completed in the volcanics that bears the hydrochemical signature of the deep carbonate aquifer (see data in Oliver and Root, 1997). Further investigations, such as the drilling program by Nye County (Bradshaw, 1998), would be needed to show whether the upward hydraulic potential near YM persists southeasterly and southward in downgradient areas.

4.5.2.7 Perched Zones

A number of perched zones have been found at YM (Burger and Scofield, 1994; Yang, et al., 1996a; Wu, et al., 1997; Striffler, et al., 1996). Perched zones have been found near the basal vitrophyre of the Topopah Spring Tuff and within the Calico Hills Formation. As of June 1996, all perched water has been found below the repository horizon. Boreholes USW UZ-1 and USW UZ-14, which are on the same drilling pad, encountered a perched zone. The perched water is 190 m above the water table, and the zone was extensive enough to be pump tested at a rate of 0.9 gallons per minute (gpm) for 67 hours (hr), producing a total of 6,000 gallons (gal). It has been estimated that this perched water zone is much more extensive than originally thought, with an approximate volume of 30 million gal. Perched water was also found in USW SD-9, which appeared to be coming from just above the basal vitrophyre of the Topopah Spring. This perched water is 120 m above the water table. Perched water has also been detected within the Calico Hills Tuffs. Boreholes that encountered perched water within the Calico Hills Tuffs include USW SD-7 and USW NRG-7/7a. The perched zone encountered by SD-7 was extensive enough to be pump tested at a rate of 3.3 gpm for 30 hr, producing a total of 12,000 gal.

Striffler, et al. (1996) summarize characteristics and occurrences of perched water at YM. The perched water hydrologic and chemical analysis are described in several reports (Kwicklis, et al., 1996; Bodvarsson, et al., 1997; and Robinson, et al., 1997). As of 1995 perched water had been found in five wells: NRG-7A, SD-9, UZ-14, SD-7, and UZ-1. Perched water in all five wells was found at least 100 m above the water table. The presence of perched water may indicate that recharge through the unsaturated zone is at least as great as the hydraulic conductivity of the confining layer that causes the perching, barring significant lateral flow of groundwater. In four of the five wells, perched water is associated with the basal units of the Topopah Spring tuffs, or with the uppermost portions of the underlying Calico Hills tuff. However, in SD-7 the perching is associated with bedded tuffs near the base of the Calico Hills.
The perched water zones were generally in fractured tuffs with low permeability matrix overlying less fractured rock units with more permeable matrix. Boreholes SD-7 and UZ-14/UZ-1 are located near faults that may tend to restrict horizontal flow, allowing perched water to accumulate in significant amounts (Striffler, et al., 1996). Striffler, et al. (1996, p. 6) reported the results of pumping tests:

> Pumping tests of the perched water were performed at UZ-14 and SD-7 to determine hydraulic conductivity, and to attempt to quantify the size of the bodies of water. Several feet of residual drawdown after the tests at SD-7 verify that the aquifer is a discrete perched water body, whereas UZ-14 recovered completely and indicates a more extensive water body. The quick rate of recovery at SD-7, relative to pumping tests performed at UZ-14, indicate that the hydraulic conductivity of the SD-7 aquifer is much higher.

Czarnecki, et al. (1997) discussed the potential for perched water occurring in boreholes G-2, WT#6, and UE-29a#2. All three of these boreholes are located within or north of the so-called large hydraulic gradient. Hydrologic testing of the Calico Hills interval in G-2 during 1996 resulted in a residual drawdown of 0.5 m after 186 days of recovery, an amount considered large enough to suggest that the pumped interval may represent perched water. The hydraulic head in this well has also declined 12 m since 1981. No hydraulic testing has been done at WT#6, but if a perched zone exists in G-2, then the much shallower WT#6 could similarly monitor a perched zone. However, unlike other perched water locations, geophysical logs for this well indicate fully saturated conditions below the reported water level elevation of 1034.5 m (Czarnecki, et al., 1996). Water levels in UE-29a#2 and the adjacent, shallower UE-29a#1 are periodically affected by streamflow events in Fortymile Wash and Pah Canyon Wash, resulting in abrupt rises in groundwater levels which slowly decline over periods of years. These periodic changes could mask long-term declines that could be caused by perched water draining downward to deeper intervals. Localized recharge can account for the observations in these wells, but perched water may also be present.

The NRC staff is aware that perched water was found in 1998 during the drilling of well WT-24, located just southeast of well G-2. This well is being drilled to evaluate the so-called large hydraulic gradient (see previous section).

Other possible occurrences of perched water have been documented. Damp or wet core was obtained various depths during the drilling of well SD-12 (Rautman and Engstrom, 1996). These cores represen zones within the Tiva Canyon Tuff and from several intervals in the Topopah Spring and Calico Hills. However, no free fluid was discovered in the borehole until the regional saturated zone was encountered. Damp features were also observed in Niches 3566 and 3650, especially the former which is located near the Sundance Fault zone (Wang, et al., 1997), although production of free water was not reported. One of the conclusions reached by Striffler, et al. (1996, p. 27) is that "...perched water probably exists near the base of the Topopah Spring Tuff virtually everywhere in the vicinity of the ESF."

4.5.2.8 Hydraulic Properties of Aquifers

The hydraulic properties of formations in the area of YM can vary greatly from one location to another. The following table provides a summary of the range of the hydraulic properties (hydraulic conductivity, permeability, and porosity) of selected aquifers and confining units that may be important to the repository performance. Additional details about hydraulic properties are given in the following sections that discuss single-well and multi-well hydrologic tests.

Table 9. Estimated range of hydraulic properties of major aquifers and confining units (Czarnecki, et al., 1997).

Hydrogeologic Unit	Hydraulic Conductivity (m/s)		Permeability (m^2)		Porosity (%)	
	High	Low	High	Low	High	Low
Valley Fill Aquifer	6.0×10^{-5}	9.2×10^{-7}	6.0×10^{-12}	9.2×10^{-14}	23	12
Valley Fill Confining Unit	3.9×10^{-5}	1.2×10^{-10}	3.9×10^{-12}	1.2×10^{-17}	66	29
Upper Volcanic Aquifer	3.2×10^{-4}	9.6×10^{-12}	1.8×10^{-13}	0	54.4	1.4
Upper Volcanic Confining Unit	4.6×10^{-5}	2.9×10^{-11}	3.9×10^{-14}	3.0×10^{-18}	50.3	12.3
Middle Volcanic Aquifer	7×10^{-4}	9.6×10^{-12}	4.5×10^{-14}	0	43.6	1.8
Middle Confining Unit	1.3×10^{-6}	6.4×10^{-11}	2.6×10^{-16}	0	27.4	9.2?
Lower Volcanic Aquifer	NA	NA	NA	NA	38.4	8.1
Lower Volcanic Confining Unit	1.7×10^{-8}	1.7×10^{-8}	4.0×10^{-16}	8.3×10^{-18}	17.0	8.8

Upper Carbonate Aquifer	4.6 × 10^{-5}	5.8 × 10^{-9}	4.6 × 10^{-12}	5.8 × 10^{-16}	16.0	0.05
Upper Clastic Confining Unit	NA	NA	NA	NA	15.1	0.06
Lower Carbonate Aquifer	2.6 × 10^{-3}	5.8 × 10^{-9}	5.4 × 10^{-15}	1.1 × 10^{-18}	16.0	0
Lower Clastic Confining Unit	4.6 × 10^{-6}	2.3 × 10^{-13}	5.5 × 10^{-19}	3.9 × 10^{-20}	7.0	0.001

- **Single-Well Hydraulic Tests**

Most saturated zone hydrologic testing at YM has been done in single boreholes. The long-term multiwell test at the C-well complex is a notable exception. Tests have focused mainly on the Tertiary volcanic section because none of the overlying alluvial deposits are saturated near YM. The valley fill becomes saturated somewhere south of wells J-12 and JF-3 at locations yet to be determined by DOE. Because of the easterly dip of strata at YM, the Tiva Canyon and Topopah Spring Tuffs, which are unsaturated at the site, become saturated to the east in Jackass Flats. The Topopah Spring Tuff and most of the Tiva Canyon Tuff are also saturated westward in Crater Flat at well USW VH-1 (Thordarson and Howells, 1987). Hydraulic data for the Paleozoic carbonate aquifer near YM are based on tests in a single borehole, UE-25p#1.

Flow surveys in YM wells show that production usually occurs from a few discrete permeable intervals that constitute a small percentage of the total thickness of rocks penetrated. These are locations where the most transmissive water-conducting fractures intersect the boreholes. A typical well at YM has more than 50 percent of the total inflow occurring over a section less than 100 m thick. Zones of enhanced inflow have been detected using borehole flow surveys in combination with geophysical logs and aquifer tests. Benson, et al. (1983, Figure 11) and Geldon (1993, Figure 27) used normalized-depth diagrams to visually portray the zones within wells that provide most of the water production. Figure 5 of Geldon, et al. (1997) depicts transmissive intervals for the C-wells. Geldon (1993, Figures 31 to 33) shows these transmissive intervals for each of the C-wells as determined from temperature and tracejector data, along with the relative percentage of total inflow that occurs at various depths. For example, in well c#1 64 percent of the inflow occurs over a 30-m section of the Bullfrog Member of the Crater Flat Tuff. In well c#2 93 percent of the inflow occurs from the central part of the Bullfrog Member, a zone only about 25 m thick, and in well c#3 a 75-m section of the Bullfrog Member produces about 75 percent of the inflow. Similar borehole-flow surveys have been documented for other wells at the site, as shown below.

Well	References
UE-25b#1	Lobmeyer, et al., 1983, Figure 8
USW H-1	Rush, et al., 1984, Figures 4-5
USW H-3	Thordarson, et al., 1985, Figure 3
USW H-4	Whitfield, et al., 1984, Figure 11
USW H-5	Bentley, et al., 1983, Figures 7-8

USW H-6	Craig, et al., 1983, Figure 7
UE-25p#1	Craig and Johnson, 1984, Figures 9-11
	Craig and Robison, 1984, Figures 11-13
UE-29a#2	Waddell, 1985, Figures 8 and 10

The borehole-flow surveys provide information about the spacing of major flow zones at YM, at least in the vertical direction. They tend to be vertically separated by tens to hundreds of meters. Not all fractures observed in wells in the saturated zone produce significant amounts of water. A potential bias is introduced by the fact that vertical boreholes will encounter few vertical fractures and will intersect non-vertical fractures. Analysis of data from the ESF suggests that this bias may not be very significant, at least for the Topopah Spring Tuff. Drift-scale air-injection tests performed in the ESF show that the fracture network generally behaves as a continuum, with the mean fracture permeability generally increasing with the scale of the system (Sonnenthal, et al., 1997a, p. 7-26, citing a personal communication with Y. Tsang). Fracture spacings were found to increase as fracture lengths increased. Fractures in the range from 0.3 to 1.0 m long had a typical spacing of 0.5 m, whereas fractures in the range from 10 to 34 m had spacings of about 21 m. Although the fracture network within the Topopah Spring may be geometrically well connected at the drift scale, it is not clear that the hydraulic connectivity would be as strong at the 100-m scale.

The YM Site Characterization Plan (DOE, 1988, Table 3-27) summarizes preliminary hydrologic characteristics of major stratigraphic units in the saturated zone. The data are derived from various types of tests, including drawdown, recovery, packer injection, and slug tests. Data were summarized for seven stratigraphic intervals: Topopah Spring, Calico Hills, Prow Pass, Bullfrog, Tram, Lithic Ridge and older tuffs, and the Paleozoic Lone Mountain Dolomite and Roberts Mountain Formation. Portions of SCP Table 3-27 are reproduced in the following table for the convenience of the reader. However, the reader should refer to the original table for cited references and discussion about the data.

Table 10. Preliminary Summary of Hydrologic Characteristics of Major Stratigraphic Units Nea Yucca Mountain (after DOE, 1988, Table 3-27).

Stratigraphic unit	Typical character	Saturated thickness (m)	Trans-missivity (m^2/day)	Average hydraulic conduct-ivity (m/d)	Well name
Topopah Spring Member	Moderately to densely welded tuff	167	120	0.7	J-13
Calico Hills	Zeolitized, non-welded tuff, vitric tuff	148	82	0.5	UE-25b#1
Composite Calico Hills and Crater Flat Tuff	Nonwelded to densely welded and bedded tuff	< 500	28 (c)	< 0.06	UE-25c#1 UE-25c#3

Prow Pass Member (Crater Flat Tuff)	Nonwelded to moderately welded tuff	116 135 174 150 111	167 150 36-142 65 14	1.4 1.1 0.2-0.8 0.4 0.1	USW H-1 USW H-1 USW H-4 UE-25b#1 UE-25p#1
Bullfrog Member (Crater Flat Tuff)	Nonwelded to densely welded tuff	125 119 159 132	0.8 70-276 65 7	6E-3 0.6-2.3 0.4 5E-2	USW H-1 USW H-4 UE-25b#1 UE-25p#1
Tram Member	Nonwelded to moderately welded ash-flow and bedded tuff	284 354 352 183	2E-3 0.7 70-276 3.3	7E-6 2E-3 0.2-0.8 2E-2	USW H-1 USW H-3 USW H-4 UE-25p#1
Lithic Ridge tuff and older tuffs	Partially welded ash-fall tuffs	594 110 371	1E-3 0.1 >10	2E-6 1E-3 >3E-2	USW H-1 USW H-3 UE-25p#1
Lone Mt. Dolomite and Roberts Fm.	Carbonate rocks of Paleozoic age	>561	108	0.2	UE-25p#1

Estimates of hydraulic conductivity and transmissivity for major hydrostratigraphic units at YM were provided by Luckey, et al. (1996, Tables 4 and 5). Their tables are reproduced below as Tables 11 and 12 for the convenience of the reader; please refer to their report for additional discussion about these parameters. The information for well JF-3 has been added to the tables by the NRC staff.

Table 11. Estimated apparent hydraulic conductivities (m/day) obtained from single-borehole tests near YM (after Luckey, et al., 1996, Table 4).

Borehole Name	Upper volcanic aquifer	Upper volcanic confining unit	Lower volcanic aquifer	Lower volcanic confining unit	Carbon-ate aquifer	Reference
USW H-1	--	--	4.3E-1	5.5E-6	--	Rush, et al. (1984)
USW H-3	--	--	< 3.7E-3	< 3.2E-3	--	Thordarson, et al. (1985)
USW H-4	--	--	4.3E-1	1.1E-1	--	Whitfield, et al. (1985)
USW H-5	--	--	6.0E-1	--	--	Robison & Craig (1991)

USW H-6	--	--	8.0E-1	1.8E-4	--	Craig & Reed (1991)
USW G-4	--	--	1.4	--	--	Lobmeyer (1986)
UE-25 b#1	--	2.6E-1	4.9E-1	< 1.0E-4	--	Lahoud et al. (1984); Moench (1984)
C-wells complex	--	2.0E-2	7.0E-2	--	--	Luckey, et al., 1996, citing Geldon (in press)
UE-25 p#1	--	--	3.3E-2	5.8E-3	1.9E-1	Craig & Robison (1984)
J-13	1.0	1.2E-1[a]	7.6E-3	2.6E-3[b]	--	Thordarson (1983)
JF-3	100-110	--	--	--	--	Plume & LaCamera (1995)

(a) Average from two tests
(b) Includes part of the lower volcanic aquifer

Table 12. Estimated transmissivity values (m^2/day) obtained from single-borehole aquifer tests near YM (Luckey et al., 1996, Table 5).

Borehole Name	Upper volcanic aquifer	Upper volcanic confining unit	Lower volcanic aquifer	Lower volcanic confining unit	Carbon-ate aquifer	Reference
USW H-1	--	--	152	5.0E-3	--	Rush, et al. (1984)
USW H-3	--	--	< 1.1	< 4.1E-1	--	Thordarson, et al. (1985)
USW H-4	--	--	178	23	--	Whitfield, et al. (1985)
USW H-5	--	--	35	--	--	Robison & Craig (1991)
USW H-6	--	--	229	6.3E-2	--	Craig & Reed (1991)
USW G-4	--	--	589[a]	--	--	Lobmeyer (1986)
UE-25 b#1	--	26	297	< 3.0E-3	--	Lahoud, et al. (1984); Moench (1984)
C-wells complex	--	2.0	21	--	--	Luckey, et al., 1996, citing Geldon (in press)
UE-25 p#1	--	--	15	2.0	118	Craig & Robison (1984)
J-13	120	3.7[b]	1.4	6.3E-1[c]	--	Thordarson (1983)
JF-3	1.3E4 1.5E4	--	--	--	--	Plume & LaCamera (1995)

(a) Average from four tests.
(b) Average from two tests
(c) Includes part of the lower volcanic aquifer

Wells J-12 and J-13 are presently used to supply the water needs for the YM Site Characterization Program and other activities at the Nevada Test Site. Combined pumpage at the two wells was about 160 acre-ft in 1990 and 1991, 120 acre-ft in 1992, and 200 acre-ft in 1993 (Plume and LaCamera, 1996). Information about the drilling and testing of well J-13 was provided by Thordarson (1983). The well penetrated 132.5 m of valley fill before penetrating Tiva Canyon tuffs. The altitude of the static water le was reported at 729 m. About 150 m of tuffs (Tiva and Topopah Spring) are unsaturated at J-13. A sta water level depth of 282.2 m was measured for tuff units above the middle of the Bullfrog Member of the Crater Flat tuffs (above a depth of 645.6 m). Below a depth of 772.7 m (Tram and Lithic Ridge tuffs), the static water level was more than a meter deeper, indicating the possible existence of a small downward hydraulic gradient. One pumping test at J-13 lasted 5500 minutes at a withdrawal rate of 44 L/s. Altogether, 15.2 million liters (12.3 acre-ft) were pumped from a dual test interval that included the Topopah, Tram, and Lithic Ridge tuffs. A semi-log plot of drawdown vs. time for this test (Thordarson, 1983, Fig. 7) suggests the influence of one or more barrier boundaries between 400 minutes and the end of the test.

Young (1972) reported that wells J-13 and J-12 were pumped extensively from 1962 to 1967 to provide water supplies for the nearby Nuclear Rocket Development Station. Based on an estimated combined withdrawal rate of 350 gpm (565 acre-ft/yr)(22 L/s), about 900 million gallons (2800 acre-ft) of water were extracted during the five-year period. The resulting water level decline at J-13 was about two feet. Young (1972) estimated the specific yield of the aquifer to be at least five percent. Given that the Topopah Spring aquifer is probably unconfined at J-12 and J-13, this value provides an estimate of drainable or effective porosity for the fractured tuffs. It is clear that wells J-13 and J-12 are hydraulically connected, as demonstrated by a three-day pumping test at J-12 (Thordarson, 1983). During February 15-18, 1964 well J-12 was pumped at a rate of 22.7 L/s, resulting in an apparent drawdown of 0.37 m at J-13.

Well JF-3 is located 1 km south of well J-12. It penetrated 146 m of valley fill and 249 m of volcanic tuffs. The water table occurs below the valley fill in tuffs, at an elevation of 728 m. The top 70-m section of the Topopah Spring is unsaturated at this location. The well was terminated near the base of the Topopah Spring Tuff. The transmissivity of the aquifer was estimated at 13,000-14,800 m^2/d. Based on a saturated thickness of 130 m, the hydraulic conductivity is 100-112 m/d (Plume and LaCamera, 1995). These valu exceed by two orders of magnitude the estimates made at well J-13, and are the highest values measu in single-well testing at the YM site. The inferred hydraulic conductivity of 100 m/d (Plume and LaCamera, 1995) exceeds all other single-well estimates by a factor of 100 or more. Using the horizontal hydraulic gradient of 1E-4 measured from well J-13 to J-12, a Darcy flux of 3.6 m/yr is computed. Wells J-12 and JF-3 have the lowest hydraulic heads in the site vicinity. Groundwater flow apparently converges on these well locations from the east, north, and west to be conducted southward along transmissive zones that underlie Fortymile Wash. DOE has not yet characterized saturated zone flow paths in tuff and valley fill south of well JF-3.

Geldon (1994) noted that multiple-well, constant-flux tests at the C-wells complex show that single-well injection and withdrawal tests are not reliable indicators of hydrologic properties at the site scale. Cross-hole tests of composite intervals in the wells generally indicate values of transmissivity and hydraulic conductivity that are about two orders of magnitude larger than obtained from single-well tests. This was interpreted (Geldon, 1994, p. 68) as "...an effect of encompassing more conduits for ground-water flow, such as faults or fracture zones, as a larger volume of aquifer is investigated."

The staff has examined data from wells USW H-4, UE-25c#1 and c#2. These wells were subjected to single-well tests and have also served as observation wells during the long-duration pumping test at UE25c#3. Single-well tests at H-4 yielded a transmissivity of about 180 m^2/day for the lower volcanic aquifer. However, a greater transmissivity of 650 m^2/day was obtained for the monitored interval in H-4 during the pumping test at c#3 (Geldon, et al., 1997, p. 37). Likewise, single-well tests in the C-wells complex provided a transmissivity estimate of 21 m^2/day for the lower volcanic aquifer (Luckey, et al., 1996). When used as observation wells, c#1 and c#2 yielded higher transmissivities of 1900 to 2700 m^2/day (Geldon, et al., 1997, p. 37).

Overall, the single-well testing has demonstrated that the Crater Flat Tuffs constitute an important aquifer zone at the YM site. The Topopah Spring Tuff is also an important aquifer where it is saturated east of YM. Based on the conclusions of Geldon, et al. (1997), single-well tests should be considered to provide low-range estimates of transmissivity and hydraulic conductivity. The short duration of most single-well tests makes it likely that the results reflect localized conditions in the fracture matrix. Long-term tests, like the C-wells test of May 1996 to March 1997, at a scale of several km with multiple observation wells, are far superior in helping to understand site-scale hydrologic processes. They provide more representative estimates of bulk hydrologic properties, demonstrate hydraulic connectivity over long distances, and give evidence of the influence of recharge or barrier boundaries. The long-term C-wells test demonstrated hydraulic connectivity between several wells, including H-4 and WT-3, a distance of over 5 km downgradient from YM, and appear to have detected one or more recharge boundaries.

- **Multiple Well Hydraulic Tests**

SZ hydraulic data for the YM region include both single well and multiple well pumping tests. It is believed that single-hole pumping tests may not sample the larger interconnectivity of transmissive zones and may underestimate the large-scale hydraulic conductivity of the volcanic aquifer (Geomatrix, 1998). For this reason, heavy reliance is placed on results of the multiple-hole pumping tests at the C-wells complex.

Geldon (1996) reports rock hydraulic properties and results from twenty-six fluid injection tests and five pumping tests conducted in the C-wells complex in 1983 and 1984. Borehole surveys indicate that, although near-vertical, south-striking, west-dipping fractures are pervasive in rocks penetrated by the C-wells, the fractures in 11 identified transmissive intervals are diversely oriented. The hydraulic tests indicated that from the water table, at a depth of 400 m, to about 520 m, transmissive intervals are unconfined; between 550 to 820 m, transmissive intervals responded as non-leaky confined aquifers; below 820 m, transmissive intervals were interpreted to be recharged from nearby faults that have offset and brecciated the rocks in these intervals. For the entire thickness of rocks penetrated by these holes, estimates of transmissivity from cross-hole pumping and injection ranged between 1900 to 3300 m^2/d; storativity estimates were between 0.002 and 0.004.

Although 11 transmissive intervals were identified, the boundaries separating one transmissive interval from another are somewhat nebulous, and some transmissive intervals are apparently connected to others. Additionally, many of the intervals that are productive in one of the C-wells are not very productive in the others. For these reasons, Geldon (1996) divides the saturated zone at the C-wells into four productive zones that are separated by three confining units. These productive zones are treated as distinct quasi-horizontal aquifers for purposes of evaluating C-wells hydraulic data. Most of these productive zones are associated with intervals where rock is moderately to very fractured; these fractures are predominantly steep-dipping and strike north to northeast. The majority of water production in all three C-wells comes from what is termed the "Bullfrog Aquifer" by Geldon (1996). In wells c#1 and c#3 one-fourth of production in each comes from fractures in the "Tram Aquifer" that are associated with the Paintbrush/Midway Valley Fault[2].

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[2]It is not clear whether the fault intersected by the C-wells is the Paintbrush Fault or the Midway Valley Fault. In this report we simply refer to the Paintbrush/Midway Valley Fault.

More recently, Geldon, et al. (1997) reported results of three multiple-well hydraulic tests conducted a' C-wells complex between 1995 and 1997. During all three tests, well c#3 was pumped. All intervals we pumped in the first test (no packers), while only the Bullfrog-Tram and Lower Bullfrog intervals were pumped during the second and third tests, respectively. Six packed-off intervals were monitored in wells c#1 and c#2 during all three tests. An important result is that all monitored intervals responded to pumping, regardless of which interval was being pumped. This is interpreted to indicate that fractures beyond the borehole walls are so interconnected that packers within the C-wells complex do not isolate the interval being pumped from other transmissive intervals within the volume of aquifer stressed by the pumping. This finding is in contrast to the previous pump tests at the C-wells (Geldon, 1996) in which some transmissive intervals were classified as confined aquifers. The results of these more recent tests clearly show that transmissive intervals at the C-wells are not confined. Estimates of local transmissivity and storativity in these C-well tests are consistent with those determined in the earlier tests (Geldon, 1996).

Geldon, et al. (1997, Background, p. 11) observed that "Despite having dual permeability, rock within about 3 km of the C-hole complex consistently responds to pumping tests as an equivalent porous medium." This observation is consistent with data from site boreholes that show major producing zones to be separated by tens to hundreds of meters. Geldon (1997, Hydraulic Tests, p. 25) also cautioned that "In a different structural setting, the Lower Bullfrog, Calico Hills, and other intervals of the Miocene tuffaceous rocks would be expected to have different hydraulic properties than indicated at the C-hole complex."

Aquifer transmissivity estimates on the scale of several kilometers were obtained during the long-term multiple-well test conducted between May 8, 1996 and March 26, 1997. Four wells completed in the Miocene tuffaceous aquifer (USW H-4, UE-25 ONC#1, UE-25 WT#14, UE-25 WT#3) and one well completed in the underlying Paleozoic aquifer (UE 25 p#1) were monitored to evaluate effects of scale, heterogeneity, and connection between the volcanic aquifer and the carbonate aquifer. Measurable drawdown was observed in all four of the wells completed in the Miocene tuffaceous aquifer; transmissi estimates from these four wells range from 650 to 2600 m^2/d; storativity estimates fall in a narrow rang from 0.001 to 0.002 (dimensionless). Two observation wells (USW H-4, and UE-25 WT#14) were interpreted to be influenced by recharge boundaries — presumably originating from nearby faults. The NRC staff note that other wells also responded to the C-wells test. Only monthly water levels are available, but these can be used to obtain crude T estimates. The staff estimate a T of 400 m^2/d for well UE-25b#1 (Crater Flat tuffs) and a T of 300 m^2/d for well UE-25 WT#4 (Calico Hills Fm.). We note a pattern of decreasing T away from Fortymile Wash toward the northwest, with highest values along the wash and lower values at H-4, WT#4, and b1.

During the long-term test, the drawdown response in well ONC#1 was delayed from about 2,000 to 5,000 minutes, and then the drawdown response resumed. This delay was interpreted as being due to delayed release of water from storage in matrix blocks. Aquifer properties were then evaluated based on a type-curve for a confined fissure-block aquifer (Streltsova-Adams, 1978). However, review of the time-drawdown plots for H-4 and c#1 show similar delays in drawdown response during the same period of time. Thus, the delay in drawdown response in ONC#1 could have been due to some regional event rather than delayed release from the rock matrix.

The drawdown measured in the observation wells during the long-term pumping test was used by Geldon, et al. (1997) to infer horizontal anisotropy due to what is believed to be a northwest trending zone of discontinuous faults that extends from Bow Ridge to Antler Wash. It should be noted, however, that this is only one possible interpretation of the results of the multiple-well aquifer tests. In the recent Saturated Zone Expert Elicitation (Geomatrix, 1998), C. F. Tsang concluded that data are too sparse and uncertain to attach much significance to the interpreted drawdown ellipse from the C-wells tests. Additionally, the cone of depression interpolated by Geldon, et al. (1997) is not supported by the transmissivity estimates obtained from the same wells. That is, the transmissivity estimates for wells ONC#1 and H-4, which are oriented northwest with respect to the pumped well, were significantly lower than those for wells WT#14 and WT#3 which are oriented northeast and southeast, respectively. Thus, if transmissivity estimates are accurate, it is not likely that a northwest-trending zone of preferential flow exists.

Hydraulic isolation of the Paleozoic carbonate aquifer was neither confirmed nor refuted by the C-wells tests (Geldon, et al., 1997). However, during the long-term pumping test no drawdown in the carbonate aquifer was observed that could be attributed to pumping at the C-wells. It should be noted that large differences in groundwater chemistry (Oliver and Root, 1997) between the carbonate aquifer system and the Crater Flat tuffs suggest that upward fluxes are relatively small compared to lateral fluxes within the tuffs.

Although much has been learned from the multiple-well pumping tests already conducted at the C-wells, further investigation of a representative elementary volume (REV) is clearly necessary to complete the characterization of hydrogeologic conditions there and at other locations. According to Streltsova (1988, p. 361), "The mean permeability varies with sample size. In a uniformly fractured rock, as in a medium with intergranular porosity, permeability is not dependent on the scale of observation as long as the sample's dimensions are large enough to include a statistical REV of the fracture network (or network of intergranular porosity). The rock volume at which the mean effective permeability of a fractured reservoir becomes representative can be found by determining the permeability of ever-increasing volumes of rock until the permeability value no longer changes significantly with a further increase in the rock volume. Such a representative elementary volume cannot necessarily be found for a rock with discontinuous or localized network of fractures if the fracture meshes lack uniformity and continue to change with further increases in the volume of the rock. Well tests with different flow durations will result in different permeability values for such a rock."

Snow (1972, p. G1-1), summarizing numerous investigations of fractured media, pointed out that the description of fractures "...can never be complete. Fractures are neither parallel, uniform, plane, smooth, regularly spaced nor uninterrupted." Because of this, fracture "permeability will remain empirical in nature."

Given the difficulties in determination of an REV for fractured media, simulations using fracture continuum approaches inherently will have severe challenges in estimating effective permeabilities appropriate for the sizes of grids or elements in the model. Properties measured on the same scale as model grid sizes may only have relevance to the measurement locations and not elsewhere in the model domain. This will also have implications for the relationship of calibrated parameter values from models of differing discretizations and domains.

Reimus, et al. (1998) propose additional hydraulic testing at three locations, including: another long-term pumping test with the inclusion of additional observation wells; expanding the C-wells complex to include 5 new wells; deepening the existing C-wells to completely penetrate the Paintbrush/Midway Valley Fault system; and conducting pumping and tracer tests specifically aimed at elucidating properties of the Paintbrush/Midway Valley Fault (Reimus, et al., 1998). However, this draft testing strategy has not yet been approved by DOE and it is presently unclear how many of these proposed tests will be conducted.

4.5.2.9 Inferences About Groundwater Fluxes from Inter-Well Pumping Tests

The long-term multiple well pumping test conducted at the C-wells complex from May 8, 1996 to March 26, 1997 has yielded hydraulic conductivity and transmissivity estimates for a scale of about 1 to 4 km around the C-wells (Geldon, et al., 1997). These estimated values have influenced the selection of aquifer parameters in groundwater flow models of the YM region (e.g., Czarnecki, et al., 1997; Cohen, et al., 1997).

Based on the transmissivity estimates from the distant observation wells (USW H-4, UE-25 ONC#1, UE-25 WT#14, UE-25 WT#3) it is possible to estimate average groundwater fluxes within about 2 to 4 km from the C-wells. Table 13 provides estimates of local groundwater fluxes for the six observation wells that were monitored during the long-term pumping test at the C-wells complex. The flux estimates are based on a hydraulic gradient in the area of the C-wells of 0.00035, estimated from the same sub-site-scale water table map used by Cohen, et al. (1997). However, several caveats to these estimates should be noted.

First, as previously mentioned, hydrogeologic characterization in the vicinity of the C-wells is far from complete. As additional data is gathered, analyses are performed, and conceptual models are modified, groundwater flux estimates are subject to change. Second, transmissivity values estimated at observation wells are direction-specific. That is, they represent transmissivity in the direction the groundwater gradient induced by the pumping test. This is not necessarily the direction of the natural groundwater gradient. Thus, in the case of horizontal anisotropy, transmissivity estimated for observation wells during a pumping test can differ significantly from transmissivity in the direction of the natural gradient. Third, the pumped well and observation wells do not fully penetrate the aquifer system down to the lower confining layer (Lithic Ridge tuffs) that separates the tuff aquifer system from the Paleozoic carbonate aquifer system. Thus, hydraulic conductivity estimates (transmissivity divided by transmissive thickness) of Geldon, et al. (1997) may not be based on the true transmissive thickness of the tuff aquifer. Fourth, hydraulic conductivity estimates of Geldon, et al. (1997) are based on the assumption that transmissive intervals extend away from the wells horizontally. However, fracture and fault orientations in the vicinity of the C-wells are predominantly steep-dipping (i.e., not horizontal) (Geldon, 1996). Thus, estimates of transmissive thickness, which are used to calculate hydraulic conductivity, may not be accurate beyond the vicinity of the well-bore. For these reasons the flux values provided in the following table must be considered as rough estimates.

Table 13. Groundwater flux estimates at observation wells.

Well I.D.	UE-25c#1	UE-25c#2	ONC#1	USW H-4	UE-25 WT#14	UE-25 WT#3
Trans-missivity (m^2/d) [a]	2400	2500	1000	650	1300	2600
Volume Flux (m^3/d/m) [b]	0.85	0.88	0.36	0.23	0.46	0.91
Estimated Transmissive Thickness (m) [a]	238	144	192	276	46 [c]	49
Estimated Hydraulic Conductivity (m/d) [a]	10	18	6.0	2.4	27 [c]	55
Estimated 1-D Groundwater Flux (m/d)	0.004	0.006	0.002	0.008	0.009	0.019

[a] values obtained from Geldon, et al. (1997).
[b] volume flux represents flow per unit length normal to flow direction.
[c] transmissive thickness assumed equal to saturated penetration depth of well.

At present, confidence in these flux estimates in not high, but they represent the current "best guess" and provide an approximate order-of-magnitude estimate of the volume of water moving beneath the vicinity of the C-wells. The volume-flux estimates can be considered more reliable than the 1D groundwater flux estimates because they do not include the additional uncertainty inherent in the estimated transmissive thickness. One may also try to postulate groundwater velocity from the 1D flux estimates (flux divided by effective porosity), however, there is a great deal of uncertainty regarding effective porosity distributions beneath YM. Therefore, given the compounded uncertainty, estimates of groundwater velocity based on these data are unwarranted at present.

4.5.2.10 Inferences About Effective Porosity from Field Tests

An iodide tracer test in the Bullfrog-Tram interval of the C-wells complex yielded a flow porosity estimate of 0.086 (Geldon, et al., 1997). This estimate of flow (fracture) porosity is unusually high for a conceptual model of flow in fractures only. It should also be noted, however, that this estimate of flow porosity is based upon the "transmissive thickness" of the Bullfrog-Tram interval, which consists of two distinct productive zones. According to Carrera, et al. (1998), the effects of matrix diffusion could lead to this overly high estimate of effective porosity. If the flow porosity is averaged over the entire thickness of the tested interval, the effective porosity estimate is closer to about 0.03, which is still high but more in line with a conceptual model of flow in fractures only. Additionally, the tested interval contains a brecciated zone (perhaps associated with the nearby Midway Valley or Paintbrush faults) that one would expect to hav higher fracture porosity. Interpretation of subsequent tracer tests by Reimus and Turin (1997) did not produce estimates of flow porosity. Instead, a lumped parameter, which combined the effects of fracture aperture, matrix porosity, and diffusion rate, was used to fit a transport model to tracer data.

If the volcanic aquifer can be assumed to be unconfined, and if release of water from storage in rock matrix can be considered negligible, then a lower bound on the effective porosity can be estimated from the aquifer specific yield obtained from pumping tests. Young (1973) discussed an estimate of aquifer specific yield in the vicinity of wells J-12 and J-13. His estimate of greater than five percent specific yield was based on approximate groundwater withdrawals at these wells over a five year period, resulting in a drawdown at J-13 of two feet. Given unconfined conditions at J-12 and J-13, this value provides an estimate of drainable or effective porosity for the fractured tuffs which compares favorably with the range of values estimated from tracer tests at the C-wells complex.

Other estimates of effective porosity that may be pertinent to the YM Project have been obtained from tracer migration experiments by the Nevada Test Site (DOE, 1997b). The effective porosity of the Lower Carbonate Aquifer was determined to be 10% from the U.S. Geological Survey Amargosa Tracer Calibration Site and 0.064 - 0.5% from Wells C and C-1. The effective porosity of the Alluvial Aquifer was estimated to be 31 - 35% from the Cambric Site (U.S. DOE, 1997b).

The DOE is currently using a range of effective porosity in their PA model that is based on estimates made during the SZ expert elicitation (Geomatrix, 1998). Currently, the range of effective porosity proposed by the DOE is from 0.0001 to 0.2, with a log-triangular distribution and a mean value of 0.02[3]. The mean value of 0.02 is consistent with the previously mentioned observations in the C-wells complex tracer tests; the lower bound of this range is based on estimates for sparsely fractured rock, and the upper bound is based on the full matrix porosity in order to account for the possibility of rapid matrix diffusion. Ongoing tracer tests in the C-wells complex may help to shed additional light on this critical parameter. NRC staff are the early stages of conducting independent interpretations of C-well tracer studies.

4.5.2.11 Groundwater Chemistry

Groundwater chemistry can often be used to help understand the residence time of groundwater and general flow patterns. A good deal of effort has been undertaken by the DOE to characterize the water chemistry of the UZ, the SZ, and the perched water bodies in the YM vicinity. Summaries of UZ water chemistry are available in sources such as Yang, et al. (1996a, b) and Murphy and Pabalan (1994). Hydrochemistry in the SZ is summarized in several studies, including McKinley, et al. (1991), Perfect, et al. (1995), and Oliver and Root (1997). The tuffaceous aquifer groundwater is a dilute, oxidizing, sodium bicarbonate solution rich in dissolved silica. Waters in the Paleozoic carbonate aquifers tend to be higher in total dissolved solids, and are dominated by calcium, magnesium and aqueous carbonate dissolved from the carbonate rocks. Water from the alluvial aquifers can be extremely high in total dissolved solids where evaporation has concentrated readily dissolved salts in playa deposits, but typically reflect the chemistry of the alluvium and valley-fill materials. The UZ groundwaters differ substantially from SZ water, being more concentrated and dominated by calcium chloride or calcium sulfate in rocks nearer the ground surface (Yang, 1992; Yang, et al., 1993; 1996a,b). Aqueous silica concentrations in excess of cristobalite saturation are observed in tuffaceous aquifers at YM (Kerrisk, 1987; Murphy and Pabalan, 1994), and

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[3]Arnold. B. 1998. Sandia National Laboratory, personal communication .

higher concentrations are observed in the UZ (Yang, et al., 1996a). The high silica contents are generated by reaction of infiltrating meteoric water with siliceous volcanic glass (White, et al., 1980).

A number of perched zones have been found at YM (Burger and Scofield, 1994; Yang, et al., 1996a; Wu, et al., 1997; Striffler, et al., 1996). Water chemistry for the perched zones is reported in Yang, et al. (1996a, b) and Striffler, et al. (1996). Current information includes major and minor elements, stable isotopes (δD, $\delta^{18}O$, $\delta^{13}C$), and radiogenic isotopes (^{14}C, $^{87}Sr/^{86}Sr$, ^{3}H). These data indicate that major element chemistry of perched water is distinct from pore water chemistry in the UZ (Yang, et al., 1996a) and more similar to the water chemistry from the SZ (e.g., McKinley, et al., 1991; Perfect, et al., 1995). In general, the perched water is more dilute than the UZ pore waters, with generally lower chloride concentrations (about 4 to 8 mg/L, with one sample up to 15 mg/L). The lower chloride concentration suggests that the perched water forms with less interaction with the host rock, suggesting a fracture source. The differences in water chemistry also indicate that the perched water is not in equilibrium with the pore water. Detectable bomb pulse tritium indicates that there is at least some rapid recharge of the perched water zones, and radiogenic ^{14}C indicates a young residence time relative to groundwater and porewater of about 7,000 yr (Yang, et al., 1996a). Deuterium and ^{18}O stable isotope chemistry indicates that perched water is isotopically heavier than SZ water and close to the current YM local meteoric water line. The heavier ^{18}O values suggest that the perched water does not contain a significant portion of isotopically light water from the last ice age supporting an age of <10,000 yr, although this does not exclude older water with a similar isotopic signature. The similarity to the YM local meteoric water line suggests that recharge of the perched water bodies is through local precipitation, principally during winter storm events, rather than from the result of lateral groundwater flow from higher elevations to the north.

- **Inferences About the Groundwater Flow System from Geochemistry**

Regional Data

Winograd and Thordarson (1975) identified five distinct hydrochemical facies in the regional groundwater system: (i) the calcium magnesium bicarbonate facies typical of waters discharged from perched springs and regional springs in the carbonate units, (ii) the sodium potassium bicarbonate facies typical of waters in the tuff aquifer, (iii) the calcium magnesium sodium bicarbonate facies typical of waters found in the east-central Amargosa Desert and at Ash Meadows, (iv) the sodium sulfate bicarbonate facies typical of waters discharged at Furnace Creek Wash and Nevares Springs in Death Valley, and (v) a playa facies, high in TDS, typical of waters discharged by evapotranspiration at Alkali Flat (Franklin Lake Playa). Waters sampled from the lower carbonate aquifer at the NTS are of the calcium magnesium sodium bicarbonate type, which lead Winograd and Thordarson (1975) to infer downward flow of water from the tuffaceous units into the Paleozoic carbonate aquifer. Waters discharging from the lower carbonate aquifer along the Ash Meadows spring line are also of the calcium magnesium sodium bicarbonate type. Waters in Pahrump Valley that originate from recharge into carbonate rocks that crop out in the Spring Mountains are typical of the calcium magnesium bicarbonate facies. Because waters in Pahrump Valley contain less sodium and sulfate than those discharged at Ash Meadows, Winograd and Thordarson (1975) believed that little if any water flows from Pahrump Valley to the Ash Meadows area. Water from Indian Springs Valley, Three Lakes Valley, and northwest Las Vegas Valley has lower sodium, potassium, sulfate, and chloride concentrations than water from the NTS and Ash Meadows, suggesting that water does not flow eastward from the NTS (Winograd and Thordarson, 1975).

The chemistry of water sampled from wells tapping the valley-fill aquifer in the east-central Amargosa Desert is different from water sampled from other valley-fill aquifers in the NTS area. While these waters have a lower ionic strength, they belong to the same hydrochemical facies as water discharging at Ash Meadows, suggesting that water flows upward from the lower carbonate aquifer and is then diluted by locally recharged water (Winograd and Thordarson, 1975). The chemical quality of water in the central Amargosa Desert varies considerably from place to place, leading Winograd and Thordarson (1975) to infer that the water is derived from at least three sources. Water with the calcium magnesium sodium bicarbonate facies is probably derived from flow across the hydraulic barrier that causes the Ash Meadows spring line (Winograd and Thordarson, 1975). Water of the sodium potassium bicarbonate facies found southwest of Lathrop Wells is probably derived from Jackass Flats, and water in the west-central and northwestern portion of the Amargosa Desert is believed to come from Oasis Valley (Winograd and Thordarson, 1975).

Claassen (1985) contoured major element hydrochemistry south of YM and identified a southeast trending trough of low concentrations centered beneath the main drainage emerging from Fortymile Canyon into the central Amargosa Desert. Higher concentrations are associated with readily dissolved playa deposits, and lower total dissolved solids (TDS) are associated with coarser, more permeable deposits. Relative to the more dilute groundwaters in the trough, higher ionic concentrations (e.g., Na^+, Ca^{2+}) were measured for groundwater samples collected from the upstream reaches of the Amargosa River channel. Further downstream, below the confluence of the Fortymile Canyon and Amargosa River drainages, concentrations decrease again, suggesting a mixing (and dilution) of the two waters. The high Na^+ of Amargosa River groundwater samples from the upstream reaches suggest interaction with tuffaceous alluvium, while the elevated Ca^{2+} may be due either to mixing of alluvial waters with upwelling water from the underlying carbonate aquifers, or to interaction with carbonate alluvium at the base of the Funeral Mountains. Silica activity may buffer mineral dissolution and secondary mineral precipitation. Silica activities in the YM vicinity and Oasis Valley are relatively constant at 10^{-3}, between saturation with cristobalite and amorphous silica (Murphy and Pabalan, 1994).

Across the concentration gradient at the west side of the trough in the west-central Amargosa Desert, Claassen (1985) noted east-west trends of decreasing Ca/Na in groundwaters from the tuffaceous alluvium. Because the potentiometric contours indicate a southerly flow, Claassen (1985) considered it unlikely that significant east-west mixing of fluids occurred; this is supported by the lack of significant changes in Cl^- concentration across the gradient. Groundwater diffusion with calcite precipitation to reduce Ca^{2+} was also considered by Claassen (1985) to be inadequate to explain the trend, due to a lack of a corresponding decrease in calcite saturation. Claassen (1985) suggested that the observed trend was more likely to be due to continued evolution of the valley-fill water by interaction with tuffaceous alluvium and increased precipitation of clinoptilolite, but offered no mineralogical evidence to support this hypothesis.

Across the gradient on the east side of the trough, Schoff and Moore (1964) used increasing Ca/Na ratios in the east-central Amargosa Desert towards the Spring Mountains to indicate mixing between $Na^+ + K^+ + HCO_3^-$ tuffaceous waters from the north and $Ca^{2+} + Mg^{2+} + HCO_3^-$ groundwaters recharged in the carbonates in the Spring Mountains. Based on major ion hydrochemistry and a change in the potentiometric contours, Claassen (1985) proposed mixing across a region 5 to 10 km northeast of the Ash Meadows discharge zone. This region, west of Rock Valley Wash, occurs near the intersection of the Specter Range Thrust Fault and the Gravity Fault, and may represent a break in the hydrologic barrier separating the Ash Meadows spring line from the Amargosa Desert. Hydrochemical and temperature data (i.e., higher temperatures in the deeper carbonate waters) support upwelling and mixing of carbonate waters with groundwaters in valley fill. Using major element chemistry and presumably conserved ions such as Cl^-, Claassen (1985) was able to show that progressive mixing of dilute waters from the center of the trough with mixed valley-fill carbonate waters leaking across the Gravity Fault/Specter Thrust intersection could produce the observed hydrochemistry. Waters closer to the intersection were comprised of a larger component of carbonate water, while there is a rough increase in the tuff waters component from north to south. A comprehensive compilation of regional groundwater chemistry is presented by Perfect, et al. (1995).

With respect to deuterium and ^{18}O, the most depleted samples in the area come from wells in tuffaceous aquifers in Pahute Mesa (δD = -109 to -114 ‰ SMOW and $\delta^{18}O$ = -14.05 to -14.75 ‰ SMOW) (White and Chuma, 1987). This is due to the high elevation on Pahute Mesa, and are similar to values sampled from springs and wells in the headwaters of Oasis Valley. A downgradient enrichment in both deuterium and ^{18}O in the Oasis Valley basin is attributed to partial evaporation and progressive mixing between waters originating in Pahute Mesa, and heavier waters recharging locally at lower elevations in the Bullfrog Hills (δD = -102 ‰ and $\delta^{18}O$ = -13.30 to -13.42 ‰ SMOW). In general, the isotopic signatures for waters from Tertiary volcanic and Quaternary valley-fill aquifers overlap. All of the waters fall on a line that parallels the global meteoric water line (GMWL) of Craig (1961), but is shifted to slightly more depleted (~5 ‰) deuterium values. Assuming that the effects are due to differences in elevation, several authors infer that this shift is due to a cooler climate during the period of recharge (White and Chuma, 1987; Stuckless, et al., 1991).

Vicinity of YM

To date, the main hydrologic use of local groundwater chemistry is to identify zones of recharge at YM and along Fortymile Wash. Changes in water chemistry and temperature during pumping tests can also indicate whether water is being drawn upward from much greater depths. The major ion chemistry of the Paleozoic carbonate aquifer as seen in well UE-25 p#1 is distinctly different from that within the tuffs, with elevated calcium ion, bicarbonate, and sulfate concentrations. Well J-11 in eastern Jackass Flats is the only well in the Tertiary tuffs that produces groundwaters with a chemistry similar to that in well UE-25 p#1. This may be evidence that the deep carbonate aquifer underlies eastern Jackass Flats and that a significant amount of groundwater migrates upward from that aquifer to the overlying tuffs.

Major-ion chemistry from well USW H-3 provides evidence that a significant groundwater flux crosses the Solitario Canyon fault from west to east under the prevailing hydraulic gradient. This well occurs just east of the fault. Concentrations of Na^+ and Ca^{2+} in H-3 more closely resemble those found in wells west of the fault (H-6, WT-7, and WT-10) than those in wells to the east (data from Oliver and Root, 1997).

The waters collected from volcanic aquifers beneath YM are significantly heavier (δD = -100 to -108 ‰ and $\delta^{18}O$ = -13.4 to -14.2 ‰ SMOW) than waters collected at Pahute Mesa. They are still shifted to a line parallel to the GMWL, but the shift is slightly less than that observed by White and Chuma (1987) for Pahute Mesa and Oasis Valley. Stuckless, et al. (1991) uses this evidence to indicate that there is little communication between recharge at Pahute Mesa and the waters beneath YM. At least in part, this lack of communication may be an explanation for the discrepancy between calculated (δD = -110 ‰ SMOW) and measured (δD = -114 ‰ SMOW) values for Pahute Mesa in the deuterium calibrated mixing model of Feeney, et al. (1987).

Additional evidence related to mixing is in the isotopic character of groundwater samples from Fortymile Canyon. These samples are enriched in both deuterium and ^{18}O relative to all other water samples from the YM region (δD = -92.0 to -97.5 ‰ and $\delta^{18}O$ = -12.4 to -13.0 ‰ SMOW). From this evidence, it seems that there is little communication between the Tertiary aquifers beneath Fortymile Canyon and those to the west under YM (White and Chuma, 1987; Stuckless, et al., 1991). Groundwater from the upper reaches of

Fortymile Canyon is closer to the modern GMWL, suggesting local, relatively recent recharge, predominantly from summer precipitation at lower elevations. Claassen (1985) used this information to support inferred overland flow and recharge in Fortymile Canyon out into drainages in the Amargosa Desert. In this model, the chemical composition of the groundwater was principally determined by interaction with alluvial fill, with little input from tuff aquifers upgradient. This would tend to argue against significant mixing and dilution between tuff groundwaters beneath YM and those in the alluvial aquifers in Fortymile Canyon. An alternative proposal (White, 1981; White and Chuma, 1987) suggests that groundwater in the Amargosa Desert originated from tuffs in Fortymile Canyon with little interaction with the valley fill. There is a gradual depletion in both deuterium and ^{18}O from wells UE-29a #1 and UE-29a #2 in the headwaters of Fortymile Canyon to wells J-12 and J-13 15 km to the south. This trend is the opposite from the enrichment that one might expect either due to progressive water-rock interaction or to evaporation. The isotopic signatures of wells J-12 and J-13 might instead be due to mixing between waters flowing from beneath YM downgradient to the southeast (Fridrich, et al., 1994).

Carbon isotope interpretation is complicated by the ready reaction of carbon between different phases in a groundwater/rock/gas system. Some inferences can be drawn from the available data. In Oasis Valley, White and Chuma (1987) observed a general downgradient decrease in $\delta^{13}C$. In the headwater region, relatively enriched ^{13}C values suggest a source derived from mixing between detritus from Paleozoic carbonate outcrops ($\delta^{13}C$ = +1.4 ‰ PDB) to the west and atmospheric CO_2 ($\delta^{13}C \sim -7$ ‰ PDB). Coupled with an order of magnitude increase in the equilibrium, PCO_2 suggests a progressive downgradient reaction of the shallow groundwater system with atmospheric CO_2. Values in the lower reaches are even more depleted, suggesting an increasing input from phreatophytes.

In Fortymile Canyon, measured groundwater $\delta^{13}C$ tends to increase from the north ($\delta^{13}C$ = -13.1 ‰ PDB in UE-29a #2) to values of about -7 to -8 ‰ PDB in the southern reaches of Fortymile Canyon and the northern Amargosa Desert (White and Chuma, 1987). Samples in the central Amargosa Desert about 10 to 15 km south of the town of Amargosa Valley are enriched further (Claassen, 1985) to $\delta^{13}C$ = -3.4 to - ‰ PDB. Heavier $\delta^{13}C$ = -5.7 to -6.2 ‰ PDB are also reported (Claassen, 1985) in the south central Amargosa Desert near the Nevada-California state line at the base of the Funeral Mountains, and just south of U.S. Highway 95 about 5 km south of Bare Mountain. Claassen (1985) used these carbon isotope results to support overland recharge through Fortymile Canyon into drainages in northern and eastern Amargosa Desert. More negative values to the north are due to plant respiration ($\delta^{13}C \sim -24$ to 25 ‰) exerting a larger control on carbon isotope systematics at higher elevations and shallower depths to water in wells UE-29a #1 and UE-29a #2. With progressive flow to the south, $\delta^{13}C$ increases through increasing interaction with atmospheric CO_2 and fracture calcite. In the southern areas, the highest $\delta^{13}C$ values may be due either to progressive upward mixing with groundwaters from the carbonate aquifers (Claassen, 1985; Stuckless, et al., 1991; Fridrich, et al., 1994) or perhaps to increased interaction with carbonate alluvium that originated in the Paleozoic carbonate uplands in the Spring, Funeral, and Bare Mountains (White and Chuma, 1987).

Peterman and Stuckless (1993) reported the results of strontium analyses for groundwaters in the vicinity of YM. In general, there is an increase in $\delta^{87}Sr$ from the Spring Mountains ($\delta^{87}Sr$ = -0.5 ‰) towards the west and the springs at Ash Meadows ($\delta^{87}Sr$ = 6 to 13.1 ‰), suggesting increased interaction with Cambrian and Precambrian clastics. There is also a general downgradient increase in $\delta^{87}Sr$ from Pahute Mesa to Alkali Flat (Franklin Lake Playa). Peterman and Stuckless (1993) suggested that this trend represents progressive water rock interaction within the volcanic units south to Amargosa Valley, where interaction with alluvial fill and increased mixing from groundwaters below the valley fill result in a general increase. The highest values to the south may result from upwelling, or possibly interaction with alluvial fill made up of

Precambrian debris from the Funeral Mountains. Peterman and Stuckless (1993) also observed about 3 ‰ "noise" in the $\delta^{87}Sr$ data obtained from wells in volcanic tuffs north of the Amargosa Desert. This probably reflects the 10 ‰ range in $\delta^{87}Sr$ for the different volcanic units and the complex structure that results in different lithologic units at the water table and complex flow. The fact that these heterogeneities are to some extent preserved in the "noise" suggests that mixing of fluids may be limited beneath YM.

The staff believes that DOE has not yet made full use of the hydrochemical data base in helping to enhance interpretations of groundwater recharge, average residence time in aquifers, etc. However, the staff also recognizes that differences in groundwater chemistry reflect many complex processes and conditions, and cannot be used in a simple way to describe the

complex flow regime at YM. These processes and conditions include local dilution from variable and episodic recharge, mineralogy of recharge zones (presence or absence of thick caliche zones), local residence time, dissolution of volcanic glass and calcite, precipitation of clays, silica, and zeolites, cation exchange, and mixing of groundwater that upwells from deeper aquifer zones or migrates laterally. It is obvious that many degrees of freedom exist in this kind of geochemical system. In such an environment, groundwater does not remain chemically "static," but instead tends toward equilibrium with local conditions as it infiltrates, migrates laterally, or upwells from deeper formations. This fact should be considered in attempting to make hydrologic interpretations based on hydrochemistry.

4.5.2.12 Dating of Yucca Mountain Groundwaters

Groundwater dating using ^{14}C also supports the general flow from north to south in Fortymile Canyon, with the youngest (uncorrected ^{14}C) measured in UE-29a #1 and UE-29a #2, and increasing in age to the south in wells J-12 and J-13. As is the case with deuterium and ^{18}O data, waters from Fortymile Canyon are distinctly "younger" (higher ^{14}C) than those in the tuff aquifers beneath YM, supporting the hypothesis of limited mixing between these two groundwaters. It is still possible that mixing between recharge waters in Fortymile Canyon with older groundwaters from beneath YM produces the observed ages in J-13 and J-12, although the complexities of carbon systematics complicate the interpretation.

Radiometric ^{14}C dating of groundwater should be regarded with skepticism for several reasons. Groundwater samples are generally mixtures of waters of differing ages. The carbon content of groundwater can come from a variety of sources including caliche, calcite, carbonate rocks, vadose zone gas, organic carbon, drilling fluid, etc. Recharging groundwater in areas with a deep vadose zone will interact with the vadose zone gas phase which can be isolated from atmospheric carbon for long periods of time. Bomb pulse ^{14}C is also a complicating factor.

Kwicklis (1997) used a mass balance approach to attempt to identify sources of carbon in groundwater samples from the vicinity of YM, and then to apply corrections to apparent ^{14}C ages. This is a good approach, and the analysis was carefully done, but it is also subject to considerable uncertainty. The results generally indicate that large corrections to apparent groundwater ages are required. Key assumptions in the analysis are that all reactions affecting dissolved carbon should be postulated. For example, all sulfate is presumed to be derived from gypsum, which is a rare or nonexistent mineral at YM. If sulfate forms by oxidation of sulfide minerals, then the estimate of calcium derived from carbonates is underestimated, and consequently carbon derived from carbonates is underestimated. All carbon derived from carbonates is assumed in the analysis to be dead (i.e., no ^{14}C), and all carbon derived from gas is assumed to be 100 percent modern carbon, even though ^{14}C in the gas phase in the vadose zone at YM decreases with depth to values of 20 percent modern carbon.

Kwicklis' (1997) results show that corrected ^{14}C groundwater ages are typically thousands of years less than the uncorrected ages. The corrected ages showed spatial patterns. West and south of YM the groundwater is about 11-12 kyr old. Beneath central and northern YM it is 6-8 kyr old, and only 4-7 kyr old beneath Fortymile Wash where some modern-day recharge is known to have occurred during runoff events. At UE-29a#2, located northeast of YM along Fortymile Wash, the corrected groundwater age is zero, which means the groundwater near the well is dominated by present-day recharge.

A promising new approach exists that may greatly improve the ^{14}C dating of groundwaters. Thomas (1996) describes the separation of dissolved organic carbon from groundwater using reverse osmosis and ultrafiltration methods. The staff believes that this method should be applied to samples collected at YM to independently estimate the average groundwater residence time at locations within the saturated zone. This technique has been applied to groundwater in the vicinity of Devils Hole, and indicates that groundwater residence times in the carbonate aquifer feeding Devils Hole are about 2-3 kyr (Winograd, et al., 1997), significantly less than earlier estimates.

4.5.2.13 Seismic and Natural Thermal Effects on the Saturated Flow Regime

NRC (1997a) previously discussed climatic effects on the potentiometric surface at YM. Non-climate-related effects are also conceivable. Although this subissue focuses on isothermal and ambient flow conditions in the saturated zone, the staff wish to provide some commentary on potential seismic effects and previous claims of hydrothermal activity at YM in the recent geologic past.

The potential for upwelling hydrothermal fluids at YM has been an area of focused study (Szymanski, 1989, 1992; Archambeau and Price, 1991; National Academy of Sciences (NAS), 1992; Archambeau, 1992; Everden, 1992; Archambeau and Szymanski, 1993; Taylor and Huckins, 1995; Hill, et al., 1995; Dublyansky and Szymanski, 1996). The existence of pedogenic deposits and other geologic evidence used by Szymanski (1992) to conclude that intermittent upwelling of hypogene fluids occurs in the YM a may be explained by two competing models. One model espoused by Szymanski (1992) argues that pedogenic deposits (calcretes, bedrock veins, and mosaic breccia) and the spatial and temporal history of subsurface alteration in the cores from the YM area were formed via intermittent upwelling of hypogene fluids. The alternative model requires that the history of hydrothermal alteration in this region was associated with the Timber Mountain caldera activity and was restricted both temporally (> 10 Ma) and spatially (never reached the surface). In addition, the alternative model requires that subsequent supergene pedogenic processes have created the near-surface deposits and altered the subsurface rocks via interaction with descending fluids. A third model is that the deposits formed by evaporation of groundwater from a shallow perched water table (shallow upwelling, pedogenic deposits).

A thorough review of Szymanski's (1989) report by the NAS (1992) concluded that none of the evidence cited as proof of ground-water upwelling in and around YM could be reasonably attributed to that process. Subsequent to the NAS's report, Szymanski (1992) issued a report that comprehensively evaluated the geologic data from the Yucca Mountain area to examine evidence of past upward flow of water and its consequent mineral deposition. Szymanski and colleagues (Archambeau and Szymanski, 1993) argued that efforts to evaluate his conceptual model of the YM region, particularly the NAS's report, did not address all the geological data from the area which had been used by him and which should be explained by any conceptual model of the geodynamics of this region.

Archambeau (1992) severely criticized the NAS report. According to Archambeau (1992, p. 23), "...one can only conclude that the Panel did not actually read Szymanski's [1989] report, or if they did read it they chose to misrepresent it. In either case this is hardly what would be expected from a NAS panel that is charged with the responsibility of evaluating a report. On this basis alone there would be reasonable grounds to seriously question the Panel's findings as it suggests an inclination to distort and misrepresent the record." Archambeau (1992) went so far as to recommend that the National Academy of Sciences re-evaluate the panel's report. The National Academy of Sciences (Press, 1993) responded to Archambeau's claims by citing Evernden (1992). Evernden's independent review found no evidence to support the claim that hydrothermal waters have risen to the surface periodically over thousands of years at YM. Evernden's (1992) review had been performed at Archambeau's request.

The prominent calcite and opaline-silica vein deposits of Trench 14 have been extensively studied to determine if a hydrothermal origin is likely. This trench was excavated across the Bow Ridge fault just east of YM. Quade and Cerling (1990) reported stable isotopic evidence that the Trench 14 deposits resemble pedogenic carbonates in the region. Several years later, Quade, et al. (1995, p. 228) observed that many years of scrutiny by different researchers (including themselves) have "... failed to identify unequivocal paleospring deposits adjacent to Yucca Mountain ..." Quade, et al. concluded that morphologically, mineralogically, and isotopically, "... the fracture carbonates in Trench 14 closely resemble pedogenic carbonate in the region ..." Likewise, Taylor and Huckins (1995, p. 36) found that "Physical, chemical, mineralogical, biologic, petrographic, and isotopic data collected indicate the calcium carbonate and opaline silica in the veins and slope-wash alluvium [at Trench 14] are characteristic of an environment with descending water - a pedogenic environment."

Hill, et al. (1995, p. 86) argued that a hypogene model for the deposits "should not yet be dismissed: the correct interpretation of these deposits awaits excavation of tunnels beneath Yucca Mountain where faults (such as the Bow Ridge fault) can be directly observed and compared with surface faults containing the COD [calcite/opal deposits]." Dublyansky and Szymanski (1996) continue to assert that thermal springs episodically existed at YM during the last 400 to 500 ky, and that the "water table locally fluctuated and rose to the mountain's surface..." The paper by Hill, et al. (1995) was critically reviewed by Stuckless, et al. (1998) of the USGS and LANL. They concluded (Stuckless, et al., 1998, p. 76) that the "...unusually large and diverse body of geologic, mineralogic, isotopic, morphologic, and paleontologic evidence that has been developed provides an overwhelming convergence toward the conclusion that the calcite/opal deposits at Yucca Mountain originated from downward-percolating water, rather than hypogene fluids, within and beneath the zone of soil-forming processes." Overall, the rebuttal paper by Stuckless, et al. (1998) casts substantial doubt about previous assertions of a hydrothermal origin for the Trench 14 deposits.

A systematic analysis of the logic used by Szymanski (1992) to conclude that at YM hydrothermal and auxiliary gas-assisted processes pose a significant hazard for time spans measured in 10^4 years was completed by CNWRA (1994). The analysis evaluated the logical form (validity) of the argument and an evaluation of the premises used to support the conclusions of his arguments. The geological evidence that was used to support each individual premise was evaluated as a part of the analysis (CNWRA, 1994). Several flawed premises, that were key components to Szymanski's (1992) overall argument, were identified by CNWRA (1994). Critical evaluation of the site data and the analysis of the logic used by Szymanski indicates there is presently inadequate documentation to support his assertions (CNWRA, 1994).

A review of the most recent reports by Szymanski, et al. has just been completed by the NWTRB (1998). The Board reached three conclusions (NWTRB, 1998, p. 2-3), which are quoted below:

1. The material reviewed by the Board does not make a credible case for the assertion that there h been ongoing, intermittent hydrothermal activity at Yucca Mountain or that large earthquake-induc changes in the water table are likely at Yucca Mountain. This material does not significantly affect the conclusions of the 1992 NAS report.

2. There are several areas where additional research could be used to further evaluate the hypotheses of ongoing, intermittent hydrothermal activity and large earthquake-induced changes in the water table at Yucca Mountain. However, because of the lack of any substantive evidence supporting either of these hypotheses, the Board views additional research on these issues, if not already carried out, as generally having a lower priority than more important issues in the evaluation of repository performance.

3. However, some fluid inclusions found in mineral deposits at Yucca Mountain do provide direct evidence of the past presence of fluids at elevated temperatures (at least 72 deg. C) in the vicinity of the proposed repository. This could be an indicator of some degree of past hydrothermal activity. The critical question is, "At what time in the past were such fluids present?" If fluids at elevated temperatures were present less than 100,000 years ago, as some of the reviewed reports claim, this could lend credence to the hypothesis of ongoing hydrothermal activity at Yucca Mountain. On the other hand, if these fluids were present around 10,000,000 years ago or earlier, they could be associated with volcanic events related to the original formation of Yucca Mountain and would have no bearing on the hypotheses of ongoing hydrothermal activity. The Board believes that the ages of fluid inclusions should be determined. A joint program between federal and State of Nevada scientists for collecting, dating, and analyzing fluid inclusions would be one way to help eliminate some of the past disagreements associated with sample collection and handling.

The NRC staff fully concurs in the above conclusions and agrees with the Board's recommendation for a joint program to collect, date, and analyze fluid inclusions at the site.

With respect to earthquakes and groundwater, the NAS (1992, p. 124) concluded that "... while there are uncertainties in current interpretations because specific site data are not available, ... there is nevertheless sufficient confidence in the aseismicity of the site and in the inability of earthquakes to generate large water table changes at the [YM] site ... to warrant further characterization of the site to determine its suitability ..." The panel recommended that the DOE conduct a literature search regarding the hydrologic effects of historic earthquakes, locally and worldwide, to determine the potential for large water table rises in response to the coupling of seismic and hydrologic systems.

Carrigan, et al. (1991) discussed the potential for water-table excursions induced by seismic events at YM. They conducted numerical simulations of tectonohydrologic coupling, and estimated that earthquakes typical of the Basin and Range province produce 2 to 3 m excursions of a water table that is 500 m below land surface. They also estimated that extraordinary events (analogous to the 1983 Borah Peak, Idaho, or Dixie Valley-Fairview Peak, Nevada, earthquakes of ~magnitude 7) could cause transient water-table excursions of less than 20 m. These estimates can now be seen in light of major earthquakes that occurred in neighboring California and an event near YM. Two major earthquakes occurred in southern California on June 28, 1992. Both were about 300 kilometers from YM and had measured magnitudes of 7.5 (Landers) and 6.6 (Big Bear Lake). The Landers and Big Bear Lake quakes caused estimated water table fluctuations of 0.9 meters and 0.2 meters, respectively, at YM (O'Brien and Tucci, 1992). The data were obtained from two wells instrumented to continuously monitor fluctuations in the water table and fluid-pressure in a deeper, isolated interval.

The earthquake that occurred near Little Skull Mountain on June 29, 1992 (magnitude 5.6) caused only a minor, transient change in the water table at the YM site. Maximum peak-to-peak fluctuations were estimated to be 0.9 m for water levels and 2.2 m for fluid pressures (O'Brien, 1993). These fluctuations lasted only 1 to 2 hr. Potentiometric levels in borehole UE-25p #1, which monitors the Paleozoic carbonate aquifer, declined a total of 0.5 m in response to these earthquakes (O'Brien, 1993), and slowly recovered to pre-earthquake levels during the next 6 months.

During the DOE expert elicitation process, the experts concluded that the changes to the water table associated with a seismic event will not be significant and will not be long-lived (Geomatrix, 1998). It was noted that a seismic event can perturb the stress field and can produce short-lived spikes of increased fluid pressure in confined aquifers. However, since these events do not cause a significant transfer of water, they are not likely to cause long-term changes in water table elevations. The short-term changes to the water table caused by a seismic event are not likely to have any impact on repository performance.

The NAS (1992) also considered whether the cause of the large hydraulic gradient in the saturated zone, located just north of the YM site, could influence future water-table rise. They recommended (NAS, 1993, p. 140) that hydrologic data be measured and collected in situ in boreholes to identify the cause of the large hydraulic gradient. The DOE originally planned to drill two holes for this purpose. One of these boreholes, WT-24, is currently being constructed and data to date indicate that a perched water system exists near the top of the Calico Hills Formation. Preliminary hydraulic head data show that the regional potentiometric surface has been intersected and occurs more than 100 m above that found in wells to the south. In the recent expert elicitation (Geomatrix, 1998), the experts concluded that the probability of any large transient change in the configuration of the large hydraulic gradient due to disruptive events is extremely low.

The NRC staff and the CNWRA (1996) are independently examining the likelihood of future basaltic volcanic events at the YM site. The most recent volcanic events known to have ensued near the site were of this type, and if they were to occur close to YM could produce associated hydrothermal activity. Based on our current understanding, the probability of future basaltic volcanic events is estimated to range between 10^{-8} and 10^{-7} per year (CNWRA, 1996, p. 2-26). Based on evidence observed to date, the NRC staff believe that, compared to climate change, other mechanisms such as seismicity appear to have the potential to produce water-level changes of relatively small magnitude or duration. Quaternary climate change has caused significant long-term changes in the regional water table (see NRC, 1997a). Szabo, et al. (1994) documented water-table fluctuations over a period of 100 ky at Devils Hole in the Amargosa Desert, with high water levels apparently occurring throughout the Wisconsin glacial stage and highest heads occurring during the glacial maximum. Water levels at Devils Hole apparently declined from that time through the Holocene. The magnitude of water-table rise that could be expected during future pluvial climates at YM is about 100 m. However, a lesser rise might be expected given the impacts of human activities. It is interesting to note that a recent paper by Whelan, et al. (1998) suggests that the water table at YM may at times have been up to 300 m lower than today. However, the timing of such events is presently unknown.

4.5.2.14 Summary of Regional and Site Scale Groundwater Modeling

Hydrogeologic studies in the Death Valley region were first undertaken in the early 1960s in order to assess the potential for radionuclides released from underground tests of nuclear devices to contaminate groundwater at the NTS and to estimate the amount of water available for use at the NTS. Although many of the early reports on the hydrogeology and water resources of the NTS were prepared by the USGS, these reports received little circulation outside of the Atomic Energy Commission (AEC). In more recent modeling exercises, regional scale modeling was conducted by D'Agnese, et al. (1997a,b) for the Death Valley Groundwater Flow System (DVGFS), the DOE (1997) for the NTS Regional Groundwater Flow System, and Cohen, et al. (1997) and Czarnecki, et al. (1997) for YM and vicinity (using boundary conditions derived from D'Agnese, et al., 1997a).

The conceptual flow models used for all previous studies can be classified by the region, area, or sub-basin considered. Three scales can be identified: (i) hydrogeographic province scale, (ii) regional groundwater flow system scale, and (iii) groundwater basin scale. The hydrogeographic province scale refers to those studies which consider all or part of the carbonate province of eastern Nevada, western Utah, and south-easternmost Idaho. Hydrogeographic province scale models include those of Dettinger (1989, 1992) and Burbey and Prudic (1991). Mifflin (1968) defines a regional groundwater flow system to be "...a large groundwater flow system which encompasses one or more topographic basins...[and]...may include within its boundaries several groundwater basins." Studies by Rush (1970), Winograd and Thordarson (1975), Waddell (1982), Rice (1984), Ahola and Sagar (1992), Sadler, et al. (1992), D'Agnese, et al. (1997a), and DOE (1997) were focused on the Death Valley regional groundwater flow system. As defined by Mifflin, a groundwater basin usually represents "...only a part of the groundwater system," but may include "...more than one [regional or local] groundwater flow system." Investigations by Czarnecki and Waddell (1984), Czarnecki (1985, 1989), and Czarnecki, et al. (1997) were focused on the YM and Amargosa Desert basins, while Feeney, et al. (1987) developed a model for the western portion of the NTS. Table 14 lists the geographic setting and the area considered in each of the studies. Other modeling efforts of various scales not described in this IRSR include Barr and Miller (1987), Sinton (1987), Haws (1990), Carrigan, et al. (1991), Ahola and Sagar (1992), Dressel (1992), Lehman (1994), D'Agnese (1994), Altman, et al. (1996), and Ho, et al. (1996).

During the DOE expert elicitation process, the experts reviewed available data on the regional-and site scale modeling and concluded that the dominant flow direction from beneath the repository is to the southeast to Fortymile Wash and then south to Amargosa Valley (Geomatrix, 1998). They also suggest that the primary flowpaths remain within the lower volcanic aquifer near YM and the valley-fill alluvium farther south. The flowpath for radionuclides probably will not include the carbonate aquifer due to the elevated hydraulic heads. However, the regional model (D'Agnese, et al.,1997a) indicates that the radionuclide flowpaths enter the carbonate aquifer about 10 km south from the repository and then re-enter the volcanic and valley fill units farther south. It was also noted by the experts that most of the flow probably occurs in channelized preferential flowpaths. Experts also noted that the faults have been incorporated in the models as vertical disruptions of HYDROSTRATIGRAPHIC units, without their hydraulic properties. It was surmised that the faults will have distinct properties with high transmissivity along strike but low transmissivity perpendicular to trend. The expert panel also cautioned that even though the models are used to account for the available data sets, they are not developed sufficiently yet to provide accurate prediction of certain key parameters, e.g., flux beneath the site.

Brief summaries of the most recent modeling efforts are provided below.

Table 14. Hydrogeologic study areas of the groundwater flow models of the Yucca Mountain region.

Hydrogeologic Study	Geographic Setting	Specified Boundaries	Setting Area (km^2)
Czarnecki and Waddell (1984)	YM/NTS	Yes	3,000
Czarnecki (1985)	YM/NTS	Yes	3,000
Feeney, et al. (1987)	Western NTS	Yes	3,740
Czarnecki (1989)	YM/NTS Amargosa Desert	Yes	4,900
Schoff and Moore (1964)	NTS	No	NA[1]
Winograd and Thordarson (1975)	Death Valley/NTS	Yes	11,700
Rush (1970)	Death Valley/NTS	Yes	17,000
Waddell (1982)	Death Valley/NTS	Yes	18,000
Sadler, et al. (1992)	Death Valley	Yes	19,000
Dettinger (1989; 1992)	Nevada carbonate province	No	NA[1]
Rice (1984); Ahola and Sagar (1992)	Death Valley	Yes	41,000
Burbey and Prudic (1991)	Carbonate province/Death Valley	Yes	52,000
D'Agnese, et al. (1997a)	Death Valley	Yes	100,000
U.S. Department of Energy (1997)	Death Valley/NTS	Yes	26,200
Czarnecki, et al. (1997)	YM/ Amargosa Desert	Yes	1,350
Cohen, et al. (1997)	YM	Yes	150

[1]Not available

- **D'Agnese, et al. (1997a)**

A study of the regional groundwater flow for Death Valley was undertaken by the U.S. Geological Survey (USGS). The objectives of this study was to estimate aquifer parameters, provide boundary conditions for a site-scale model, and estimate the water budget. D'Agnese et al. (1997a) modeled an area of 100,000 km^2 using MODFLOWP (Hill, 1992), a three-dimensional (3D) finite difference mathematical model with nonlinear least square regression for parameter estimation. This regional model is based on a 3D hydrologic framework model, geologic maps and cross sections, and lithologic well logs. The hydrologic framework model provides a description of the geometry, composition, and hydraulic properties of the materials that control the regional groundwater flow system. Most surface recharge to the regional flow system occurs at high altitude where precipitation is much greater than at lower altitudes. Discharge from the groundwater system mainly occurs through evapotranspiration, spring discharges, and well pumping. The water budget for the regional system suggests that the outflow exceeds inflow. This can be attributed to the poor definition of the discharge volume, specifically pumping. D'Agnese et al. (1997a) also surmised the Death Valley system to be an open system and used interbasinal transfer of water in the deeper Paleozoic system to achieve a water balance during the modeling.

The regional system was modeled by using a 3D steady-state simulation using a finite difference grid consisting of 163 rows, 153 columns, and 3 layers. The grid cells were oriented north-south and of uniform size: 1,500 × 1,500 m. The three layers occurred at the following intervals below the water table: 0–500 m, 500–1,250 m, and 1,250–2,750 m. This simulation exercise supported the analyses of interactions between the relatively shallow local and subregional flow paths and the deeper regional flow paths controlled by the carbonate aquifer. A series of conceptual models was evaluated to test the validity of various interpretations about the flow system. The conceptual model providing the best fit during the calibration exercise was retained as the final optimized model. This final model showed water balance discrepancy (117,100 m^3/d) and high head residuals (up to 300 m).

The boundaries selected for the flow system were modified from Waddell et al. (1984), Hurl et al. (1985), and Bedinger et al. (1989). Most system boundaries were no-flow boundaries. However, inflows to the model may occur from Pahranagat Valley, Sand Springs Valley, Railroad Valley, Stone Cabin Valley, Ralston Valley, Fish Lake and Eureka Valley, Saline Valley, Panamint Valley, Pilot Knob Valley, and Soda Lake Valley. The flux estimate for Pahranagat Valley is 20,000 m^3/d (Winograd and Friedman, 1972). No estimate is available for the other inflows. The Death Valley regional system was modified and divided into three major subregional flow systems: Northern Death Valley, Central Death Valley, and Southern Death Valley. There is, however, evidence of groundwater flow across the subregional boundaries. In each subregion, the flow paths are grouped in groundwater basins containing various groundwater sections. The Northern Death Valley subregion was divided into four dominant groundwater sections: Lida-Stonewall, Sarcobatus Flats, Grapevine Canyon, and Oriental Wash. The Central Death Valley subregion was divided in three groundwater basins: Pahute Mesa-Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek. The Southern Death Valley subregion was divided into four groundwater sections: Pahrump Valley, Shoshone-Tecopa, California Valley, and Ibex Hills.

During the study, numerous conceptual models were evaluated to test the validity of various flow system interpretations. These conceptual models were tested for (i) the location and type of flow system boundaries, (ii) the extent and location of recharge areas, and (iii) the configuration of the hydrogeologic framework model. The conceptual model changes that produced a significant improvement in flow model results were incorporated into the final model. Model calibration was performed by estimating 18 parameters. During calibration, however, some of the parameters were lumped together. After calibration, the model was evaluated by comparing the measured values with the simulated values. The comparison included hydraulic heads and spring flows; hydraulic conductivities, vertical anisotropy, and infiltration; and water budgets. The residuals for hydraulic heads showed a good match (~ 20 m) with observed heads in some areas of flat hydraulic gradient; however, a more moderate match (~ 20–60 m) dominated the flat hydraulic gradient area. Poor match (>60 m) to observed heads was simulated in the large hydraulic gradient areas. The simulated spring flows were generally lower than the observed flows. Evaluation of estimated parameters indicated that the values of hydraulic conductivity, vertical anisotropy, and recharge rates were all within expected range. The model simulation also indicated a reasonable water budget for the system. The model errors were attributed to coarse vertical discretization of the system and non-random distribution of weighted residuals of hydraulic head and spring flow. It was surmised that further calibration of the system will provide improved accuracy in model prediction. This model is currently being refined to incorporate a higher vertical resolution with 16 hydrostratigraphic layers and a better representation of structural features.

Another study (D'Agnese et al., 1997b) was undertaken to estimate the effects of future climates on the regional groundwater flow system. The effects of climate change on Death Valley groundwater flow system were simulated using the regional groundwater flow model (D'Agnese et al., 1997a). Climate change was implemented in the groundwater flow model by changing the distribution of recharge. Two simulations were performed to simulate the effects of full glacial conditions using climate conditions approximately 21,000 yr ago and global warming using climatic conditions in the future representing a doubling of atmospheric CO_2 concentration. The climate scenarios were simulated by the National Center for Atmospheric Research modeling approach, which is based on a nested global circulation model (GCM) and a regional climate model (RCM). The future climate scenario suggested that the atmospheric CO_2 concentration will double in the next 100 yr. The future climate scenario resulted in temperature increases of 2–3 °C. Due to inherent limitations imposed by modeling assumptions and the coarse grid of RCM and GCM, the simulated effects of climate change should be considered conceptual in nature.

In the past climate simulation, the water levels rose over the entire model domain due to increased recharge rates. The water levels rose significantly beneath areas of higher elevations due to a greater increase in recharge in these areas, and the large hydraulic gradients became more pronounced. The simulated recharge over the region increased five-fold relative to present-day recharge. The simulated water levels near YM were generally 60–150 m higher than the present-day levels. Simulated groundwater flux beneath YM increased by a factor of about 4 relative to present-day conditions. The most dramatic increase, on the order of about 500 m, occurred in the Timber and Shoshone Mountain areas. Even with these large changes in the water levels, the shape of the potentiometric surface did not change substantially. The potentiometric surface downgradient of YM was generally the same in past and present climate scenarios, suggesting that SZ flow paths will not change under full glacial conditions. No particle tracking simulations were performed to define the flow paths. The simulated water budget indicated that the model was close to being in balance, and the recharge accounted for 97 percent of water entering the system. The rest of the water entered the system as underflow via constant head cells on the northern boundary. In the future climate scenario, the potentiometric surface rose less than 100 m in most of the model domain. Simulated water levels in parts of Amargosa Valley, Amargosa River Drainage, and Death Valley were equal to or lower than present-day conditions. At YM, the water levels rose less than 50 m in this scenario. Again, the largest increase in water levels was in the Timber and Shoshone Mountain areas. The potentiometric surface configuration was much similar to present-day conditions. Although no particle tracking simulations were performed, based on the potentiometric surface it appears that the flow paths will not change in the future climate scenario.

The regional scale flow modeling results were used in the TSPA-VA (DOE, 1998b) and the Technical P Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 19. to provide groundwater flux multipliers for the long-term average and super-pluvial climatic conditions. These groundwater flux multipliers were used to calculate the groundwater flux for each of climate states relative to present-day conditions.

- **U.S. Department of Energy (DOE, 1997b)**

The NTS regional groundwater flow system covers approximately 26,200 km^2 of the Death Valley groundwater flow system. The area is bounded by Death Valley, the Funeral Mountains, Bullfrog Hills, and the Cactus Range on the west; by the Kawich, Reveille, and Quinn Canyon ranges on the north; by the Timpahute, Pahranagat, and Sheep ranges on the east; and by parts of the Spring Mountains, the Resting Spring Range, and the Greenwater Range on the south. The digital geologic model consists of the distribution and thickness of the aquifers and confining units and their depths relative to the hydrologic basement. The geologic model also incorporates major structural features that control groundwater flow and migration of contaminants within the regional flow system. Hydraulic parameters consist of hydraulic conductivity and effective porosity. Data on hydraulic parameters were gathered and evaluated to help describe the hydrogeologic framework of the groundwater flow system. Within the NTS region, groundwater occurs within alluvial, volcanic, and carbonate geologic units.

The direction of groundwater flow is locally influenced where structural and geologic conditions have controlled the distribution and thickness of the Lower Carbonate Aquifer. In some areas of the regional flow systems groundwater encounters structural and geologic conditions, such as structural highs of the Lower Clastic Confining Unit, that promote an upward flow component. The upward flow component brings water to discharge at the surface in the form of a wet playa or springs. The discharge is then lost from the flow system through evapotranspiration. Such discharge characteristics are observed at Oasis Valley, Penoyer Valley, and Amargosa Flat. There is groundwater flow between basins in the form of subsurface inflow outflow. Ultimately, however, the groundwater is lost from the flow system at other surface discharge ar located downgradient.

Recharge and discharge occur either through the external boundary of the groundwater flow system or the surface. There is no groundwater crossing the boundary by underflow along much of its length. Areas where underflow occurs include the boundaries with Pahranagat Valley, Sarcobatus Flat, Pahrump Valley, and the Amargosa Valley near Eagle Mountain. An inflow in the range of 5,400-60,800 m^3/d occur from the Pahranagat Valley to the Desert Valley. The inflow from Pahrump valley is in the range of 5-7,600 m^3/d. The outflow in the range of 8,50-3,400 m^3/d occurs at Eagle Mountain. Areas of recharge were mostly assumed to correspond to precipitation areas. The greatest recharge occurs on the Spring Mountains in the south, followed by the Sheep Range to the east. Other mountain ranges in the NTS groundwater flow system are areas of moderate recharge. Lower-elevation areas such as Death Valley are not recharge areas. However, in some areas such as Fortymile Canyon, recharge is known to occur. Thus, some of the recharge assumed to occur at higher elevations was redistributed to lower elevations in the vicinity of the NTS. Eight surface-discharge areas were identified. The estimated total amount of groundwater recharge to the NTS regional groundwater flow system ranges between 1.83×10^5 to 3.60×10^5 m^3/yr. The total amount of groundwater discharge ranges between 1.36×10^5 to 3.06×10^5 m^3/yr.

The groundwater flow model was designed to provide a basis for predicting the movement of contaminants from the underground test areas on a regional scale. It was also intended to provide a means for evaluating the range of uncertainty in these predictions due to uncertainties associated with the geologic and hydrologic data. In the future, the model will also be used to provide boundary conditions for more detailed models of the underground testing areas that are consistent with the regional groundwater budget. The geologic model domain was subdivided into a 3D grid consisting of 68 columns by 76 rows and 20 layers. The large number of layers was used to accurately simulate the geologic complexity of the thinner, hydrologically significant hydrostratigraphic units, primarily located in Pahute Mesa and Yucca Flat, and to increase numerical accuracy. The grid was constructed to simulate more accurately the hydrology of the areas of concern that include the underground testing areas and downgradient regions. It was also aligned with the average fracture direction in the primary testing areas of concern, Pahute Mesa and Yucca Flat. Boundary conditions were specified to match communication of the NTS groundwater flow system with neighboring flow systems.

The calibrated model, based on MODFLOW, provided a good match overall and accurately reproduced several observed, prominent features of the hydrology of the NTS and surrounding areas. The high gradient between Emigrant Valley and Yucca Flat along the northern border of Yucca Flat was present as was the high gradient north of the YM area. The higher water levels in the western part of Yucca Flat above the Upper Clastic Confining Unit were present. A moderately low gradient across Timber Mountain, increasing to the north beneath Pahute Mesa, was well simulated. The very low gradient throughout most of the area underlain by the Lower Carbonate Aquifer was present as was the moderate gradient between the Penoyer and Desert Valleys. The high gradient between the Amargosa Desert and Death Valley was reproduced along with recharge mounds in the Spring Mountains, the Sheep Range, the Kawich Range, and the Grant Range. The eastward gradient present in the western part of the Pahute Mesa testing area was not well represented in the model, and there was a slight gradient reversal in this area.

Flowpaths from selected nuclear test locations were identified with the particle-tracking code. Particle-starting locations were chosen (415 of them) so that each test area (Pahute Mesa, Rainier Mesa, Yucca Flat, Climax Stock, Shoshone Mountain, and Frenchman Flat) was represented. Results indicated that the particles originating in the Pahute Mesa testing area discharge in Oasis Valley. Particles originating in the eastern testing areas (Yucca Flat and Frenchman Flat) discharge in Death Valley or the Amargosa Desert, but not at Ash Meadows. Particles originating in other testing areas did not leave the NTS during the simulated time period.

Extensive sensitivity analyses were performed to evaluate the impact of parameter uncertainty on water level and boundary flux responses and on particle-tracking results. Two types of sensitivity analyses were performed. The first type involved changing basic assumptions of the model such as using different versions of the regional geologic model and different recharge distributions. The second type was a systematic variation of the hydraulic-conductivity parameters. The sensitivity analysis of the different geologic models confirmed that a barrier to flow in the area of Calico Hills westward to Bare Mountain was needed to match estimated discharge rates at Oasis Valley and observed gradients in that area. This barrier was based on structural relationships associated with the Belted Range Thrust and alteration of volcanic rocks in the Claim Canyon caldera segment and northern YM. This interpretation was consistent with geologic and hydrologic information in the area. Changes in the geologic model near Penoyer Valley resulted in an improvement in the hydrologic model; however, a lower hydraulic conductivity for the Lower Carbonate Aquifer in the northeastern part of the model was needed to match water levels and estimated fluxes. The sensitivity analysis performed on 116 hydraulic conductivity values showed that the effect on water levels and boundary fluxes was small. The response in an area was dependent on local conditions such as the geometric relationships between hydrogeologic units and the 3D extent of the hydrogeologic unit.

The groundwater pathlines from underground test locations at or below the water table were calculated from the flow model. Three of the fastest pathlines, which were closest to the southern edge of a test ε were selected for transport simulations to represent each of the main underground test areas. This transport model was used to calculate the tritium concentration in groundwater downgradient from underground test locations and to assess the impacts of flow and transport parameter uncertainty on the predicted downgradient tritium concentrations. The transport model required the following parameters to be defined at each node: initial tritium concentrations, radioactive decay coefficient, specific discharge, dispersivity, effective and matrix porosity, and the effective diffusion coefficient. The maximum flow path length was 99 km, based on preliminary scoping simulations.

The transport modeling results suggested that: (i) the regional geology is the dominant factor controlling the horizontal and vertical position of paths; (ii) matrix diffusion is an important mechanism governing the migration of tritium in fractured carbonate and volcanic rocks; (iii) source term concentration uncertainty is most important near the nuclear test locations and decreases in importance as the travel distance increases, (iv) the recharge coefficient which accounts for the total groundwater flux uncertainty is as important as matrix diffusion at downgradient locations.

- **Cohen, et al. (1997)**

Cohen, et al. (1997) developed a subsite-scale SZ model that covers an area of approximately 150 km^2 (10 km x 15 km). The 3D integral finite-difference numerical model is based on TOUGH2. There are 23 model layers with approximately 50,000 gridblocks. The model represents the SZ from the water table down to the confining unit separating the volcanic and carbonate aquifers. The geologic units were divided to account for vertical variation of rock properties as evidenced by welding characteristics and vertical flow surveys in boreholes. The model preserved the thickness, orientation, dip, and lateral continuity of the strata as defined in the 3D geologic model of YM, ISM 2.0 (Clayton, et al., 1997). Displacement by faults was also explicitly considered; however, the faults were assumed vertical. The faults are discretized sι that the fault zone properties can either be explicitly assigned or faults can be displacement-only featurι

The steady-state model has been calibrated to measured hydraulic heads and to long-term pumping tests at the C-hole complex. The calibrated heads were within approximately 1 m of measured heads. The initial C-hole complex pumping test results match steady-state results; however, the grid size was not large enough to study transient effects. The model results suggested that the flow geometry is greatly influenced by fault properties, whether faults are high-permeability fault zones, low-permeability fault zones, or fault with displacement only. The majority of flow is contained within the Bullfrog Tuff and travels with its dip downgradient. When the Bullfrog unit is offset by faults, the vertical flow is induced, and flow can rise back to the water table from below. Based on the model results, it was recommended that an additional multihole complex be designed to characterize flow parameters in a southern model area. It is feasible to integrate this model with UZ models, which could result in a greater understanding of perched water conditions, especially the large hydraulic gradient. Based on a preliminary dual porosity grid for this model it was suggested that flow and transport had to be considered as a coupled process.

- **Czarnecki, et al. (1997)**

The site-scale flow model was developed by USGS (Czarnecki et al., 1997). This steady-state numerical model covered an area approximately 1,350 km^2 (30 × 45 km) over a saturated thickness of about 1,500 m. The specific objectives of this model were (i) to estimate groundwater flow direction and magnitude from the repository to the accessible environment, (ii) to characterize the complex 3D behavior of flow through heterogeneous media, and (iii) to identify the potential role of faults in groundwater flow. The transport results from this modeling study (Czarnecki et al., 1997) were not directly used in the TSPA-VA for various reasons listed in the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998).

The model grid was based on a digital hydrogeologic framework model and sampled at 1,500 × 1,500 m with variable thickness. The 3D model domain was discretized in a tetrahedral finite element mesh consisting of 9,279 nodes and 51,461 elements with 16 layers representing different hydrogeologic units. The faults were not incorporated as distinct hydrologic features. Only the top two layers were selected from the regional model. Flow simulations were performed using the Finite Element Heat Mass Nuclear (FEHMN) groundwater flow and transport code. Calibration of the flow model was performed with the Parameter ESTimation (PEST) code. The constant head boundary condition was derived from the regional model of D'Agnese et al. (1997a). The results from the flow simulations are presented by Czarnecki et al. (1997). Results from the transport simulations are presented by Zyvoloski et al. (1997). The transport simulations, are not reviewed here because they are not directly used in the TSPA-VA (DOE, 1998b).

The site-scale model assumed constant head along all four boundaries. The constant head values for the boundary were obtained from the regional flow model (D'Agnese et al., 1997a). No flow was assumed from the lower boundary of the model, whereas, the upper boundary of model, (i.e., the water table) received recharge along the upper reaches of Fortymile Wash. The large hydraulic gradient was simulated by incorporating a low permeability fault. The moderate hydraulic gradient was similarly simulated by incorporating a low permeability fault. Recharge due to infiltration was not applied in this model, and no pumpage was assumed in the model domain.

Model calibration was performed by an automated parameter estimation method to match the observed hydraulic heads at 94 locations by varying selected permeability values. During calibration, it was indicated that the available data were not sufficient to estimate all parameters individually. The hydrogeologic units with similar permeability values were lumped to minimize the number of estimated parameters. For various combinations of fixed and estimated parameters, 40 PEST runs were completed.

The simulation results suggest that the model performed optimally when the low permeability barriers were added corresponding to the Solitario Canyon fault and the downgradient side of the large hydraulic gradient, and also when the permeability of upper volcanic confining units was varied. The optimized model produced hydraulic head residuals in the range of −5 to +5 m. A greater disparity was noticed in flux across the model boundaries when compared with the regional model. Comparison between site-scale and regional models showed almost twice the amount discharging from the southern end of the site model and substantially different amounts for the north and east sides. It was suggested that the major flux difference between the two models at the northeast corner of the site model is due to recharge from the north that is diverted east and discharges in part because of the interaction of constant head boundaries and the low permeability east-west barrier representing the large hydraulic gradient.

Although the preliminary results provide a good fit with the measured head values, the permeability values used to attain this good fit show a large range for each aquifer, especially for the middle volcanic aquifer, where the value used to fit the model is three orders of magnitude smaller than the values reported for the C-Well complex. The authors attributed this to model error or to a local, large-permeability zone, which was not represented in the model, near the C-Well complex.

The major assumptions of the site-scale flow model include (i) bulk permeability is uniform within each hydrogeologic unit, (ii) the flow system is at steady state, (iii) the SZ can be represented as a single continuum, and (iv) the groundwater flow system is isothermal at 44 °C. Use of this model is limited to provide a large-scale description of the hydrogeologic framework of the SZ flow system, provide the flow field to perform preliminary transport simulations and estimate groundwater velocities, and provide initial estimates of permeability for the 16 hydrogeologic units and the recharge from Fortymile Wash. The authors listed the following limitations for the model.

- Simulations are restricted to fully saturated conditions from the water table and below.
- The model does not account for the variations in temperature within the flow system.
- It is likely the flow model is nonunique.
- The large hydraulic gradient is poorly understood and greatly affects model calibration, simulated permeability values, and flux.
- Flux into the site model domain is poorly defined.
- Limited hydraulic test data exist for constraining permeability values used in the model.
- Definition of the hydrogeologic units within the model is limited by the sampling interval.

The authors suggested numerous ways to improve the model: (i) conduct sensitivity studies to identify the parameter having the greatest effect on the sum of the squared residuals for head; (ii) refine the hydrogeological framework model; (iii) use higher resolution sampling; (iv) use faults explicitly as surfaces; (v) use additional hydrochemical, flux, and isotopic data for model calibration; and (vi) include vertical flux through the bottom of the model.

- TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE VIABILITY ASSESSMENT APPROACH TO SATURATED ZONE FLOW AND TRANSPORT

The TSPA 3D SZ flow model was developed using FEHMN with a model domain of about 20 × 36 km t depth of 950 m below the water table (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). The model domain was discretized into a uniform orthogonal mesh with 500 × 500 × 50 m elements. The model was based on a refined hydrogeologic framework model used by D'Agnese et al. (1997a). A total of 16 hydrogeologic units were represented as homogeneous and isotropic. The large and moderate hydraulic gradients were represented by three linear vertical features with low permeability. The SZ flow was modeled as steady state. The focused recharge along Fortymile Wash was included as specified flux, and the specified pressure boundaries were applied to the lateral boundaries. The no-flow boundary was assigned to the bottom of the model domain. The model simulations were performed with isothermal conditions and uniform permeability for each hydrogeologic layer.

The trial and error calibration was performed to compare simulated hydraulic heads with observed hydraulic heads. In general, there was good agreement between simulated and observed heads and the head residual was about 2 m along the potential flowpaths down gradient of the repository. The simulated direction of groundwater flow was also consistent with the conceptual model of SZ as suggested by the regional and site-scale flow modeling. Solute transport simulations indicated an average simulated Darcy velocity of 0.61 m/yr along the flow path matching the 0.6 m/yr, as suggested by SZEE. A particle tracking simulation was used to estimate the flowpath lengths in the SZ through each of the hydrogeologic units downstream from the repository. The flow was mostly in the four hydrogeologic units: upper volcanic aquifer, middle volcanic aquifer, middle volcanic confining units, and alluvium/undifferentiated valley fill. The streamtubes generated by particle tracking simulations were used for the one-dimensional (1D) transport simulations.

The TSPA 1D transport model was developed to generate the radionuclide concentration breakthrough curves for the TSPA-VA analyses using FEHMN. The 1D approach eliminated the transverse dispersion inherent in the 3D approach due to coarse gridding. The longitudinal and transverse dispersion was included in the model as a postprocessing step in the form of a dilution factor. Flow and transport occurred in the six 20-km-long streamtubes, which are about 3,000 m in width and 10–20 m in depth. The volumetric flow rate of each streamtube was determined at the water table from the unsaturated zone (UZ) site-scale model (Bodvarsson et al., 1997). The Darcy velocity into each streamtube was 0.6 m/yr under current climatic conditions. The cross-sectional area of each streamtube was proportional to the volumetric groundwater flow rate. The transport simulations were performed with a 5-m grid spacing in the streamtubes and a steady, unit radionuclide mass source at the upstream end of the streamtube. Nine radionuclides were simulated separately.

A convolution integral method, assuming linear system behavior and steady-state flow system, was used to determine the concentration of each of the radionuclides in the SZ at the receptor locations. This method provides an approximation of the transient radionuclide concentration at a specific point down gradient in the SZ in response to the transient radionuclide mass flux from transport in the UZ (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). This computationally efficient method makes full use of a single detailed transport realization for all subsequent TSPA-VA realizations. The input to the convolution integral approach includes a unit concentration breakthrough curve in response to a step-function mass flux source as simulated by the SZ flow and transport model and the radionuclide mass flux history as simulated by the UZ transport model (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). The effects of varying climatic conditions on RT were incorporated in the convolution integral simulations by varying the magnitude of groundwater flux and assuming there is an instantaneous change from one steady state to another due to climate change scenarios. The multiclimate convolution code was verified against a 3D SZ transport simulation using FEMHN, and the results compared well.

4.5.2.15 Dilution Processes in the Saturated Zone

Current hydrogeologic studies (Luckey, et al., 1996) indicate that radionuclides that enter the SZ beneath YM would generally flow to the south-southeast into western Jackass Flats through the welded tuff aquifer and then south-southwest into the Amargosa Desert, where the water table lies within an alluvial aquifer. Within the fractured tuffs, the migration of radionuclides is expected to be primarily through zones of higher bulk fracture permeability. Farther down-gradient, the migration is likely to be through alluvial sediments that can be modeled more defensibly as a porous media continuum than the flow and transport through the fractured tuff. Assessments of dose at 20 km are affected by the impact of the radionuclides migrating through the fractured tuff and the alluvial sediments of the Amargosa Desert. The location where the water table transitions from the tuffs to the overlying valley fill and alluvium is important because of differences in transport behavior between the fractured tuff and the alluvial sediments. However, the location of the transition is not well known.

Dilution of radionuclides in a potential plume emanating from the repository at YM can be taken as a function of all processes that will reduce the concentration of the radionuclide at the receptor point. The primary processes are the extent and magnitude of lateral flow beneath YM from the west and north, advective dispersion, molecular diffusion, intra-basin mixing of water caused by large-scale variations in the groundwater velocity field in the welded tuff and alluvial aquifers, well-bore mixing at a domestic or agricultural pumping well, sorption of radionuclides on the porous media, and decay of radionuclides. Although a strict definition of dilution would not include all these processes, they would be included from the perspective of PA. The first three processes are discussed in this section. Diffusion as incorporated into dispersion in the same continuum is discussed here; however, diffusion into another continuum, as is the case of diffusion from fracture flow into the matrix continuum, is discussed in the section on matrix diffusion. Sorption and decay are discussed in more detail in the IRSR for Radionuclide Transport (RT) (NRC, 1998d).

- **Dispersion**

Transport of radionuclides strongly depends on the distribution of velocities in a porous medium. At YM, the likely path for radionuclides moving to a potential critical group is through the fractured tuff and the alluvial sediment aquifers. At the large scale of the SZ modeling for YM, equivalent porous media representations for the fractured tuff and the alluvial sediments are presumed. At small scales the hydrologic properties of the fracture networks are highly anisotropic. Dispersive transport is presumed to be Fickian, i.e., the dispersive mass flux is proportional to the concentration gradient. While it is recognized that dispersion in fractured rock is physically different from dispersion in a porous media, similar expressions for dispersion are utilized.

Dispersion is caused by heterogeneities at all scales from the pore-scale to the stratigraphic layering-scale or the length between structural features such as faults. The largest features should be explicitly incorporated into the site-scale models. The dispersion due to smaller scale features is tied into a dispersion model, which, in its simplest form, is a function of seepage velocity and dispersivity. The scale dependency of dispersivity values has been noted in a wide variety of hydrogeologic environments including fractured rock (Gelhar, et al., 1992). Both longitudinal and horizontal transverse dispersivity increase with the scale of the problem, perhaps to an asymptotic level (Molz, et al., 1983). However, both the available data and geologic considerations suggest that they are bounded by some unknown limit, dependent on the additional heterogeneity encountered by solutes along the flow path. Vertical transverse dispersivity values do not exhibit a scale dependency (Gelhar, et al., 1992). Borehole tracer tests such as the C-hole complex test can be used to estimate site-specific dispersivity, although some caution is warranted. Strictly speaking, dispersivities determined using 1D models should only be applied in 1D predictive models since the calibrated value encompasses both longitudinal and transverse dispersion. Further uncertainty is introduced since longitudinal dispersivity is the calibrated parameter using borehole tracer tests, yet dilution may be more sensitive to transverse dispersivity.

The classical approach to modeling solute transport in porous media is to incorporate diffusion into the dispersion term, incorporate sorption by modifying the dispersion and velocity terms, and incorporate decay by adding an additional term to the equation (Huyakorn and Pinder, 1983). Diffusion may attenuate the plume by physically spreading the radionuclides, possibly into stagnant pore water areas. However, mechanical dispersion is more effective than diffusion at spreading a plume in areas of high velocities and less effective in extremely low-velocity areas. Solute transport in fractured rock may have the additional diffusion component of movement from the fracture into the matrix, thus providing a potentially large increase in the potential for sorbing of the radionuclides on the media. Dispersion is also affected by the connectivity, tortuosity, and multiple flow paths in the fractured tuffs. Splitting of a plume may occur as the plume migrates across a fault, depending on the offset of the conductive zones. Depending on the scale of the modeling, splitting of a plume may cause the apparent dispersivity to be larger than the actual value if the two portions were modeled separately. Convergence of a plume may similarly occur. The processes of decay and sorption are discussed in the IRSR for RT (NRC, 1998d).

Depending on the complexity of the problem and the availability of supporting data, the advective-dispersive equation may be solved analytically or numerically. Analytical solutions are valid only for steady-state flow conditions and homogeneous material properties, although transient transport solutions are readily developed. Analytical solutions for 1D, 2D, and 3D problems have been developed for a constant concentration source term and many source configurations (Wexler, 1992). A specified flux boundary condition may be desirable for the source term at the YM repository. Codell, et al. (1982) has utilized a convolution integral approach to transpose an instantaneous constant concentration source into a variable specified flux condition.

The impact of steady-state or transient models of flow on the extent of dispersion may be significant. As noted in Kessler and McGuire (1996), dispersive transport processes are relatively ineffective at reducing contaminant concentrations in a steady-state groundwater flow regime. If there are large temporal variations in the magnitude and direction of the groundwater velocity field, then mixing and attendant dilution during transport may be significant. Current conceptual models of the YM saturated groundwater system would suggest that the flow regime is relatively unperturbed by fluctuations in the magnitude and location of recharge and discharge. Increased pumping for irrigated agriculture in the Amargosa Farms area over the past 30 yr may have had some effect on the groundwater flow, but this should not significantly affect conditions near YM unless safe yields are exceeded. Pumping at J-12 and J-13 since the 1960's has probably had some local effects on the groundwater flow system. Young (1972) reported that wells J-13 and J-12 were pumped extensively from 1962 to 1967 to provide water supplies for the nearby Nuclear Rocket Development Station. Based on an estimated combined withdrawal rate of 350 gpm, about 900 million gallons of water were extracted during the five-year period, resulting in a water level decline at J-13 of only two feet. The work of Czarnecki (1992) is an important 10-year forecast of how future groundwater levels near YM will be affected by site characterization activities. It will be possible to see how well the regional USGS groundwater model predicted perturbations caused by pumping at wells J-12 and J-13.

- Intrabasin Mixing

Mixing of intrabasin waters is a concept useful in the streamtube approach for flow and transport. Water moving with radionuclides is assumed to mix with clean water from within the basin. Site-scale and regional models of flow suggest that the flow of water from the YM block mixes with other water in Fortymile Wash (Luckey, et al., 1996). Water moving southward along Fortymile Wash from north of YM may be larger in volumetric flux than the water coming from the YM block. However, Dr. Neuman (Geomatrix, 1998) suggested that there is no scientific basis to assume that the waters mix in Fortymile Wash. Recharge in Fortymile Wash, as another case of intrabasin mixing of water, is periodic and small, on the order of 1.3 % of precipitation (Savard, 1995: Osterkamp, et al., 1994). Savard (1998) estimated long-term groundwater recharge rates along four reaches of the Fortymile Wash drainage system using the total groundwater recharge estimates over three selected time periods: 1992-1995, 1983-1995, and 1969-1995. The following estimates were based on the 1969-1995 period.

Reach	Groundwater Recharge Rate (m^3/yr)
Fortymile Canyon	27,000
Upper Jackass Flats	1,100
Lower Jackass Flats	16,400
Amargosa Desert	64,300

The ability of groundwater flow characterization methods to predict flow patterns and magnitude, and hence, dilution and mixing, under climatic variation should be considered. This issue is briefly discussed herein. However, the performance of the potential repository should be assessed over periods of time sufficiently long that climatic variation will be a factor.

Climate is expected to change significantly during the many tens of thousands of years that disposed nuclear wastes will remain hazardous. Based on the paleorecord of glacial cycles, the long-term average climate over the period of repository performance will be cooler and wetter as compared to the current dry portion of the cycle. Changes in precipitation, and hence infiltration, will likely induce other changes, such as fluctuations in the elevation of the regional water table. Recharge over areas of the potential path of the radionuclides will impact the movement and shape of the plume. Therefore, it is essential that present-day percolation in the repository block and recharge in areas around the repository block be reasonably understood to predict estimated dilution under future conditions.

- **Dilution Due to Wellbore Mixing**

Borehole dilution refers to dilution of the resident contaminant concentrations in a wellbore due to pumping a well that captures both contaminated and uncontaminated portions of the aquifer. The most important factors that may significantly affect the borehole concentration are: (i) total pumping rate and well distribution in the well field, (ii) aquifer properties, (iii) hydrostratigraphy and anisotropy, (iv) well desigr (penetration depth, length, and location of screen), (v) vertical and horizontal contaminant plume distribution, and (vi) regional hydraulic gradient,. Analytical solutions for flow can incorporate the effects of these factors under certain restrictions for a sensitivity analysis. Two-dimensional capture zone analysis was developed by Javandel and Tsang (1986) using equations and a type-curve method for determining the shape of a capture zone of one or more fully penetrating wells. However, partially penetrating wells create 3D groundwater flow and transport systems. In the 3D case, vertical anisotropy (the ratio of horizontal to vertical hydraulic conductivity) can significantly affect the shape and size of the capture zone (Zlotnik, 1997). For a partially penetrating well in confined and unconfined aquifers, Bahr and Lahm (1996) presented solutions for capture zone analysis. Complex numerical models are generally required to analyze the effects of heterogeneity in the hydraulic properties and simulate complex plume configurations, especially if 3D effects are considered important, such as in partially penetrating wells.

Analytic solutions (Schafer, 1996; Faybishenko, et al., 1995; Grubb, 1993) and analytic element methods (Strack, 1989; Haitjema, 1995) have been published for estimating capture zones for partially penetrating wells in steady-state 3D flow fields. Sensitivity analyses of effects that include vertical movement of water or solute in a heterogeneous domain require the use of numerical models. Fedors and Wittmeyer (1998; Attachment B) combined an analytical solution for a partially penetrating well with an analytical solution for a patch-shaped source in a 3D field to estimate dilution factors. Numerical simulation methods implemented for 3D flow in the vicinity of a single well have been published in a number of articles (Bair and Lahm, 1996; Chiang, et al., 1995; Akindunni, et al., 1995; Reilly, et al., 1989). The methods for estimating dilution of solutes either use particle tracking or direct solution of advective-dispersive equation for the concentration.

The radionuclide dose to which users of the groundwater system, the critical group, may be exposed is controlled by several factors. Some of the more widely discussed factors include the engineered barrier systems at the location of the repository and the natural processes operating in the travel path such as dispersion, radionuclide decay and retardation processes. One factor that is not often discussed but which may be of importance in reducing radionuclide concentrations reaching the biosphere is dilution at receptor locations due to pumping. Dilution of this nature results from the mixing of contaminated and uncontaminated waters within well bores, thereby, reducing concentration. This process should not be confused with dilution along the flow path that is a consequence of dispersion processes operating within the aquifer.

DOE and NRC both recognize the potential importance of well bore dilution for achieving compliance at receptor locations as is discussed in the VA (DOE, 1998b) and the TPA Version 3.2 code. Indeed, not accounting for this process increases the potential radionuclide exposure to members of the critical group, and thus, may be viewed as a conservative estimate.

A standardized approach for defining dilution at pumping wells is lacking. Current approaches for modeling dilution at pumping wells are based on volumetric flux relationships or concentration relationships. However, despite the approach used, well bore dilution appears influenced by the following factors: pumping or extraction rate, well design parameters (e.g., the depth and length of the well screen), aquifer heterogeneity, plume release rate, dimensions and concentration distribution, and groundwater flow rates. Due to the number of parameters that influence well bore dilution, abstraction of this process into performance assessment (PA) methodologies is complicated.

In the VA (DOE, 1998b), DOE currently is not taking credit for dilution due to pumping. This position is stated in the following two excerpts:

> (vol. 3, chap. 5, sec. 5.8.2)
> "There is no dilution during withdrawal of water from the aquifer; that is, there is no mixing of contaminated water and uncontaminated water when water is pumped from the ground or when water is stored in a tank."

and

> (vol. 3, chap. 6, sec. 6.4.17)
> "No credit is taken for the pumping dilution in the base case analyses of the reference design."

As a result of its position, the DOE has not proposed any models for this phenomenon.

Standardized approaches for modeling and quantifying well bore dilution for abstraction into PA methodologies are currently lacking. Two approaches have been proposed in literature: volumetric flux-based methods and dispersive-transport-based methods. A summary of these methods is presented in the following paragraphs.

Volumetric flux-based dilution estimates are determined by comparing the dimensions of the migrating contaminant plume and the pumping well capture zone. With this approach, concentration variations along the flow path are not taken into account. Instead, the mass released into the system is considered the transported property. Using this approach, dilution may be quantified based on the ratio of the cross-sectional area of the capture zone to the cross-sectional area of the plume that intersects the capture a in the plane perpendicular to the principal direction of flow (Fedors and Wittmeyer, 1998). This approa allows for the quantification of dilution through dilution factors, which may be expressed as functions of the applied pumping rate. Because the method is based on purely volumetric relationships, no credit is given to the concentration distribution within the plume.

NRC TPA Version 3.2 code utilizes a volumetric approach to calculate radionuclide concentrations at a pumping well receptor location. This approach allows the explicit calculation of dilution factors at the well bore such as described by Fedors and Wittmeyer (1998). In the NRC TPA Version 3.2 code approach, the volumetric relationship of interest, used to calculate the mass of radionuclides reaching the receptor, is based on the fraction of the plume volume captured (Vc); for high-capacity pumping rates such as those associated with irrigation wells, it is assumed the entire plume volume is captured (Vc = 1), whereas for low-pumping rates such as those associated with residential wells, it is assumed only a fraction of the plume volume is captured (Vc<1).

Dispersive-transport models may also be used to estimate dilution at extraction well bores. With this approach, concentration variations along the transport path are explicitly taken into account. One such approach has been described by staff at Sandia National Laboratories (SNL) in CRWMS M&O (1997). In this study, well bore dilution factors were defined that related the concentration in the well bore to the maximum concentration adjacent to the well bore. Fedors and Wittmeyer (1998) also proposed an approach for quantifying dilution at extraction wells for the dispersive-transport scenario. Under this approach, dilution factors at the well bore were determined based on the ratio between the integrated concentration distribution across the portion of the plume captured and the source concentration. Dilution factors defined in this manner may also be expressed as applied pumping rate.

Despite the approach used to quantify dilution at the well bore, a common finding is that the estimate is sensitive to the following factors (i) extraction rate at the well, (ii) hydraulic properties of the medium, (iii) well design characteristics, and (iv) plume geometry. Because DOE currently is not accounting for dilution due to pumping in the TSPA-VA (DOE, 1998b), the reviewers have no concerns. Should the DOE revise its position and decide to take credit for dilution at pumping wells, we have provided an appropriate acceptance criterion (see section 5).

- Estimates of Dilution in Performance Assessment

As discussed above, a number of approaches for incorporating dilution into PA have been used in TSPA efforts. There is a direct connection between dilution of radionuclides in the groundwater and the reduction of dose to a critical group. However, different types of dilution factors, not all of them consistent, are developed, depending on the approach. In one approach, the dilution factor due to dispersion of a solute during transport is calculated as the ratio of concentration at the source area to that at the receptor point. The second approach addresses dilution due to mixing and is calculated as the mass release rate divided by the largest flux of water into which the solute may be mixed and used by a critical group. The third approach addresses dilution due to the intersection of the capture zone of a pumping well with the plume configuration at the withdrawal location. The dilution factor due to wellbore mixing is calculated as the ratio of the plume area intercepted by the capture area and the entire capture area. The third approach describes borehole dilution from the geometric standpoint. It may be linearly combined with the first approach for a total borehole dilution factor. Usage of the first two approaches is further described below.

Baca, et al. (1996) and Kessler and McGuire (1996) used the first approach to calculate dilution factors of 5 to 50 due to dispersion in an aquifer at a single point. Under assumptions of steady-state flow, estimated dilution factors due to dispersive mixing along the SZ transport pathway from the proposed YM repository to locations 20 to 30 km to the south have ranged from 5 to 50 for Baca, et al. (1996) using 2D finite-element model and from 4 to 44 for Kessler and McGuire (1996) using an analytical solution for 3D transport. Baca et al. (1996) contoured the point dilution factor, while Kessler and McGuire (1996) tabulated point dilution factors based on centerline concentration. In TSPA-93 (Wilson et al., 1994), dilution factors for 5 km ranged from 5 to 20, although initial mixing below the repository was not included. TSPA-95 (TRW Environmental Safety Systems, Inc., 1995) dilution factors based on centerline concentration values ranged from 4,500 to 190,000 at 5 km and 31,000 to 1,300,000 for 30 km. The large dilution factors are believed to be due to the use of large transverse dispersivity values. In TSPA-95, a dilution factor of 3.5 was used due solely to mixing of waters from groundwater basins influent to the central region of the Amargosa Desert.

Using an analytical solution for a single partially penetrating well, dilution factors ranged from 1 to 40 for the 25-km location when calculated based on geometric considerations for a capture zone and the shape of a plume. The large irrigation wells typically had higher dilution factors than the domestic and quasi-municipal wells. Dilution factors were less than 80 when based solely on the distribution of radionuclides in the portion of the plume captured at the 25-km location. Values of dispersivity in the three directions had a large impact on the dilution factor; dispersivity ratios between 100:10:1 m to 20:2:0.2 m were used.

The current approach used by the DOE for estimating a dilution factor is to use an equivalent porous media approach to simulate numerous 3D solutions of flow and transport (Arnold, 1998). The FEHM code is used with the option for the direct solution of the advective-dispersive equation to create a library of solutions from which the PA simulations may draw solutions (TRW Environmental Safety Systems, Inc., 1997a). Problems with incorporating reasonable values of vertical dispersivity in the numerical simulation are leading DOE to alternative approaches for incorporating vertical dispersion at this time. For 20-km flowpaths, DOE appears to be using dilution factors that range from 1-100, with a median value of 12. These estimates were derived from the conclusions of three members of a five-member expert panel (Geomatrix, 1998), and consider dispersion effects. The other two panel members did not estimate the dilution range. The estimates do not include the additional effects of dilution within wellbores or intrabasin mixing. Two experts questioned the concept of a mixing depth below the repository horizon.

4.5.2.16 Uncertainties in the Data and Conceptual Model Flow System

The current conceptual SZ flow model used in the performance assessment of YM assumes that the measured uppermost water levels in the volcanic sequence represent hydrostratigraphic intervals in a laterally continuous ground water flow regime. But, as stated by Luckey, et al. (1996) and Czarnecki, et al. (1997), data uncertainties and variability result in uncertainties in the conceptual models of the flow system. Luckey, et al. (1996, page 52) stated, "No matter how well the saturated-zone flow system at Yucca Mountain and vicinity is described, uncertainty will always remain." Snow (1972, p. G1-1), summarizing numerous investigations of fractured media, pointed out that the description of fractures "...can never be complete. Fractures are neither parallel, uniform, plane, smooth, regularly spaced nor uninterrupted." Because of this, fracture "permeability will remain empirical in nature." Stearns (1968, p. 97) commented that the path to a "complete understanding of fractures in the deformation history of rocks is an overwhelming mystery." In discussing the potentiometric surface at YM, Czarnecki et al (1997, page 25) stated, "Because the potentiometric data dictate a complex three-dimensional flow system, a number of different conceptual models of the flow system are possible. In particular, the different conceptual models may result in different potentiometric surfaces. Although the boreholes are open at different depths below the hydraulic head and are open to different geologic zones, water levels in most of the wells appear to represent a laterally continuous aquifer system. The well-connected system may result from the presei of many faults and fractures...and, at the scale of the site model, the ground-water flow system may behave as a porous medium."

The following are specific data and conceptual ground water flow model uncertainties described by Luckey, et al. (1996): (1) the potentiometric surface of the carbonate rocks beneath and in the vicinity of YM and its relationship to the lower volcanic confining unit and the lower volcanic aquifer;(2) how ground water flow moves through the Timber Mountain area and its relationship to the regional scale flow system; (3) the volume of ground water that flows beneath YM; (4) the uncertainty about how the flow system behaves in the area of the large hydraulic gradient and the moderate hydraulic gradient; (5) whether numerical modeling should represent the system as either a porous-media continuum or as a finite number of discrete fracture; (6) the time scale at which the flow system comes into equilibrium with climate, and thus recharge; (7) the transmissivities (or hydraulic conductivities) on a scale large enough to be representative of the site-scale flow system; (8) the storage properties, though not needed for steady state flow simulations, which are important in estimates of ground-water velocities and transport; (9) the amount of discharge from the Alkali Flat-Furnace Creek Ranch subbasin of the Death Valley regional flow system, and (10) the hydrochemical characterization of the site.

Czarnecki, et al. (1997) also identified several data uncertainties which result in limitations of the ground water flow model. These included 1) the spatial variability of permeability due to limited multi-well hydraulic test data, 2) variations in temperature within the flow system, 3) an understanding of the large hydraulic gradient, and 4) the flux, or the amount of recharge, into and out of the flow domain.

In view of the data variability and uncertainties described by Luckey, et al. (1996) and Czarnecki, et al. (1997), the staff concludes that a definitive delineation of groundwater flow pathways at YM may not be possible based on currently available data and interpretations. In the "real world" state-of-the-art practi hydrology it is rare that groundwater investigations can provide such definitive interpretations, given the variability introduced by subsurface stratigraphy and structure and the generalizing assumptions that should be made to interpret hydrologic and tracer tests.

The lack of hydrologic data for valley fill is a data gap in DOE's site characterization of saturated zone hydrology. Emphasis should be placed on reasonable determinations of heads, transmissivity, hydraulic conductivity, effective porosity, and dispersion coefficients. The hydraulic and geochemical characteristics of the likely flowpath that exists south of well JF-3 have not been evaluated. It is unknown at which locations the water table transitions from fractured tuff to overlying valley fill. The hydraulic properties, and geochemical properties of valley fill have not been determined for the region that lies between well JF-3 and the Amargosa Desert. DOE's cooperative well drilling program with Nye County, Nevada could accomplish this if the wells are sited and tested to characterize the hydrology along likely flow paths in a timely manner. Large data gaps between Nye County wells could be augmented by exploratory drilling methods.

The first set of data from Nye County wells has recently been received at NRC (Nye County, 1999). Some of the Nye County wells are located outside of potential pathways. However, three new wells, 2D, Washburn 1-X, and 5S have been added to the south and southeast in the valley fill aquifer. These three wells confirm that the water table lies within thick valley-fill deposits and that none of the wells penetrated the Paleozoic carbonate aquifer. The presence of thick alluvial deposits is favorable for the YM site.

However, there still remains a significant data gap south of well JF-3 where Nye County plans new well drilling.

The staff believe that the three-phase SZ testing strategy described in Reimus, et al. (1998) could, if implemented, significantly improve understanding of the hydrogeologic system. New wells may be needed, but possible locations for such testing using existing wells would include (1) J-12, JF-3, and J-13; (2) H-4, SD-12, and WT-2; or (3) SD-6 and H-5. Other combinations are also possible, and other wells could be expected to respond to long-term pumping tests. Because fractures and faults have preferred orientations, and can act as preferred flow pathways, quantitative studies require that more than one representative elementary volume of rock be sampled.

Based on the staff's current understanding of the site saturated zone, potential flow paths for radionuclides that in future may escape from the proposed repository are likely to follow the paths defined in the current NRC/CNWRA numerical model. They are expected to migrate over thousands of years southeast (i.e., along the natural hydraulic gradient) from the repository along fracture-dominated pathways in the general direction of well J-12, and thence southward (paralleling Fortymile Wash) in saturated valley fill toward the Amargosa Desert (NRC, 1998c). This is the general direction of flow that was interpreted by panelists in a recent expert elicitation on the site saturated zone (Geomatrix, 1998), and is also the flow pattern that is best supported by available site data, including hydraulic heads, results of pumping tests, and the presence of pervasive fracture networks in the tuffs. Southeasterly flow is the direction used in the NRC/CNWRA performance assessment model where saturated zone flow and transport are simulated in a series of stream tubes. However, we now assume that the tuff aquifer could range from being isotropic to highly anisotropic in transmissivity. Anisotropy could induce more southerly flow paths. We therefore find that some due-south flowpaths should be included in performance assessments to bound the range of reasonable paths. The southerly paths would have reduced lengths of saturated valley fill. Data available to date suggest that thick valley fill exists at the 20-km distance for various flowpaths.

The southeasterly flow path assumes that the fractured tuff aquifer is an equivalent porous medium at the site scale under isotropic conditions. Treating the aquifer as an equivalent medium at a large scale is supported by the pervasiveness in the tuffs of faults and fractures oriented in many directions, and by results of long-term testing at the C-wells. Geldon, et al. (1997, background, p. 11) observed that "Despite having dual permeability, rock within about 3 km of the C-hole complex consistently responds to pumping tests as an equivalent porous medium." The staff does not know if these conditions would apply over the entire site, but it is very useful to have this information, including large-scale estimates of hydraulic properties, from a long-term test downgradient from the site. The long-term C-wells test demonstrated hydraulic connection (i.e., induced drawdown) in an approximate radial flow pattern. According to Reimus, et al. (1998), four wells (WT-4, b#1, H-1, and WT-1), in addition to those specifically used as observation wells in the test, also responded to pumping at UE-25 c#3. Drawdown was observed along directions coincident with the approximate direction of the natural hydraulic gradient and northwest trending faults. Staff will continue our analysis of the previous and ongoing C-wells testing.

Groundwater flow in the tuff aquifer is dominated by structural features. This causes anisotropic conditions where structures may act as high- and/or low-permeability zones, and this is most evident at small spatial scales. At larger scales the hydrologic properties of interconnected fault and fracture networks are expected to dominate flow conditions. Because of uncertainties about large-scale anisotropy, current DOE simulations assume that ~10-percent of transport pathways never come into contact with saturated valley fill. There are presently no data concerning the isotropy of saturated valley-fill materials.

Merrill, et al. (1999) show that anisotropy in the fractured tuff aquifers could indeed significantly influenc flow directions. They concluded that:

> The dominant north-south (~005) trend of faults at Yucca Mountain, coupled with slip-tendency and dilation-tendency considerations suggest anisotropic transmissivity, with maximum transmissivity in the azimuth range between 005 and 030. The anisotropic transmissivity estimated at Yucca Mountain has a maximum principal direction of approximately 030, consistent with the hypothesis that transmissivity is controlled by faults and fractures in the present-day in situ stress field.

Merrill, et al. (1999) also noted that "Because of uncertainty associated with aquifer pumping tests, and the limitation of having only the minimum number of data points to constrain an ellipse, the ratio of minimum to maximum directional transmissivity is poorly constrained." However, even if the aquifer is highly anisotropic, we find that a due-south flow direction effectively bounds flow paths on the west. Analyses of the C-wells pumping tests show that the data support a broad interpretation ranging from isotropic to highly anisotropic conditions in transmissivity. Therefore, we have developed a bounding approach to encompass all reasonable horizontal flowpaths. We find that these flowpaths are constrained within a 25° arc of azimuth, bounded on the west by a line running due south from the repository site, and on the east by a line running through Nye well 5S.

Flow conditions in the Paleozoic carbonate aquifer beneath YM are known from only one well, UE25 p#1. Heads in this well are about 22 m higher in the Paleozoic carbonate aquifer and lower volcanic confining units than in the Crater Flat tuffs (lower volcanic aquifer), indicating a strong upward gradient. Likewise, heads in the lower volcanic confining units in wells H-1 and H-3 are also higher than in the Crater Flat Tuffs, providing evidence that significant upward hydraulic potentials probably exist over most of the site east of Solitario Canyon. This condition is favorable for waste isolation because an upward gradient, if maintained in the future, would protect the deep Paleozoic carbonate aquifers from contamination. DOE's cooperative drilling program with Nye County, NV, should provide timely additional data regarding the vertical gradie between the Paleozoic carbonate aquifers and overlying tuffs or valley fill. However, none of the Nye w to date has reached the carbonates. It should also be noted that large differences in groundwater chemistry (Oliver and Root, 1997) between the carbonate aquifer system and the Crater Flat tuffs suggest that upward fluxes are relatively small compared to those introduced by lateral flow within the tuffs.

The staff's current model is subject to revision as new site data are collected and analyzed. The staff continues to analyze whether there are other viable SZ conceptual flow models which can be supported by currently available data.

- **Heterogeneity and flow channelization**

The base case considered in DOE's viability assessment assumed that the hydraulic properties of hydrostratigraphic units beneath YM are uniform. Faults were considered as offsets in the hydrostratigraphic framework, but potential permeability enhancements near or along faults were not considered. These simplifications of the complex geological system neglect potential connected high-permeability pathways and flow channeling induced by small-scale permeability heterogeneities. The sensitivity of repository performance to these simplifications was addressed in the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). The introduction of permeability heterogeneity is a significant advance over the base case scenario. However, these sensitivity studies are based on limited heterogeneity characterization and contain unjustified assumptions and potential numerical artifacts that may be masking the underlying effects.

Of greatest concern is numerical dispersion in the coarsely gridded solution to the advection-dispersion equation. Although the base case scenario used a streamtube approach to avoid the issue of numerical dispersion, the heterogeneity studies used a conventional 3D finite element solution with 500 × 500 × 50 m elements. Numerical dispersion in this coarsely gridded model is unacceptably large and probably masks any differences between the heterogeneous and base case models. The simulations do not address in a credible manner the topic of heterogeneity-induced flow channeling.

The DOE study of sensitivity to flow channeling and fast flow paths employed geostatistical simulation methods to create realizations of permeability. The average bulk permeability in each unit was constrained to match the permeability obtained by calibrating to hydraulic head measurements. In one set of simulations, permeability enhancements associated with major mapped faults were also added to the heterogeneous property distributions. In both situations, the resulting hydraulic heads matched measured values at least as well as the base case with uniform properties, indicating that the existence of high-permeability zones along or near faults cannot be ruled out solely using measured heads.

The heterogeneity model employed for the fractured units is poorly constrained by heterogeneity data and is nonconservative. The study used the geostatistical technique sequential Gaussian simulation (SGS) to create realizations of the permeability in the fractured volcanic units. The correlation range used in the model was not estimated from permeability data directly due to sparseness of data. It was estimated instead from matrix porosity data presumed correlated with the degree of welding, and thus, the permeability of the fracture system. The standard deviation in the logarithm of permeability, another important parameter in the SGS algorithm, was reduced by a factor of one-half from the available well-derived permeability measurements to account for the different scales of the simulated and measured permeabilities.

The mathematical model underlying the SGS algorithm, the multi-Gaussian model, is known to be nonconservative for contaminant transport. That is, it is possible to construct alternative models with more flow channeling and the same two-point correlation structure and univariate statistics (Rubin and Journel, 1991). The multi-Gaussian model tends to produce isolated values of high permeability distributed more or less uniformly throughout the simulation domain, whereas geological systems may have more connected regions of high permeability leading to more flow channeling. Given this bias in the SGS algorithm and the limited characterization of the fractured units, the topic of potential flow channeling in the fractured units is not addressed adequately. At the least, the consequences of assuming the multi-Gaussian model for heterogeneity need to be assessed.

Permeability characterization of the alluvium is even more limited than the fractured units. Here DOE relied on more geologically based methods. Categorical (indicator) methods were used for the simulation. Two classes were used in the simulation, a low-permeability class corresponding to fine-grained paleosols and debris flow deposits and a higher-permeability class corresponding to coarse-grained sands deposited during flood events. Qualitative information obtained from similar alluvium deposits in nearby Frenchman's Flat were used to constrain the model parameters. In general terms, this approach may be more defensible than the SGS approach used for the fractured units, despite the lack of direct characterization of the valley/fill alluvium. Indicator simulation does not suffer the same limitations as the SGS method. In particular, it is able to better reproduce connected regions of high permeability. Nevertheless, the characterization requirements are greater for the alluvium compared to the volcanic aquifer because repository performance is known from sensitivity studies to be much more sensitive to the hydraulic properties of the alluvium. The DOE heterogeneity models would be more defensible if based on direct measurements of hydraulic properties in the alluvium.

Permeability enhancements associated with major faults could potentially provide radionuclides with fast pathways through the tuff portions of SZ pathways. DOE addressed the sensitivity of transport to these potential features by enhancing permeability in grid blocks crossed by major faults. Each of these grid blocks was assigned a permeability value of 1×10^{-11} m^2, consistent with values inferred from multiwell testing of the faulted interval in the C-Wells. Potential anisotropies in the permeability were not considered. Depending on the details of the flow geometry, such permeability anisotropies may act to channel flow more efficiently than the isotropic permeability model employed by DOE.

DOE and NRC have both recognized the potential significant controls structures exert on groundwater flow and resulting potential radionuclide migration pathways at YM (Civilian Radioactive Waste Management System, Management and Operating System, 1998). Lehman and Brown (1996) suggested that the failure to account for structural controls of groundwater flow and transport could adversely affect estimates of potential radionuclide exposure to members of the critical group. However, the sensitivity analyses by NRC/CNWRA suggest that the radionuclide dose is much more sensitive to the properties of valley fill and alluvium than it is to tuff properties. We believe that the valley fill will have slower groundwater velocities and higher retardation potential, including matrix diffusion. Therefore, characterizing the valley fill should be a higher priority effort. We also believe that the effects of structures on flow paths can be effectively bounded by assuming a range of flowpaths based on varying aquifer anisotropy.

4.6 MATRIX DIFFUSION

The staff's technical review of DOE's treatment of matrix diffusion will be based on an evaluation of the completeness and applicability of the data and evaluations presented by DOE. It is expected that DOE will summarize or document the results of all significant matrix diffusion-related studies that have been conducted in the YM vicinity or in DOE laboratories. The staff will determine whether DOE has reasonably complied with the acceptance criteria listed below.

4.6.1 Acceptance Criteria

The following are acceptance criteria for matrix diffusion in the unsaturated and saturated zones:

(1) If credit for matrix diffusion in the UZ is taken, then transport predictions must be consistent with site geochemical and isotopic data.

(2) If credit for matrix diffusion in the SZ is taken, rock matrix and solute diffusion parameters must be (i) based on a SZ transport model that reasonably matches the results of the field tracer tests that are conducted over different distance scales and flow rates with multiple tracers of different diffusive properties, and (ii) consistent with laboratory data.

(3) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

(4) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

4.6.2 Technical Basis for Review Methods and Acceptance Criteria

A discussion of matrix diffusion theory; available conceptual models; model parameter sensitivity; laboratory, field, and modeling investigations relevant to YM repository performance; and recommendations for further research can be found in Winterle (1998), which is included in Attachment C. The following sections summarize the NRC staff's understanding of matrix diffusion in terms of implications for repository performance, and the defensibility of the DOE approach to abstracting UZ and SZ matrix diffusion into a YM TSPA model. Figure 13 illustrates 1D breakthrough curves for three transport scenarios for a constant-flux source of a long-lived, nonsorbing tracer that can diffuse into rock matrix separated by equally spaced fractures (refer to Attachment C for model specifics). When diffusion is very slow relative to the transport time, the impact is negligible in terms of initial solute arrival time, but there is a slight long-term attenuation of peak solute concentration. If diffusion is fast relative to transport time, the impact is a significant delay in solute arrival at the receptor point. At intermediate diffusion rates, the impact is a modest delay in initial solute arrival time, with significant attenuation of solute concentration. For comparison, breakthrough curves for zero matrix diffusion and infinitely fast matrix diffusion are also shown (solid lines).

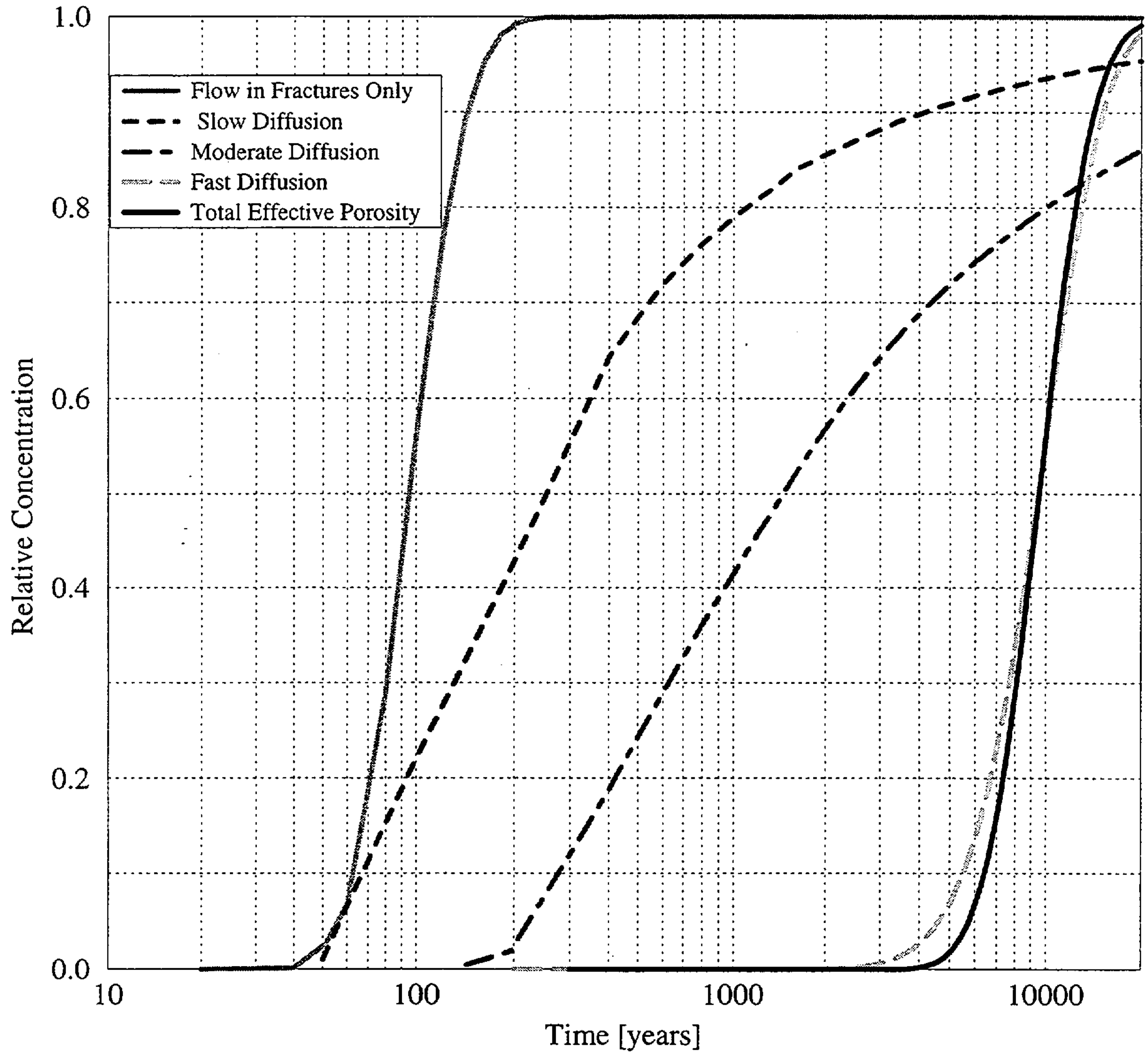

Figure 13. Dashed lines show differences in solute breakthrough for slow, moderate, and fast matrix diffusion scenarios. Solid lines represent flow in fractures only (no matrix diffusion) and uniform flow through the total system porosity (complete and rapid diffusive exchange).

It is important to note in Figure 13 that, although the slow diffusion case results in earlier tracer arrival time, the long-term attenuation of peak solute concentration lasts much longer than in either of the faster diffusion scenarios. The implications of this behavior on repository performance depend, to a large extent, on the release scenario and whether compliance with performance standards is dependent on meeting a time-based criterion or a concentration-based criterion. For example, consider performance criteria that require (i) peak doses at the receptor point to be less than 25 mrem/yr, and (ii) a compliance period of 10 ky. Under a scenario in which long-lived radionuclides (e.g., Np, Pu) that are only slightly in excess of the 25 mrem standard are released early, all the scenarios illustrated in Figure 13 would result in contaminant arrival in less than 10 ky, but in the slow-diffusion scenario, the reduction in peak concentration lasts well beyond 10 ky. Thus, in certain scenarios, it is possible for slow matrix diffusion to be more desirable than rapid matrix diffusion in terms of achieving compliance with performance standards.

Previous attempts to incorporate matrix diffusion into TSPA models are summarized in Attachment C. More recently the DOE has used a Residence-Time Transfer Function (RTTF) particle tracking model (Robinson, et al., 1997) to abstract the effects of UZ matrix diffusion into the TSPA model. Additionally, an increased-effective-porosity approach (Zyvoloski, et al., 1997) has been proposed by the DOE to abstract matrix diffusion effects in the SZ. These matrix diffusion conceptual models for the UZ and SZ are discussed separately in the following sections.

4.6.3 Determination of Diffusion Model Input Parameters

In order to assess the relative importance of matrix diffusion in the overall performance of the proposed repository, it is necessary to have, at a minimum, knowledge of the following three model parameters: (i) effective pore-water diffusion coefficients for each radionuclide of concern; (ii) the effective spacing between flowing fractures; and (iii) mean groundwater flow velocity.

In general, effective matrix diffusion coefficients for YM rocks have been well-studied in laboratory experiments conducted at LANL. Discussion of methods and results of previous laboratory experiments at LANL and elsewhere may be found in Attachment C. In the most recent laboratory studies reported by Triay, et al. (1996), effective diffusion coefficients for non-sorbing tracers ranged from approximately 1×10^{-10} m^2/s to 5×10^{-11} m^2/s depending upon rock and solute properties. This range of diffusion coefficients is reasonable when compared to literature surveys of similar matrix diffusion experiments in low-porosity rocks (e.g., Ohlsson and Neretnieks, 1995). However, the NRC staff remain cautious about applying laboratory-determined diffusion coefficients to in-situ rocks for the following reasons:

- It is not clear whether samples collected from YM for diffusion experiments are representative of zones of preferential groundwater flow.
- Release of in-situ stress and subsequent mechanical stress during sample preparation can result in significant increases of estimated diffusion coefficients.
- Laboratory methods typically rely on measurement of solute concentrations outside of the actual rock sample and therefore yield no information about how solutes diffuse through rock or the volume of the rock sample that participates in the diffusive transport process.

The 1D ^{3}H transport model for the Nevada Test Site (DOE, 1997b) included matrix diffusion as a mechanism for retardation. Limited site-specific batch sorption experiments using fabricated rock beakers from USW G-4, USW G-3, and a TSw formation outcrop (Triay, 1993), yielded ^{3}H effective diffusion coefficients ranging from 1.0 x 10^{-10} to 3.5 x 10^{-10} (m^2/s). The DOE (1997) used effective diffusion coefficients that ranged from 8.2 x 10^{-12} to 2.5 x 10^{-10} m^2/s after reviewing available literature and site-specific data. A log-normal distribution was chosen to describe the variation in the diffusion coefficient with a $\log_{10}$ mean of −10.34 and a $\log_{10}$ standard deviation of 0.24.

Confidence in the applicability of existing data on effective matrix diffusion coefficients could be increased by conducting comparable experiments on samples that are collected from drill cores from known zones of preferential groundwater flow. Analyses could also be conducted to evaluate the impact of in-situ stresses on the diffusion of solutes through matrix pore waters. Additionally, methods have been recently developed by which diffusion of tracers through rock matrix can be directly visualized using x-ray techniques (e.g., Tidwell, et al., 1997); the argument for the occurrence of matrix diffusion in YM rock samples could be bolstered significantly by the ability to visualize the solutes as they move through the sample. Visualization could also be useful for determining whether diffusive transport may be dominated by movement of solutes through microfractures introduced during sample preparation.

By far the greatest uncertainties in assessing the role of matrix diffusion in repository performance lies in the paucity of data related to the effective spacing between flowing fractures and effective groundwater flow velocities. It is likely that these two parameters are correlated because, for a given groundwater flux, flow through many closely spaced fractures is likely to be a result of a higher effective flow (fracture) porosity, and hence, a lower groundwater velocity. Some light has been shed on effective flow porosities by the C-hole tracer tests, but much work remains to be done to obtain reliable estimates of flow velocity and spacing between flowing fractures. Flowmeter tests performed on numerous site wells by the USGS are a source of information on effective spacing between flowing fractures. These tests show that pumped wells in the fractured tuffs produce most of their water from a few discrete zones which tend to be separated by tens to hundreds of meters. In the meantime, the DOE approach has been to evaluate repository performance in their PA models over the entire range of possible values for these parameters.

4.6.4 Matrix Diffusion in the Unsaturated Zone

According to TRW Environmental Safety Systems, Inc. (1997a), diffusion of solutes from fractures into the matrix of the volcanic tuffs is expected to contribute significantly to the effective retardation of radionuclide movement in both the UZ and SZ. However, Bodvarsson and Bandurraga (1997) conclude that, although flowing fractures are pervasive enough in the YM UZ to be treated as a continuum for flow modeling, the fractures seem to have limited interaction with the matrix. This limited interaction may be due to low-permeability fracture coatings that have been found to significantly reduce imbibition into the matrix of YM tuff samples (Thoma, et al., 1992). If the reduced permeability caused by fracture coatings is due to the blockage of matrix pores at the interface, then a reduction in the effective diffusion coefficient for any given solute would also be expected. Another possible explanation for reduced imbibition is that altered fracture surfaces may create capillary barriers at the fracture-matrix interface; this would have little effect on matrix diffusion. Results of matrix diffusion experiments on natural fracture surfaces of YM tuffs, though preliminary, seem to suggest that the effect of fracture coatings on matrix diffusion is minimal.[4]

Geochemical evidence for limited matrix diffusion in the UZ is provided by White, et al. (1980) and Murphy and Pabalan (1994), who point out significant differences between the geochemical signatures of fracture

[4]Triay, I. 1998, Los Alamos National Laboratory, personal communication.

water and matrix pore water in the UZ near YM and at Rainier Mesa. Murphy and Pabalan also point out similarities between fracture water at Rainier Mesa, and YM SZ water. Yang, et al. (1996) presented YM data showing marked differences in the geochemical signatures of UZ pore waters and SZ well water, and similarities between perched zone water at YM and SZ water. If perched zone and SZ water geochemistry are indicative of fracture water in the UZ at YM (as they appear to be at Rainier Mesa), then one can conclude that matrix diffusion in the UZ is somewhat limited over the time scale of fluctuations in the geochemical signature of fracture water.

Natural analogue studies have also been used to suggest limited matrix diffusion in the UZ. For example, investigations of the Nopal I uranium-deposit (Pearce, et al., 1995) in the Peña Blanca mining district of Mexico revealed that occurrence of uranium in unfractured tuff matrix was limited to distances less than 1 mm from uranium enriched fracture filling minerals. Many other natural analogue studies suggest limited matrix diffusion: for example, Ohlsson and Neretnieks (1995), after reviewing several natural analogue studies, concluded that matrix diffusion seems to be limited to weathered or altered zones. Poorly constrained initial and boundary conditions, and the action of other possible transport mechanisms (e.g., imbibition, evaporation), make it difficult to draw unambiguous conclusions regarding matrix diffusion from analog studies.

The DOE has chosen to include UZ matrix diffusion in its most recent TSPA model. A new particle tracking technique, developed by Robinson, et al. (1997), is used to generate radionuclide source functions as a boundary condition for the SZ in the TSPA model. This particle tracking model has several possible modes of operation, which include: the use of a residence-time transfer function (RTTF) to account for the effects of matrix diffusion, and the choice of either a single-continuum or a dual-permeability model formulation. Based on this approach, Robinson, et al. (1997) conducted analyses of sensitivity to matrix diffusion in their 3D UZ transport model that show the potential for nearly hundred-fold increases in transport time from the repository to the water table.

NRC staff have two specific concerns with the DOE approach to UZ RT. First, the RTTF for matrix diffusion is based on an assumption that solutes enter matrix by diffusion only (Tang, et al., 1981), which is invalid when the dual-permeability formulation is used. It is possible that this invalid assumption still provides a reasonable approximation of UZ transport processes; however, no analyses or modeling results have been put forward to demonstrate the reasonableness of this method. A series of simple 1D models, covering a range of transport scenarios, could be used to provide such a demonstration. A second concern is that the DOE UZ transport model does not address the previously mentioned lack of geochemical equilibrium between matrix and fractures in the UZ. Clearly, it is possible to have significant matrix diffusion, in terms of repository performance, without resulting in complete geochemical equilibrium between matrix and fractures. The DOE could greatly improve the defensibility of its UZ transport model by calibrating model results to agree, at least qualitatively, with UZ geochemical evidence for limited matrix diffusion.

An additional concern is that a range and distribution of effective diffusion coefficients used to generate RTTFs has not been specified. If the RTTF algorithm is used by DOE to account for matrix diffusion in the UZ in their PA models of YM, the range and distribution of effective distribution coefficients, and the basis for their selection should be completely transparent.

4.6.5 Matrix Diffusion in the Saturated Zone

The DOE conceptual model for radionuclide transport in the SZ also includes matrix diffusion. According to Zyvoloski, et al. (1997), migration of radionuclides in the fractured tuff aquifer is expected to occur primarily through regions of higher fracture permeability; it is speculated that flow within individual joints probably occurs in channels rather than as sheet flow through parallel-plate fractures. In the development of the conceptual model, Zyvoloski et al. (1997) cite the interwell tracer tests at the C-wells (Reimus and Turin, 1997) as being the most relevant evidence pointing to the validity of matrix-diffusion models. These tests used tracers with different diffusion coefficients to show that differences in solute transport could be detected in accordance with matrix-diffusion model predictions (section 4.5.2.8).

A TSPA Peer Review Panel (TRW Environmental Safety Systems, Inc., 1997b) cited a report by Robinson (1994) in which numerical simulations were used to estimate "approximately complete diffusive exchange between the fractures and matrix for travel times in excess of 100 yr." However, such an assertion can only be true if it is assumed that the distance between flowing fractures is on the order of about 1 m or less. Conversely, an expert elicitation panel (Geomatrix, 1998) provided estimates of the distance between significant flowing fractures at YM that ranged from 10 to 100 m. Using even the lowest value in the range given by the expert elicitation panel, the time scale required to achieve effectively complete diffusive exchange between fractures and matrix increases by more than a factor of 100 (the time-scale for diffusive transport increases in proportion to the fracture spacing squared). Thus, the NRC staff believes that it would be unwise to assume *a priori* that complete diffusive exchange will occur between matrix pore water and solutes flowing in fractures.

The current DOE approach to abstraction of matrix diffusion in the TSPA model is to use a range of "effective porosities" to account for the combined uncertainties in fracture porosity and matrix diffusion effects (Zyvoloski, et al., 1997). The rationale for this approach is that the increased solute transport time caused by matrix diffusion can be accounted for by simply assuming a higher flow porosity and, hence, slower groundwater velocity. This abstraction method applies only to solute transport in fractured rock; it is assumed that matrix diffusion is not an important process for transport in saturated valley fill. Because the impact of matrix diffusion is affected by fracture spacing, groundwater flow velocity, matrix physical and geochemical properties, and solute diffusion coefficients, the uncertainties in all of these parameters ar tacitly encompassed by the use of a range of effective porosity. While the NRC staff believe that this approach has merit, the technical basis for selecting a range and probabilistic distribution of effective porosities has not been clearly identified. For example, at a recent DOE/NRC Technical Exchange, Arnold (1998) presented a range of effective porosities from 0.0001 to 0.2 with a log-triangular distribution and a mean of 0.02. The low end of this range is based on estimates of minimum fracture porosity beneath YM (little or no matrix diffusion); the high end of the range is based on average total porosity (complete diffusive exchange). However, the basis for selecting the mean value of 0.02 and the log-triangular distribution is not clear. As pointed out by the PA Peer Review Panel (DOE, 1998a), the effect of matrix diffusion is time-dependent, and therefore effective porosities should also be time-dependent. Additionally, rates of diffusion and fracture spacings also affect the overall significance of matrix diffusion. As such, technical justification for the effective porosity distribution used in the DOE PA model should be based on reasonable ranges of the following: time-scales for transport; effective spacing between flowing fractures; and effective diffusion coefficients.

The DOE is currently using a range of effective porosity in their PA model that is based on estimates made during the SZ expert elicitation (Geomatrix, 1998). Currently, the range of effective porosity proposed by the DOE is from 0.0001 to 0.2, with a log-triangular distribution and a mean value of 0.02[5]. The mean value of 0.02 is consistent with the previously mentioned observations in the C-wells complex tracer tests; the lower bound of this range is based on estimates for sparsely fractured rock (little or no matrix diffusion), and

[5]Arnold. B. 1998. Sandia National Laboratory, personal communication .

the upper bound is based on the full matrix porosity (complete diffusive exchange) in order to account for the possibility of rapid matrix diffusion. Ongoing tracer tests in the C-wells complex may help to shed additional light on this critical parameter. NRC staff are in the early stages of conducting independent interpretations of C-well tracer studies. The basis for DOE's selection of a mean effective porosity and the log-triangular distribution is not clear.

Zyvoloski, et al. (1997) discuss a modeling approach that could prove useful for providing a technical basis for the probabilistic distribution of effective porosity. They select effective porosities to match arrival times of the 50-percent relative concentration, predicted using a numerical matrix diffusion model. They provide several examples to show that, with modest rates of matrix diffusion, the effective porosity can easily be as high as the total system porosity. However, the NRC staff is concerned that matching the effective porosity model to the matrix diffusion model based on the 50-percent relative concentration arrival is nonconservative. The basis for this concern can be seen in Figure 13 by noticing that the shapes of matrix diffusion model breakthrough curves (dashed lines) can change dramatically depending on the model scenario, while the effective porosity curves (solid lines) maintain the same shape over the entire range of effective porosity when the time axis is plotted in log-scale. If one imagines an effective porosity curve that intersects the 50-percent concentration point of a matrix diffusion curve, it can be seen that the effective porosity approach can result in predicted *initial* solute arrival times that are much later than those predicted by the matrix diffusion model—an inherent nonconservatism. The effective porosity approach is conservative, however, in the sense that it predicts *peak* concentration arrival times earlier than the matrix diffusion model. Thus, the conservatism of the effective porosity approach depends on whether compliance depends on contaminant arrival time or contaminant peak concentration. NRC staff believes that this problem could be mitigated by basing the effective porosity approach on the 10-percent relative solute concentration arrival time.

An additional concern with the effective porosity approach is that although matrix diffusion behavior is different for each solute, the same effective porosity is applied to transport of all solutes. Thus, effective porosities should be based on the least-diffusive solute that is likely to have an impact on performance.

The NRC staff point out that matrix diffusion could be a significant process in the saturated valley-fill materials south of YM. In this case the diffusion would occur into tuff clasts contained within these poorly consolidated sedimentary deposits. Matrix diffusion could therefore further enhance the ability of the valley fill to retard radionuclides. Diffusion experiments on intact tuffs should provide a basis to take some credit for this process.

In summary, the NRC staff believe that the effective porosity approach to including matrix diffusion in the DOE TSPA model has merit. However, technical justification is needed for the probabilistic distribution of effective porosities used in the TSPA model. The modeling approach of Zyvoloski, et al. (1997) could prove useful for providing such technical justification if the resulting range of effective porosities is based on 10-percent relative solute concentration arrival times, predicted from multiple realizations of their numerical matrix diffusion model, encompassing the ranges of uncertainty in input parameter values.

5.0 STATUS OF SUBISSUE RESOLUTION AT THE STAFF LEVEL

The comments and status of resolution following each acceptance criterion reflect the staff's review of DOE's Total System Performance Assessment for the Viability Assessment (TSPA-VA) and supporting documents.

5.1 CLIMATE CHANGE

Paleoclimate records clearly indicate that the Earth's climate transitions between glacial and interglacial modes. Currently the earth is in an interglacial mode, but we know that changes to and from a glacial mode are quite likely over the long time scales required for nuclear waste isolation. In the YM region, it is thought that a switch to a glacial mode will result in cooler and wetter conditions. Accordingly, two aspects of climate are considered: mean annual precipitation (MAP) and mean annual temperature (MAT). This information is necessary input for the Key Elements of Subsystem Abstraction (KESA) (see Figure A-1).

5.1.1 Summary of U.S. Department Of Energy Treatment of Climate Change Issues in Total System Performance Assessment - Viability Assessment

DOE estimates that climate fluctuations between glacial and interglacial modes average about 100 kyr in length; because this basic time scale is corroborated by other climate records, it was selected by DOE as the average climate cycle. Thus, future climate is estimated based on what is known about past climate. Climate is assumed by DOE to shift in a series of step changes between three different climate states (TRW Environmental Safety Systems, 1998a, Section 11.2.1.1 2): present-day (dry climate), long-term-average climate (about twice the precipitation of dry climate), and superpluvial climate (about three times the precipitation of dry climate). For performance assessment the duration of the present-day climate is sampled between 0 and 10 kyr. The duration of the subsequent dry climates is sampled uniformly between 0 and 20 kyr. The duration of the long-term-average (LTA) climate is sampled uniformly between 80 ky and 100 kyr. The superpluvial climate is sampled uniformly between 0 and 20 kyr. TSPA calculations begin with the present-day dry climate and then alternate between dry and LTA climates for 250 kyr, after which the end of the last LTA climate is replaced by a superpluvial climate. After the first superpluvial, the model returns to the alternating dry and long-term-average climates for 400 kyr, after which the end of the last LTA is again replaced by a superpluvial climate. The model then returns to alternating dry and LTA climates. Thus, about 80 percent of future time is predicted to have precipitation two to three times present amounts. Changes in the climate states change the seepage flux through the emplacement drifts and, consequently, the potential for water to contact the waste packages.

5.1.2 Acceptance Criteria For Climate Change Subissue

Projections of future climate change in the Yucca Mountain Region will be acceptable provided that:

(1) Climate projections used in performance assessments of the YM region are based on paleoclimate data, considering, at a minimum, information contained in Forester, et al. (1996); Winograd, et al. (1992); Szabo, et al. (1994).

> **Analysis:** Forester, et al. (1996) and Winograd, et al. (1992) are discussed and cited on page 2-30 of the TSPA-VA, Volume 1. Page 2-34 of the same volume cites Szabo, et al. (1994). Numerous paleoclimate references are given in section 2.2.2.3 of Volume 1. Sufficient detail is

provided to meet this acceptance criterion. These references are also cited in Chapter 4 of the Yucca Mountain Site Characterization Plan (TRW Environmental Safety Systems, Inc., 1998b)

Status and path to resolution: Closed. The staff have no further questions at this time.

(2) DOE has evaluated long-term climate change based on known patterns of climatic cycles during the Quaternary, especially the last 500 k.y.

Analysis: In Section 2.2.1of the TSPA-VA Technical Basis Document (TRW Environmental Safety Systems, 1998a), DOE noted that climate fluctuations average about 100 kyr in length, and because this basic time scale is corroborated by other climate records, it was selected by DOE as the average climate cycle. Section 2.2.1 also notes that "Future climate is estimated based on what is known about past climate..."

Figure 11-24 in (Chapter 11 of the TSPA-VA Technical Basis Document shows the climate history for a single TSPA realization and notes that others look similar. It shows a doubling of precipitation starting about 5 kyr in the future, glacial/interglacial cycles of 100 kyr, interglacials of about 20 kyr duration, and superpluvials occurring at 400 kyr intervals. Based on this figure, compared to today's climate, 80% of future time would have precipitation at two to three times present amounts.

Status and path to resolution: Closed. The staff have no further questions at this time.

(3) If used, numerical climate models are calibrated with paleoclimate data and their use suitably simulates the historical record, before being used for projection of future climate.

Analysis: Refer to the discussion under criterion 2. DOE's approach is based on the idea that past climates are the key to understanding future climates.

Status and path to resolution: Closed. The staff have no further questions at this time.

(4) Climate-affected parameters (e.g., onset times for climate change, MAP, and MAT) used in YM performance assessment models include, as a bounding condition, a return to full pluvial climate (higher precipitation and lower temperatures) for at least a part of the first 10-k.y. period, using parameter values that are supported by scientific data and analyses.

Analysis: DOE's probabilistic approach, as discussed in Section 11.2.1.1 of the TSPA-VA Technical Basis Document (TRW Environmental Safety Systems, 1998a), meets the intent of this criterion. DOE's approach for each realization (within RIP, executive driver program) assigns the duration of the first dry climate by sampling uniformly between 0 and 10 kyr. The assumed long-term climate with doubled precipitation therefore begins on average around 5 kyr after present. DOE notes on page 3-13 of TSPA-VA Volume 3 that present temperatures are more than 5 °C higher than for the assumed long-term average. Page 3-13 notes that effects of temperature differences on infiltration rates were neglected for TSPA-VA, but will be addressed in future TSPA analyses.

Status and path to resolution: Closed. The staff have no further questions at this time.

(5) If used, expert elicitations are conducted and documented using the guidance in the Branch Techn' Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

Analysis: DOE has not yet used expert elicitation to refine climate change assumptions. However, we note that DOE has had tentative plans to conduct such an elicitation in the future. An expert elicitation on the saturated zone (Geomatrix, 1998) was previously conducted.

Status and path to resolution: Closed. The staff have no further questions at this time. Staff will attend any elicitation on climate that may be conducted by DOE.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

Analysis: To be determined (TBD).

Status and path to resolution: TBD. Also see NRC comments on DOE's viability assessment (Paperiello, 1999).

5.2 HYDROLOGIC EFFECTS OF CLIMATE CHANGE

The expected hydrologic effects of increased MAP and decreased MAT are twofold: (i) an increased rate of shallow infiltration, and hence, increased deep percolation through the repository horizon; and (ii) increased water table elevations induced by increases in regional groundwater recharge rates. This information is necessary input for the Key Elements of Subsystem Abstraction (KESA) (see Figure A-1).

5.2.1 Summary of U.S. Department Of Energy Treatment of Hydrologic Effects of Climate Change Issues in Total System Performance Assessment - Viability Assessment

Changes in the climate states are implemented by changing the steady-state flow fields in the UZ and SZ, including changes in the water-table elevation.

5.2.2 Acceptance Criteria For Hydrologic Effects of Climate Change Issues

Projections of future climate change and the hydrologic effects of climate change in the Yucca Mountain Region will be acceptable provided that:

(1) If bounding analyses are used to predict climate-induced effects (water table rise, for example), the analyses are based on a reasonably complete search of paleoclimate data pertinent to water-table rise and other effects (for example, changes in precipitation and geochemistry), including, at a minimum, information contained in Paces, et al. (1996), Szabo, et al. (1994), Forester, et al. (1996).

Analysis: Szabo, et al. (1994) and Forester, et al. (1996) are cited in the Volume 1 of the TSPA-VA: Forester, et al. (1996) is discussed and cited on page 2-30; Szabo, et al. (1994) are cited on page 2-34. Staff could not find any reference to Paces et al. (1996a) in the TSPA-VA. However, the treatment of water-table rise in TSPA is consistent with conclusions reached in the report, and therefore this criterion appears to be met. This important reference should, however, be cited in future licensing documents that may be submitted by DOE.

Status and path to resolution: Closed. The staff have no further questions at this time.

(2) Regional and sub-regional models for the SZ that are used to predict climate-induced consequences are calibrated with the paleohydrology data, and are consistent with evidence that the water-table rise during the late Pleistocene was up to 120 m.

Analysis: Commentary related to water-table rise was found on page 3-138 of Volume 3 of the TSPA-VA. Conclusions of the expert elicitation on the saturated zone (Geomatrix, 1998a) are also pertinent to this criterion: the experts concurred with the interpretations of paleospring data that water-table rises of 80-120 m beneath the repository could occur in response to past climatic variations. In DOE's TSPA-VA analyses (see Vol. 3, p. 3-116) the water table is assumed to fluctuate in response to climate change. For example, the water table was assumed to be 80 m higher than present under long-term average climate, and 120 m higher for the super-pluvial climate state. These values are based on assumed (extrapolated) water levels at the locations of the diatomite deposits at the southern margin of Crater Flat. New data from Nye County's (1999) drilling program shows that the water table occurs about 16 m below the surface at well NC-EWDP-1D and about 30 m below the surface at well NC-EWDP-9S, indicating that groundwater has lowered by these amounts since the Wisconsin glacial maximum, about 20 ky before present. DOE has assumed a greater amount of water table rise, and therefore this criterion appears to be reasonably met. Finally, DOE's probabilistic treatment of climate and infiltration induces water-table rise at an expected future time 5 kyr hence.

Status and path to resolution: Closed. The staff have no further questions at this time.

(3) DOE has incorporated future climate changes and associated effects in its performance assessments. For example, available information does not support an assumption that present-day climate will persist unchanged for 10 k.y. or more.

Analysis: The handling of water-table rise for TSPA-VA analyses is discussed in section 7.4.4.2 of the TSPA-VA Technical Basis Document (TRW Environmental Safety Systems, 1998a). In the UZ model the elevation of the water table is set as an imposed boundary condition. When a long-term average climate state begins, the water table is assumed to instantaneously rise 80 m above present levels at the onset. For the super pluvial, which has the highest mean infiltration rate, the water table is assumed to rise instantaneously to 120 m above present levels. Radionuclides that were in the UZ at the time of the climate shift are assumed to be immediately available for SZ transport when "immersed" by a rise in the water table. This criterion appears to be reasonably met.

Status and path to resolution: Closed. The staff have no further questions at this time.

(4) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

Analysis: DOE has not yet used expert elicitation to refine climate change assumptions. ' has had tentative plans to conduct such an elicitation in the future. However, an expert elicitation on the saturated zone (Geomatrix, 1998) was conducted that touched on climate issues. Panelists concurred with the interpretations of paleospring sites that water-table rises of 80-120 m beneath the repository might have occurred in response to past climatic variations. See discussion on p. 3-138 of the VA, Vol. 3. We note that the panelists did not yet have the information from Nye County's drilling program, that shows the water table is only 16 and 30 m below land surface at two deposits of the Lathrop Wells Diatomites. In the VA, DOE has assumed a greater amount of water table rise (80+ m) than that inferred from drilling at the diatomites. DOE's approach appears reasonable.

Status and path to resolution: Closed. The staff have no further questions at this time. Staff will attend any elicitation on climate that may be conducted by DOE.

(5) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

Analysis: To be determined (TBD)

Status and path to resolution: TBD. Also see NRC comments on DOE's viability assessment (Paperiello, 1999).

5.3 PRESENT-DAY SHALLOW INFILTRATION

Shallow infiltration at YM is affected by several spatially variable factors, including local precipitation, surface runoff, evaporation, plant transpiration, soil type and depth, and underlying bedrock geology. Shallow infiltration may also vary considerably with time. Precipitation events that cause enough shallow infiltration to escape the rooting zone, becoming deep percolation, are infrequent; several years may pass between such events. Over much longer time scales, climate cycles between glacial and interglacial periods are also expected to affect shallow infiltration. This information is necessary input for the Key Elements of Subsystem Abstraction (KESA) (see Figure A-2).

5.3.1 Summary of U.S. Department of Energy Treatment of Shallow Infiltration in the Total System Performance Assessment - Viability Assessment

Infiltration modeling used to support their TSPA-VA document (Flint et al., 1996) indicates that the nominal case average present-day mean annual infiltration (MAI) flux over the repository horizon is 7.7 mm/yr. Note that this is an area-average value; in the DOE site-scale UZ flow model (Bodvarsson et al., 1998), MAI is treated as a spatially variable boundary condition with areas of highest predicted MAI associated with ridge tops and shallow soil depth. To account for uncertainty, DOE TSPA-VA analyses used MAI multipliers of 1, 1/3, and 3 to create three different present-day infiltration scenarios: the nominal case (average of 7.7 mm/yr over the repository); one-third the nominal case, and three times the nominal case, respectively. In the TSPA-VA the MAI multiplier selected for a given realization was based on the following probability assignments: p[1] = 0.6, p[1/3] = 0.3, and p[3] = 0.1.

5.3.2 Acceptance Criteria and Status of Resolution for Shallow Infiltration Issues

Site characterization and analyses related to estimations of present-day shallow infiltration in the YM region will be acceptable provided that:

(1) DOE has estimated present-day shallow infiltration at YM for use in TSPA using mathematical models that are reasonably verified with site-specific climatic, surface, and subsurface information, and the fundamental effects of heterogeneities, time-varying boundary conditions, evapotranspiration, depth of soil cover, and surface-water runoff have been considered in ways that do not underestimate infiltration.

> **Analysis:** Integration of all sources of data used to estimate MAI, including perched-water data, and the natural variability of these data suggests that the TSPA-VA nominal-case, area-averaged MAI may be too low by as much as factor of two. For example, the DOE modeled estimate for present-day area-averaged MAI over the repository is 7.7 mm/yr, but perched water chloride mass balance calculations (Fabryka-Martin et al., 1997) result in a range of MAI estimates between 11 and 23 mm/yr, with an average of 16 mm/yr. Additionally, the DOE estimate for present day MAI averaged over the domain of the site-scale UZ flow model (Bodvarsson et al., 1998) is 4.9 mm/yr; however, observed borehole temperature profiles covering approximately the same area indicate an average MAI of 6.7 mm/yr, based on a fit of individual borehole estimates to a log-normal statistical distribution (Winterle et al., 1999).
>
> **Status and Path to resolution:** Closed. DOE's nominal-case, present-day MAI estimates could be improved by calibrating the shallow infiltration model to match the higher estimates of MAI obtained from perched water geochemistry and borehole temperature profiles. However, we conclude that the present uncertainty in present-day MAI is likely to fall well within the range encompassed by the use of MAI multipliers in TSPA calculations. The staff have no further questions at this time.

(2) DOE has analyzed infiltration at appropriate time and space scales for performance assessment, and has tested the abstracted model against more detailed models to assure that it produces reasonable results.

> **Analysis:** Earlier technical reviews related to this criterion were documented in previous IRSRs (NRC, 1997b, 1998e). The 30 m by 30 m pixel size used in the DOE model is sufficient to capture spatial variability in surface infiltration. As for time scale, the assumption of a steady-state shallow infiltration rate for TSPA analyses is inconsistent with the highly episodic nature of infiltration events, however this discrepancy is addressed under Criterion 2 of the deep percolation subissue (see section 5.4.1).
>
> **Status and path to resolution:** Closed. The staff have no further questions at this time.

(3) DOE has characterized shallow infiltration in the form of either probability distributions or deterministic upper-bound values for performance assessment, and provided sufficient data and analyses to justify the chosen probability distribution or bounding value.

Analysis: Staff agree that the use of MAI multipliers is a reasonable means to incorporat uncertainty in MAI estimates into the TSPA abstraction; however the methodology used tc assign probabilities to the MAI multipliers (1/3, 1, or 3) for TSPA realizations is biased towards selecting the lower values. This results in probabilities assigned to MAI multipliers being biased toward producing low values for MAI. A more detailed discussion of the staff's analysis of the MAI multipliers can be found in Winterle et al. (1999).

Status and Path to resolution: This acceptance criterion will be met if DOE adopts the equation

$$p_{1/3} \log \frac{1}{3} + p_1 \log 1 + p_3 \log 3 = 0$$

for use in assigning probabilities to MAI multipliers in TSPA analyses: where $p_{1/3}$, p_1, and p_3 are the probabilities that the selected MAI multiplier will be 1/3, 1, or 3, respectively. In simpler terms, this equation requires that $p_{1/3}$ and p_3 must be equal. Alternatively, DOE may demonstrate another approach that achieves the same result. The staff will determine whether the criterion is met by reviewing future DOE performance assessments.

(4) If DOE can show through TSPA and associated sensitivity analyses that refinements of shallow infiltration estimates will not significantly alter performance predictions, no further refinement will be necessary.

Analysis: It is well established in both DOE and NRC performance assessments that TSPA predictions are quite sensitive to shallow infiltration estimates. We therefore expect refinements as new data become available.

Status and path to resolution: Closed. The staff have no further questions at this time.

(5) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

Analysis: The expert elicitation on DOE's unsaturated flow model (i.e., Geomatrix, 1997b) was conducted and documented in an acceptable way.

Status and path to resolution: Closed. The staff have no further questions at this time.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

Analysis: To be determined (TBD)

Status and path to Resolution: TBD. Also see NRC comments on DOE's viability assessment (Paperiello, 1999).

5.4 DEEP PERCOLATION (PRESENT-DAY AND FUTURE [POST-THERMAL PERIOD])

Deep percolation refers to the flow of water from the near surface to the water table. The deep-percolation subissue addresses (i) changes in the temporal and spatial variability of infiltration as water moves downward from the zone of shallow infiltration to the repository; (ii) how the temporal and spatial distribution of water flux at the repository may influence the quantity of water that contacts waste packages, and the number of waste packages that may get wet; and (iii) flow velocities and pathways below the repository, which are important to assess rates of radionuclide transport.

The amount of water contacting WPs has consistently been identified as one of the most important parameters affecting performance of the proposed HLW repository at YM. The number of WPs expected to be contacted by dripping water is a function of two key factors: (i) the areal distribution of percolation fluxes reaching the repository horizon that could potentially result in seepage into the drift cavity and (ii) the amount of seepage exclusion from drifts (around or down the walls of the open drift space) due to capillary forces in the fracture and rock matrix flow systems. This information is necessary input for the Key Elements of Subsystem Abstraction (KESA) (see Figure A-3).

5.4.1 Summary of U.S. Department of Energy Treatment of Deep Percolation in the Total System Performance Assessment - Viability Assessment

In the modeling approach used for the TSPA-VA, MAI is used as a steady-state flux boundary condition to the dual-continuum, 3D UZ site-scale flow model (Bodvarsson et al., 1998). This UZ flow model is used under the various climate and infiltration scenarios to (i) create maps of predicted deep percolation flux at any given location of the proposed repository horizon; and (ii) delineate flow and transport pathways from the repository to the water table.

For the TSPA-VA analyses, the repository flux maps are divided into six repository subregions of differing area-averaged deep-percolation flux rates. The flux rates for the six subregions are then used as boundary conditions in a drift seepage model. The drift seepage model uses a single-porous-media continuum approach. That is, the network of intersecting fractures in the proposed repository horizon is treated as a continuous porous medium. The process-level seepage model calculates two quantities for each of the six repository subregions that are used in TSPA analyses: (i) the fraction of waste packages that receive dripping water (seepage fraction), and (ii) the flow rate of dripping water hitting wetted packages (seep flow rate). Uncertainty is handled by obtaining model results for nine different combinations of two key model parameters—fracture permeability and fracture alpha value. Each of the nine combinations of these two parameters is assigned a discrete probability of occurrence, such that the nine probabilities have a sum of one. DOE assumes that results obtained from the nine parameter combinations bound the realm of possible outcomes. The resulting ranges and probability distributions for the seepage fraction and the seep flux rate are independently sampled in DOE's TSPA code.

For calculations of flow and transport beneath the repository, steady-state flow fields are calculated using the 3D, dual-continuum UZ flow model. These steady-state flow fields are then input to a radionuclide transport model to simulate radionuclide transport to the water table. Dispersion and matrix diffusion are handled using what DOE refers to as a residence time transfer function, or RTTF, in which the residence time a radionuclide "particle" spends in any one model cell is sampled from a probabilistic distribution that is based on more conventional flow and transport analytical models. The UZ flow and transport model is run for each TSPA realization. The model output provides values for radionuclide mass flux at the water table to the transport model for the SZ. Uncertainty is accounted for by using an array of calibrated steady-state UZ flow fields, and probabilistic parameter distributions for sorption coefficients, matrix diffusion coefficier' dispersion coefficients, and fracture aperture.

5.4.2 Acceptance Criteria and Status of Resolution for Deep-Percolation Issues

(1) Estimates of deep percolation flux rates and the fraction of flux that occurs in fractures will be acceptable provided that they are: (i) shown to constitute a conservative upper bound, or (ii) based on a technically defensible UZ flow model that reasonably represents the physical system, including flow in fracture systems and matrix-fracture interaction. The flow model has been calibrated using site-specific hydrologic, geologic, and geochemical data.

Analysis: The values assigned to fracture continuum hydraulic properties in the TSPA-VA parameter sets are not justified by the distribution of fracture apertures seen on the model-grid scale. For example, DOE estimates of fracture alpha values are based on estimates of "effective fracture aperture" obtained from air permeability studies in the ESF. It is difficult to draw a simple relationship between fracture aperture and fracture alpha values. Even if such a relationship held true, the values calculated for fracture-alpha should be related to the largest aperture sizes encountered on the model grid-block scale. Similarly, values assigned to the fracture *m* parameter should be related to the range and distribution of aperture sizes from narrowest to widest. But ESF fracture surveys mainly include only larger apertures. Additionally, the calculated range of fracture-alpha values considered in the TSPA-VA may be biased because ESF line surveys of fracture frequency have not been corrected for the under-representation of fractures that intersect the ESF at low angles. Fracture frequency estimates may also be biased by use of a one-meter cutoff length for the fracture surveys, and the difficulty of counting fractures in swarms. Underestimating fracture frequency results in overestimation of effective fracture apertures which, in turn, overestimates the fracture alph^ An additional concern is that there are no reported data about fracture properties at the sc concern in the proposed repository formation (i.e., Tptpll).

The uncertainty regarding UZ rock and fracture hydraulic properties is addressed in the TSPA-VA using a variety of 3D, calibrated, steady-state flow fields derived from different assumptions about infiltration rates and rock properties. However, from the parameter sets provided by DOE in Chapter 2 of the TSPA-VA Technical Basis document [TRW Environmental Safety Systems, Inc., 1998, (tables 2-19 through 2-23 and tables 2-63 to 2-67)], it appears that only the uncertainty in fracture-alpha values and the rate of present-day infiltration is investigated, and all other parameter values are held constant for all of the calibrated steady-state flow fields used in the TSPA-VA base case analysis. It also appears that the only parameter that was adjusted to achieve model calibration was the fracture-matrix (F/M) reduction factor. This approach does not reasonably bound the uncertainty in the distribution of UZ flow between rock matrix and fractures. Additionally, using the F/M reduction factor as the sole model calibration parameter for the base case flow fields results in the false conclusion that the assumed fracture hydraulic properties have little effect on predictions of repository performance.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending review of data reports for the ESF, cross drift, the Busted Butte facility, and future performance assessments. These concerns could be resolved by conservatively assuming that the fraction of flow in the matrix is negligible and that all deep percolation occurs in fractures. For each hydrostratigraphic layer in which a significant fraction of deep percolation is considered to flow in rock matrix, DOE should demonstrate that parameter values for fracture and rock-matrix hydraulic properties are consistent with site observations. *In situ* measurements of rock matrix water potentials and saturation that are being collected in the east-west cross drift should help in this regard. Fracture line surveys used to calculate effective apertures or permeabilities should be corrected to account for under-representation of fractures that intersect the ESF at low angles. The variety of generated UZ flow fields used in TSPA analyses should fully bound the distribution of mass flux between rock matrix and fractures by accounting for the uncertainty in rock matrix properties and potential biases in borehole saturation profile measurements. The modeling approach and parameter estimates used in the LBNL UZ Flow Model and drift-scale seepage models could be validated by sealing off a section of the east-west cross drift—preferably a section that includes the Tptpll formation—and allowing equilibration with natural conditions. Relative humidity sensors could be used along with instrumentation already in place to show that equilibration with natural conditions has occurred. This is an important experiment to perform because the east-west drift underlies areas where infiltration is believed to reach a maximum.

(2) To estimate deep-percolation flux, spatial and temporal variability of model parameters and boundary conditions must be considered. Model parameters must be averaged over appropriate time and space scales. DOE must also consider climate-induced change in soil depths and vegetation.

Analysis: The fast-path contributions to flow, as suggested by geochemical data, are not adequately represented in the LBNL UZ Flow Model. This is likely a model artifact caused by the assumption of homogenous model layers and volume averaging matrix and fracture properties over the model grid. In other words, subgrid heterogeneity is not adequately addressed in the DOE approach, and failure to consider subgrid heterogeneity may lead to qualitatively incorrect results. Small scale modeling of heterogeneous zones is one approach that may be used to support use of uniform properties in hydrostratigraphic units of the site-scale UZ flow model. Additionally, the assumption of steady-state infiltration fluxes in the LBNL UZ Flow Model precludes an assessment of the impact of episodic infiltration that may bypass the PTn layer and travel quickly to the repository horizon. The DOE acknowledges in their TSPA-VA report that as much as 80–90 percent of infiltration may bypass the PTn layer via fast pathways (DOE, 1998b, Volume 1, page 2-51). Flow in these fast pathways is likely to be episodic, and such transient flow is more likely to result in seepage into repository drifts.

An additional concern is that DOE has not shown that effects on deep percolation of climate-induced changes in temperature, vegetation, and soil can be neglected while still providing a conservative bound on deep percolation and seepage fluxes under future climates. This concern stems from the fact that decreases in temperature can result in increased infiltration, even when precipitation does not change. Although this effect may be limited by increased vegetation, the interplay between these factors has not been investigated. Further, observations of soil thickness and texture on YM indicate these properties have been significantly different in the past. If it can be shown that the overall impact of these effects is minor relative to changes in precipitation, then the present method is acceptable.

Finally, in shallow infiltration models used to support the TSPA-VA analyses, DOE did not account for the effects of overland flow (i.e., surface runoff) and shallow subsurface lateral flow. These effects are potentially important because they are likely to change the calculated patterns of MAI by lowering predictions at topographic high points and increasing predictions at topographic low points. It is the staff's understanding that future repository performance assessments for YM will make use of shallow infiltration estimates that have been refined ι an infiltration model that includes a surface water flow routing module (e.g., Hevesi, 1998). As this refined shallow infiltration model is, at present, unpublished, the staff have not had the opportunity to review the DOE approach to accounting for overland flow. It does not appear that subsurface lateral flow will be included in the DOE shallow infiltration model, however, preliminary staff analyses indicate that the effects of subsurface lateral flow on net infiltration may be minimal.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending review of future DOE performance assessments. Although volume-averaging approaches may be adequate for site-scale flow calculation, alternative models should be used to confirm the results or to confirm the parameters used to run the site-scale model. In the latter case, the use of alternative models would be used to scale up properties to the cell sizes used in the site-scale model. Additionally, the LBNL UZ Flow Model should account for heterogeneity or discrete features that result in fast flow through the PTn layer, consistent with geochemical evidence for fast transport to the repository horizon. Additionally the DOE UZ flow model should include features that allow rapid transient percolation to bypass the PTn layer. The effect of these transient pulses on seepage into repository drifts could then be examined.

(3) For estimates of the amount of water that may contact waste packages DOE must (i) demonstrate that coupled thermal-mechanical-chemical changes in rock mass properties will not focus deep percolation into the drifts; and (ii) rigorously justify estimated diversion of deep percolation away from the waste package footprints. This must include direct observations of dripping in test drifts or tunnels under ambient (unventilated) conditions in the repository horizon, or in an analog horizon with similar characteristics. Also needed are model calculations that account for the effects of backfill (if used), drift collapse, and coupled thermal-mechanical-chemical changes to rock properties. The models have been calibrated to niche studies and tracer tests in the ESF, or using an analog with characteristics similar to the repository horizon.

Analysis: The DOE drift-scale process-level seepage model, used to calculate seepage fraction and seep flow rate for TSPA, does not include several potentially important processes, and has not been shown to yield reasonably conservative upper bounding values. The analyses used to support TSPA-VA deal with uncertainty in the parameter by obtaining model results using nine combinations of two key model parameters—fracture permeability and fracture-alpha value. However, it has not been adequately demonstrated that the range of values used in these parameter combinations bounds the range of uncertainty in these important characteristics. Further, the discrete probabilities assigned to the nine TSPA parameter sets appear to be arbitrary. Many physical properties of repository drifts are not considered in the seepage model. Heterogeneity in the hydraulic properties of the rock that surrounds drift openings may be the single most important factor affecting water flux into open drifts, yet the DOE seepage model does not account for the multiple scales at which heterogeneity occurs. Small scale features near the drift crown, such as surface roughness and fractures dead-ending at the drift crown, would result in much less effective capillary retention and more seepage into the drifts for a given percolation flux, but these features are not accounted for. Other considerations not included in the DOE seepage model are that the geometry of the drifts is likely to change due to rockfall, and the properties of the repository formation may have changed due to thermally driven geochemical alteration. A final concern is that the seepage model does not consider the importance of transient (episodic) infiltration. This could be important at early times due to potential penetration of the boiling isotherm. At later times, sequential transient episodes can cause more water to enter the drift than at either steady-state or during a single transient pulse. As a result of this uncertainty, the quantity of water that would contact WPs may be significantly underestimated.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending review of future DOE performance assessments. Prediction of capillary diversion through fracture networks and seepage into drifts is an extremely complex endeavor. It may never be possible to develop a reliable model of drift seepage. Therefore, conservative assumptions are needed. For example, if the fraction of deep percolation flux intercepting the areal footprint of the WPs is considered as contacting the WPs, then the entire issue of diversion of water away from the drifts can be resolved. Estimates of seepage fraction and seep flow rates should be supported by data, field studies, and natural analog observations under conditions likely to exist in the repository subsequent to dissipation of the thermal pulse. Modeling studies used to demonstrate diversion of percolation flux away from drifts and WPs should be supported by data, reasonably account for important sources of heterogeneity and uncertainty, and include coupling to models of drift collapse and alteration of hydraulic properties. Additionally, scoping calculations should be performed to assess the likely effects of drift collapse and alteration of hydraulic properties.

(4) In predicting likely flow and transport pathways beneath the proposed repository horizon, DOE must either (i) conservatively assume that all deep percolation below the repository level bypasses the bulk of the non-welded units, either by lateral movement above the units or through vertical flow through fractures and faults; or (ii) demonstrate that the estimated fraction of deep percolation that flows vertically through the matrix of the non-welded units is supported by (a) characterization data and (b) two-dimensional or three-dimensional modeling that accounts for spatial and temporal variability that may result in lateral diversion of flow, and uses model parameter values appropriate for the scale of model discretization.

Analysis: There is little supporting data for the hydrologic and transport parameter values used in the modeling studies of transport below the repository. Existing parameter estimates for the 3D site-scale model are based on one-dimensional (1D) inversions to match borehole saturation data, and thus do not adequately represent the impact of lateral flow, resulting in higher estimates of matrix permeability in the nonwelded layers below the repository horizon. The uncertainty in the UZ flow patterns below the repository, acknowledged by DOE, needs to be addressed and incorporated into TSPA analyses. Ongoing studies in the Busted Butte Transport Facility will be useful to answer some of the questions concerning matrix and fracture flow in the Calico Hills vitric unit. This field experiment will contribute to characterization of permeability and sorption in a slightly altered vitric tuff within a single hydrostratigraphic unit. However, hydrologic and transport properties of the nonwelded devitrified tuffs, and variations related to extent of alteration and welding are likely to remain uncertain. Accordingly, larger scale vertical and lateral flow patterns in the non-welded to densely welded vitric, devitrified, or zeolitically altered Calico Hills and Crater Flat hydrogeologic units will remain uncertain.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending review of future DOE performance assessments. This acceptance criterion could be resolved by conservatively assuming that all deep percolation below the repository level bypasses the bulk of the units of the CHn formation, either by lateral movement above the units or through vertical flow through fractures and faults. If credit is taken for matrix flow through the CHn formation, field experiments must be used to support the hydraulic properties used in UZ flow models. DOE should continue with plans to replace the parameter sets obtained from 1D calibrations with those obtained from 3D UZ model calibrations. Additional work on flow patterns in highly zeolitized tuffs at the Busted Butte Transport Facility would be useful, presuming there are zeolite horizons immediately below the facility. Estimates of the proportions of matrix and fracture flow at various percolation rates in the vitric and devitrified horizons also requires further study, especially regarding appropriate values for F/M reduction factors. Development of a transport scale model with a refined grid that includes heterogeneity would be useful for comparison with the results of the site-scale flow and transport simulations. For a transport scale model, the variation in hydrologic and sorption properties corresponding with variations in alteration and degree of welding should be characterized for the Calico Hills Formation, Prow Pass and Bullfrog Tuffs.

(5) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

Analysis: The expert elicitation on DOE's unsaturated flow model (i.e., Geomatrix, 1997b) was conducted and documented in an acceptable way.

Status and path to resolution: Closed. The staff have no further questions at this time.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

Analysis: TBD

Status and path to resolution: TBD. Also see NRC comments on DOE's VA (Paperiello, 1999).

5.5 SATURATED ZONE AMBIENT FLOW CONDITIONS AND DILUTION PROCESSES

The characterization of the ambient flow conditions and dilution processes in the SZ at YM is important for the repository performance. Ambient flow conditions are affected by the subsurface geology, areal recharge patterns, inter-basinal/inter-aquifer mixing/transfer of groundwaters, and long-term climate cycles. Reliable estimates of groundwater flowpaths downgradient of YM, groundwater flux along these flowpaths, transmissivity of the tuff and alluvial aquifers, and transport properties of the tuff and alluvial aquifers are needed to estimate radionuclide concentrations and arrival times at receptor locations, should a release occur. Pluvial conditions during glacial periods will increase recharge to the groundwater, resulting in a higher water table and presumably longer flowpaths in the valley-fill aquifer. Dilution processes in the SZ include mixing during groundwater movements due to dispersion, and mixing with other groundwaters such as recharge, inter-basin transfers, and wellbore dilution. This information is necessary input for the Key Elements of Subsystem Abstraction (KESA) (see Figure A-4).

5.5.1 Summary of U.S. Department of Energy Treatment of Saturated Zone Ambient Flow Conditions and Dilution Processes in the Total-System Performance Assessment - Viability Assessment

During TSPA-VA analyses, 3D flow modeling was used to determine groundwater flowpaths. Six 1D streamtubes were used to perform transport modeling to determine the concentration breakthrough curves at receptor locations for unit releases of the radionuclides. The volumetric flux from the UZ into each streamtube was determined by the LBNL UZ Flow Model. This UZ contribution to each streamtube is added to the estimated specific discharge in the SZ for each streamtube. The transport simulations implicitly assume complete mixing of the radionuclide mass into the volumetric groundwater flux specified for each streamtube. The convolution integral method was used to combine radionuclide transport breakthrough curves for each streamtube with the time varying radionuclide source from the UZ. Transport distances through each of four hydrostratigraphic units (i.e., middle volcanic aquifer, upper volcanic aquifer, middle volcanic confining unit, and alluvium/valley fill) were determined for each streamtube by particle tracking in a 3D flow model. The radionuclide concentrations at the receptor locations were divided by a dilution factor, as suggested by the Saturated Zone Expert Elicitation (SZEE). The TSPA-VA sensitivity analyses were conducted to assess the importance of the dilution factor, the fraction of the flowpath in valley fill, and the method for calculating the final concentration from combined six streamtubes.

5.5.2 Acceptance Criteria and Status of Resolution for Saturated Zone Ambient Flow Conditions and Dilution Processes Issues

Site characterization and analyses related to SZ ambient flow conditions and dilution processes in the YM region will be acceptable given that:

(1) DOE has considered conceptual flow and data uncertainties. Uncertainties due to sparse data or low confidence in the data interpretations have been considered by analyzing reasonable conceptual flow models that are supported by site data, or by demonstrating through sensitivity studies that the uncertainties have little impact on repository performance.

> **Analysis:** The reference Luckey et al. (1996) does an excellent job of describing the various conceptual models of site-scale hydrology as they were known at that time. Since then, a great deal of hydraulic and tracer test data has been collected from the C-Holes complex and analyzed. The staff's review of these most recent data has been based to a large extent on draft reports and informal discussions. Confidence in DOE's characterization of flow in the tuff aquifer system could be improved by publication of final peer-reviewed reports regarding hydraulic and tracer testing at the C-Holes. Also see NRC comments on DOE's VA (Paperiello, 1999).
>
> **Status and path to resolution:** Open pending review of future DOE groundwater modeling reports, milestone reports, and other submittals.

(2) DOE has reasonably delineated possible flow paths from beneath the repository to potential receptor locations based on data that is sufficient to elucidate (i) the relative travel distances through aquifers of differing hydrologic and geochemical properties; (ii) in fractured-rock aquifers, the portions of flow

through rock matrix and fractures; (iii) flow directions with respect to the hydraulic gradient, consid the potential effects of horizontal anisotropy; (iv) approximate volume fluxes and pore velocities; a (v) vertical hydraulic gradients, including the potential for flow between the Paleozoic carbonate aquifer and the volcanic tuff aquifer. A sufficient number of wells and exploratory holes should be drilled, and an adequate number of tests conducted, to reasonably bound the hydraulic and transport properties of the units downgradient from the proposed repository.

Analysis: See NRC comments on DOE's VA (Paperiello, 1999). DOE has yet to delineate where the water-table transitions from the tuffs to the overlying valley-fill aquifer. The Nye County wells drilled to date have been too far to the south to help in this regard, although they have helped characterize the valley-fill. Another factor that may affect the relative travel distances through tuff and valley-fill aquifer systems is horizontal anisotropy in the fractured tuff aquifer due to preferential north-south orientation of fractures and faults. A high degree of horizontal anisotropy could conceivably cause significant diversion of flow to the south, resulting in a greater fraction of radionuclide transport pathways occurring in fractured tuff. Although the SZ Expert Elicitation Panel (Geomatrix, 1997a) indicated the need to consider anisotropic transmissivity, DOE SZ flow models have not bounded the possible effects of anisotropy on groundwater flow paths.

Reasonable bounds can now be set on water-table flowpaths from the proposed repository. The bounds are obtained by integrating all available data, including hydraulic heads, groundwater chemistry, geophysics, stratigraphy, slip- and dilation-tendency analysis of faults, and analysis of anisotropy in horizontal aquifer flow. As discussed below, we believe that potential transport paths from the repository site are contained within a narrow arc of 25° azimuth that extends from Nye County well 5S on the east to a location on Highway 95 ~7 km west of Amargosa Valley. This point is due south of the proposed repository. Three Nye County wells lie along this arc and all three confirm that the water table exists within the va fill aquifer. Likewise, a group of wells in Amargosa Valley also confirm a thick valley fill aqu. Well data are given in the following table for wells from west to east. Data sources are Oliver and Root (1997) and Nye County (1999).

Table 15. Data for Selected Wells in the Valley-Fill Aquifer

	Total depth (m)	Depth to water (m)	Surface elevation (m)	Head (m)	Date of measure
Nye 2D	493	95	801.2	706.2	3/15/99
15S/49E-22a1	174	90	796	706	4/24/58
Washburn 1X	201	109	824.1	714.6	3/26/99
NDOT (in Amargosa Valley)	151	105	810	705	5/17/95
Nye 5S	366	113	839.4	724.1	3/26/99

The lowest heads occur along a line from 2D to Amargosa Valley and range from about 705 to 706 m. This includes well 15S/49E-22a1, located 4 km west of Amargosa Valley (although the head measurement at this well is decades old). Heads east and northeast of Amargosa Valley are considerably higher, 724 m at both Nye 5S and TW-5. Heads in eastern Jackass Flats are 733 m at J-11. Aquifer productivity in well 5S was the lowest in any Nye county well to date. In fact, the well was thought to be dry until water slowly rose within the wellbore, stabilizing at ~724 m, consistent with well logs for 5S that show the local valley fill is clay-rich. Flowpaths from YM appear unlikely to reach areas east of well 5S.

At the Lathrop Wells Cone west of Nye 2D, the head is 730 m in the volcanics at the Cind-R-Lite well. This head is virtually identical to those in the low-gradient zone east of YM and shows that flow paths from the site must lie to the east. A substantial eastward hydraulic gradient exists from Cind-R-Lite to well 2D. Hydraulic heads at YM all confirm a potential for flow to the east and southeast, toward Fortymile Wash. The largest transmissivities (T) and lowest heads near YM occur at JF-3 (Plume & LaCamera, 1996), confirming that a southerly "drain" exists beneath the wash. The estimated T of ~14,000 m^2/day may be an underestimate because the result is based on a single-well test. The T may actually exceed 14,000 m^2/day. We also have historical evidence of large aquifer productivity at wells J-12 and J-13 (Young, 1972; Thordarson, 1983). Roughly 2800 acre-ft (3.4 million m^3) were extracted over 5 years in the 1960's, causing a water-table decline of <1 m at J-13. It is clear that the tuff aquifer (Topopah Spring) near the wash is highly productive.

The western extreme of the flow arc includes flowpaths directly south from the repository. These paths are valid only if a very high degree of anisotropy exists within the tuffs. Such paths also require the assumption that north-south structural conditions and the anisotropy ratio are relatively continuous out to 20 km. There is little evidence that this assumption is correct. Analyses of the C-holes tests show that the ratio of minimum to maximum directional T is poorly constrained (Merrill et al., 1999; Geldon et al., 1997). The data can support a full range from nearly isotropic conditions to highly anisotropic, such that the north-south T exceeds east-west T by as much as 17 to 1. East of Yucca Mt., equipotentials almost parallel Fortymile Wash, so even a high degree of anisotropy will produce flow oriented SSE. We therefore conclude that a due-south flowpath effectively bounds flow under highly anisotropic conditions.

Groundwater beneath Fortymile Wash is dominated by recharge phenomena. This is confirmed by the groundwater chemistry (Oliver and Root, 1997) and by spikes in heads seen in wells UE-29a#1 and #2 after runoff events (Savard, 1998). This recharge may inhibit flowlines from crossing beneath the wash from west to east, and the effect would be greater during pluvial climates when recharge in the wash is much larger. Resulting streamlines at the 20-km distance would cross beneath Highway 95 near its intersection with Fortymile Wash. It is therefore quite possible that flowpaths under future conditions of water-table rise would be similar to those of the present day, except that longer pathways from the repository would exist in the valley-fill aquifer. If it is concluded that horizontal flowpaths from beneath YM could not readily cross beneath Fortymile Wash, then the arc of transport paths would be shorter than the 25° of azimuth mentioned above.

The Nye County drilling so far shows that saturated valley-fill aquifer lies along all reasonable flowpaths. Geophysical data (gravity and electrical sounding) indicate that the valley fill aquifer north of Amargosa Valley is quite thick . The Bouguer anomaly map of Snyder and Carr

(1982) reveals a gravity low at Amargosa Valley that extends to the NNW across the wash. This could be caused by the presence of a thick valley-fill aquifer beneath Fortymile Wash extending at least 5 km north of Highway 95. Based on a vertical electric sounding survey, Oatfield and Czarnecki (1989) estimated that, 5 km north of Amargosa Valley, the valley fill exceeded a depth of 1000 m.

Properties of the valley-fill aquifer south of Yucca Mountain are poorly known. Short-term tests in three Nye County wells (1-S, 3-D, and 9-SX) yielded T values ranging from 200-5000 m^2/day, but these wells apparently produce water from a composite of valley fill and volcanics. These three wells are west of the Lathrop Wells volcanic cone and do not occur on flow paths from YM. Nye County wells 2D and Washburn are along potential flow paths but are reportedly not highly productive (personal communication, T. Buqo, Nye Co.). More quantitative information should be available in the near future as Nye County's drilling and testing program helps fill the data gap south of well JF-3.

Volume fluxes have been estimated with some confidence in areas where well data permitted hydraulic gradient and transmissivity to be estimated, however much of the potential flow path to a receptor group remains to be characterized. Pore velocity estimates are poorly constrained over the entire flow path due to a wide range of estimates regarding effective flow porosities in the fractured tuff aquifer, and paucity of data for the valley-fill aquifer. Average linear groundwater velocities and residence times can be estimated through groundwater dating. Numerous YM groundwater samples have undergone ^{14}C dating, but it is difficult to correct for the significant amounts of "dead" carbon from various sources dissolved in the groundwater. A promising new approach may greatly improve the ^{14}C dating. Thomas (1996) describes the separation of dissolved organic carbon from groundwater using reverse osmosis and ultrafiltration methods. We believe that this method should be applied to samples collected at YM to independently estimate the average groundwater residence time at locations with the saturated zone. This technique has been applied to groundwater near Devils Hole, and indicates that groundwater residence times in the carbonate aquifer feeding Devils Hole are about 2-3 kyr (Winograd, et al., 1997), significantly less than earlier estimates.

Information about flow conditions in the Paleozoic carbonate aquifer beneath YM is based on only one well, UE-25 p#1. The existence of an upward hydraulic gradient from the carbonate aquifer (Craig and Robison, 1984) is not incorporated in the current DOE studies. In the Nye County wells drilled to date, the depth to the carbonates has been greater than anticipated and none of the wells penetrated the deep Paleozoic carbonate aquifer.

Status and path to resolution: Partly resolved. Flow paths from the proposed repository to a 20-km distance appear to be bounded within a relatively narrow arc. DOE should continue efforts to fill in data gaps with new wells in the valley fill deposits that lie along the possible flow paths to the exposure group, and to interpret existing data from the tuff aquifer. Hydraulic and tracer testing should be conducted on a scale large enough to include a statistically representative elementary volume in the fracture network in tuffs (i.e., latest tests in the C-wells and hydraulic tests at SD-6) and in the valley-fill aquifer. The valley-fill aquifer has great potential to retard contaminants that reach that distance. Exploratory drilling and geophysical surveys should be used in addition to the Nye County wells to obtain data within data gaps to delineate where the water table transitions from the tuff aquifer to the overlying valley-fill aquifer, and to reveal lengths of flowpaths in the valley-fill. One location to explore is about 2 km northwest of well 2D, which would confirm the length of a due-south flowpath in valley-fill materials. Another key area to investigate is the data gap between the Washburn 1-X well and JF-3. Repository performance predictions should be made for a reasonable set of conceptual flow models.

(3) DOE has provided a hydrologic assessment to describe likely causes of the "moderate hydraulic gradient" and the "large hydraulic gradients."

Analysis: The cause of the so-called large hydraulic gradient is still uncertain but evidence from wells WT-24 and G-2 points to a simple model with a thick, low-permeability confining unit that perches water above and within it and tends to restrict lateral flow. Perched water may be partly responsible for the very high heads reported for wells USW G-2 and UE25 WT#6.

Characterization of the moderate hydraulic gradient will be aided by the recently completed well SD-6. Preliminary reports indicate that the water- table elevation in SD-6 is about 731 m above sea level (personal communication from Chad Glenn, NRC onsite representative). This water level is similar to those observed in wells WT-11, and H-3 (upper interval), which are also located just east of the Solitario Canyon Fault (SCF). Significantly higher water table elevations are seen in wells WT-10, WT-7, and H-6 to the west of the SCF, indicating that the moderate gradient is caused by a zone of reduced permeability across the SCF. East of the fault, elevated heads occur in wells H-5 and UZ-14, indicating that significant head differences can occur locally without large fault offsets. For example, heads transition from 778 m in UZ-14 to 731 m in H-1 (upper interval). The SCF has been encountered within the east-west drift, where it contains a ~1m- thick, clay-rich fault gouge. Planned hydraulic testing in well SD-6 should be sufficient to complete characterization of the moderate hydraulic gradient, provided that nearby wells H-6, H-5, and others east of the SCF are monitored during the testing. Preliminary reports suggest that the well is not highly productive and that the scale of hydraulic testing may therefore be limited.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending submission and staff review of DOE reports on the drilling and testing of wells WT-24 and SD-6.

(4) DOE has provided maps of approximate potentiometric contours of the regional uppermost aquifer for an area that, at a minimum, includes wells J-11 on the east, VH-1, VH-2, and the GEXA Well on the west, UE-29a #2 to the north, and domestic and irrigation wells south of Amargosa Valley (aka Lathrop Wells). Maps of regional and site-scale recharge and discharge should be provided, along with site-scale hydrostratigraphic cross sections constructed along the paths to the accessible environment, and site-scale flow-net analysis of the SZ.

Analysis: The TSPA-VA analysis included a site scale potentiometric map. However, the map does not include data from irrigation wells south of Amargosa Valley. The regional infiltration, evapotranspiration, spring discharges, and pumping estimates are currently being prepared or are being refined. No flow net analyses were performed by the DOE. Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending review of relevant DOE milestone reports.

(5) DOE estimates of key hydrologic parameters are described in the form of either probability distribı or deterministic bounding values that are reasonably consistent with site data. These parameters should include transmissivity, hydraulic gradient, effective flow porosity, effective immobile porosity, and effective aquifer thickness.

Analysis: DOE used probability distributions to represent key hydrologic parameters in TSPA-VA. The probability distribution for the parameters is either based on measured/interpreted values from field testing or is provided by the Saturated Zone Expert Elicitation. The staff's confidence in estimated SZ hydrologic parameters for the valley-fill aquifer is low due to the paucity of hydrologic data for valley fill. Emphasis should be placed on obtaining heads, transmissivity, hydraulic conductivity, effective porosity, and dispersion coefficients for the valley-fill aquifer. Presently, hydraulic properties of the valley-fill remain uncharacterized for the area that lies between well JF-3 and the Amargosa Desert. DOE's cooperative well drilling program with Nye County, Nevada will still leave a data gap of ~6 km. Additionally, the data collected during drilling and hydraulic testing, scheduled to be completed in FY2001, may not be available to include in the LA.

In the tuff aquifer, hydraulic properties have been better characterized, but considerable uncertainty remains regarding effective flow porosities. Hydraulic and tracer testing at the C-well complex continues to be interpreted and may result in improved estimates of flow porosity. An additional concern is that preferential fracture and fault orientations in the tuff aquifer may result in aquifer anisotropy, yet transmissivity in DOE flow models has been treated as an isotropic parameter.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open pending review of future Nye County reports and D milestone reports on testing in the tuffs. DOE should continue efforts to fill in data gaps with new wells in the valley fill (alluvial) deposits that lie along the possible flow paths to the exposure group. Effective porosity is a critical parameter that has not yet been evaluated for the valley fill. Estimates should be obtained and compared using various methods, such as field tracer tests, lab analyses, borehole geophysics, and specific yield. Field tracer tests are especially needed to estimate effective porosity and dispersivity for the valley fill. DOE should also perform downhole logging with an accelerator porosity sonde (APS) in any new Nye County wells. We believe this tool, along with other logs, would provide the best borehole logging results for formation porosity in the valley fill, even better than that given by previously developed compensated neutron systems. The neutron logs should be appropriately calibrated, standardized, and corrected to obtain reasonable porosity estimates for the valley fill. APS logs should also be obtained for existing Nye wells that can readily be re-entered. DOE should prepare a report to summarize the resulting porosity data, that also includes analysis of the physical and chemical properties of valley fill materials sampled below the water table. Data should include conventional particle size analyses (percentages of clays, silts, sands, gravels, etc.). The report should include x-ray analyses of clay mineral types and abundances.

Interpretation of existing data from hydraulic and tracer tests in the tuff aquifer should continue, and hydraulic testing should be conducted in the recently completed wells SD-6 and WT-24. DOE should use exploratory boring techniques to help fill in large data gaps between existing and planned Nye County wells. This would help confirm lengths of flowpaths in saturated valley fill.

(6) DOE has used mathematical groundwater model(s) that incorporate site-specific climatic and subsurface information. The models were reasonably calibrated and reasonably represent the physical system. Fitted aquifer parameters compare reasonably well with observed site data. Implicitly- or explicitly-simulated fracturing and faulting are consistent with the data in the 3D geologic model. Abstractions are based on initial and boundary conditions consistent with site-scale modeling and the regional models of the Death Valley groundwater flow system. Abstractions of the groundwater models for use in PA simulations should use appropriate spatial- and temporal-averaging techniques.

Analysis: The boundary conditions for the TSPA SZ flow model are derived from the U.S. Geological Survey (USGS) regional flow model. The regional model is based on a hydrogeologic framework model and this framework model currently does not have sufficient information on the hydrogeology of the area downgradient of YM due to lack of borehole or geophysical information. As a result of this lack of site data, the regional flow model is also not adequately calibrated. Also, the USGS regional model does not have a capability to assess effects of the climate-induced water-table rise that is expected to occur under future cooler, wetter climates. A water-table rise would induce flow through hydrostratigraphic units that are presently unsaturated, possibly resulting in altered flow directions and velocities. Thus, the effects of climate-induced changes on regional flow patterns may not be reasonably bounded in the TSPA -VA, which derives estimates of SZ flux and flow direction from the regional flow model.

The TSPA-VA flow and transport simulations, performed using a 3D flow model and a 1D transport model, assume the system as isotropic and homogeneous at large scale. There is ample evidence this may not be the case. Use of a dilution factor approach to incorporate the effects of transverse dispersivity is not supported by analyses. However, we understand that the methods proposed by DOE for future TSPA analyses will not use this dilution factor approach.

Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and Path to resolution: Open pending review of future DOE performance assessments. The hydrogeology framework model needs to be updated to fill the large data gaps south of YM. Also, the model should incorporate horizontal anisotropy. Further calibration of the regional flow model should be performed to better match the range of estimated parameters with observed values and reduce the hydraulic head residuals.

For the climate change effects on regional flow, the top layer of the model should be treated in a manner that accounts for climate-induced water-table rise. Alternatively, DOE can demonstrate that the neglect of water-table rise will be conservative, in terms of SZ transport, due to an increase in length of the flowpath in the valley-fill aquifer.

(7) If credit for wellbore dilution is taken, a demonstration has been provided that reasonable assumptions have been made about well design, aquifer characteristics, plume geometry, withdrawal rates, and capture zone analysis for the receptor location.

Analysis: In TSPA-VA analyses DOE is not taking any explicit credit for wellbore dilution. is acceptable to the staff. If DOE takes credit for wellbore dilution in future submittals the s will evaluate the information to determine if the acceptable criterion has been met.

Status and path to resolution: Resolved. The staff have no further questions at this time.

(8) If credit is taken for dilution due to dispersion, groundwater mixing below the repository footprint, or mixing of the YM water with water from the north in Fortymile Wash, reasonable assumptions have been made about spatial and temporal variations of aquifer properties and groundwater volumetric fluxes.

Analysis: The complete mixing and dilution factor approach was used in the TSPA-VA analyses. However, the DOE is proposing to use random walk particle tracking approach for radionuclide transport in TSPA-LA. Also see NRC comments on DOE's VA (Paperiello, 1999).

Status and path to resolution: Open, pending review of future DOE performance assessments. At that time we will evaluate the use of random walk particle tracking in the overall TSPA.

(9) DOE has incorporated key conclusions regarding potential geothermal and seismic effects on the ambient SZ flow system (e.g., National Research Council, 1992; NWTRB, 1998; memorandum from R. Craig to S. Brocoum, October 8, 1997).

Analysis: The staff await results of a program to collect, date, and analyze mineral fluid inclusions from the underground at YM. This program had been recommended by an NWTRB review panel (NWTRB, 1998).

Status and path to resolution: Open pending review of data on fluid inclusions, and review future DOE performance assessments.

(10) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

Analysis: The expert elicitation on SZ flow and transport (i.e., Geomatrix, 1997a) was conducted and documented in an acceptable way.

Status and path to resolution: Resolved. The staff have no further questions at this time.

(11) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

Analysis: TBD.

Status and path to resolution: TBD. See NRC comments on DOE's VA (Paperiello, 1999).

5.6 MATRIX DIFFUSION

Matrix diffusion refers to the dilution that occurs when solutes moving in fractures diffuse into the relatively stagnant pore waters of the adjacent rock matrix, thereby reducing solute concentrations in the mobile fracture waters. For radionuclides that sorb to mineral surfaces, the benefit of matrix diffusion is even more pronounced because of the high sorptive capacity afforded by the mineral surface area in rock matrix. This information is necessary input for the Key Elements of Subsystem Abstraction (KESA) (see Figure A-5).

5.6.1 Summary of U.S. Department of Energy Treatment of Matrix Diffusion in the Total System Performance Assessment - Viability Assessment

In the TSPA-VA, the process of matrix diffusion is treated differently for UZ and SZ transport calculations. In the UZ Radionuclide Transport module a RTTF is used to account for the combined effects of advection, dispersion, retardation in both fractures and matrix, matrix diffusion between fractures and matrix, and radionuclide decay. The RTTF is a particle-tracking approach in which particle residence times in any given model cell are based on functions derived from one-dimensional analytical solutions to radionuclide transport equations. The RTTF used to account for matrix diffusion is based on an analytical solution developed by Tang et al. (1981).

Matrix diffusion in the SZ is handled implicitly in the TSPA-VA by simply increasing the upper limit of the distribution of sampled effective flow porosities for the fractured tuff aquifer. The increased flow porosity is used to account for the delay in transport caused by matrix diffusion.

5.6.2 Acceptance Criteria and Status of Resolution for Matrix Diffusion Issues

(1) If credit for matrix diffusion in the UZ is taken, then transport predictions must be consistent with site geochemical and isotopic data.

Analysis: The DOE UZ Radionuclide Transport module, as implemented for TSPA-VA, has not changed significantly since NRC concern over the UZ matrix diffusion approach was first conveyed (letter to S. Brocoum, dated July 6, 1998). To summarize, the staff is concerned with the application of matrix diffusion in the dual-permeability formulation of DOE's RTTF approach to UZ transport modeling. When matrix diffusion is implemented in the dual-permeability formulation, there is an implied existence of two model domains representing rock matrix: an explicitly considered mobile domain in which advective transport can occur, and an implicit immobile domain in which solutes are exchanged with the fracture domain by diffusion only. We are concerned because this modeling approach violates an underlying assumption of the Tang et al. (1981) solution, upon which the matrix diffusion RTTF is based—that solutes enter and leave the matrix continuum through diffusion only. The result is a bias towards predicting faster diffusion from fractures into matrix, because the model allows solutes to diffuse from fractures into the immobile matrix domain, but does not allow solutes in the mobile matrix domain to diffuse into the fracture domain.

We also consider that the single effective diffusion coefficient, assumed to apply to all radionuclides, is consistent with values determined in the laboratory for a saturated rock matrix system. However, for unsaturated systems, effective diffusion coefficients are saturation-dependent; thus, the value should be reduced in proportion to the reduction in water-saturated cross sectional area. Also, in the UZ flow model it is recognized that the wetted contact area that couples fractures and matrix is less than the full fracture-matrix interface area, becaus all fractures conduct water, and those that do are not fully saturated. As such, a fracture-r reduction factor is used to reduce flow rates between the two model domains. The same principle should apply to diffusive exchange. Thus, we expect that the effective diffusion coefficient in the UZ transport model should be reduced by a factor similar to that used to reduce advective fracture-matrix exchange in the UZ flow model.

Furthermore, UZ transport model predictions are not consistent with UZ geochemical data (e.g., Yang, et al., 1996), which suggest that waters within rock matrix at YM have different geochemical signatures than fracture waters. Predictions should also be consistent with ^{36}Cl evidence (e.g., Fabryka-Martin, et al., 1996) for rapid transport pathways to the repository horizon. However, no such analyses are provided.

Status and path to resolution: Open, pending review of future DOE performance assessments. If credit is to be taken for UZ matrix diffusion in TSPA calculations, detailed small-scale discrete feature models are needed to verify that the RTTF approach can provide a reasonable approximation of matrix diffusion effects when used with the dual-permeability formulation. Additionally, the assumed value of the diffusion coefficient for radionuclide diffusion must be appropriately scaled to account for diminished diffusive transport due to reduced matrix saturation and reduced F/M interface area in the UZ.

(2) If credit for matrix diffusion in the SZ is taken, rock matrix and solute diffusion parameters must be (i) based on a SZ transport model that reasonably matches the results of the field tracer tests that are conducted over different distance scales and flow rates with multiple tracers of different diffusive properties, and (ii) consistent with laboratory data.

Analysis: DOE's current assumptions about matrix diffusion in the SZ are supported to so extent by field and laboratory results to date. In the TSPA-VA, DOE uses a range of values effective porosity in the SZ, described by a log-triangular distribution that ranges from 0.0001 to 0.2, with a mean of 0.02 (2%). This represents a simplification of the many variables that affect matrix diffusion by assuming that resulting delay in radionuclide arrival time can be adequately represented in a model by simply increasing the effective flow porosity. The staff agree that this approach can be implemented in a conservative manner, however, DOE would have to provide a technical analysis to support the chosen distribution of effective flow porosities.

It is the staff's understanding, that for future TSPA analyses, the DOE will adopt a different approach to including matrix diffusion processes in SZ transport models—an approach that explicitly considers aquifer physical properties such as spacing between flowing fractures. As this approach is currently under development by DOE, the methods have yet to be made available for staff review.

Status and path to resolution: Open pending review of future DOE performance assessments and milestone reports.

(3) If used, expert elicitations are conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

Analysis: The staff is not aware of DOE plans for an elicitation on matrix diffusion.

Status and path to resolution: Closed. The staff have no further questions at this time.

(6) The collection, documentation, and development of data, models, and computer codes have been performed under acceptable Quality Assurance Procedures (QAP). If they were not subject to an acceptable QAP, they have been appropriately qualified.

Analysis: TBD.

Status and path to resolution: TBD. Also see NRC comments on DOE's viability assessment (Paperiello, 1999).

5.7 STATUS OF OPEN ITEMS

5.7.1 Items Resolved at the Staff Level

The following table gives the status of resolution of the six subissues under this KTI.

Table 16. Status of Subissue Resolution

Summary of Subissues	Status of Resolution at the Staff Level
1. Future climate change	Achieved resolution about methodology, upper bound for pluvial precipitation, and likely depression of mean annual temperature for pluvial climates
2. Hydrologic effects of climate change	Achieved resolution about upper bound estimate of climate-induced water-table rise
3. Rates of present-day shallow infiltration	Achieved resolution on methodology; reliable upper bound has been determined; upper bound can be refined downward by further incorporating effects of vegetation; resolution on data likely through agreement on refined bounding value and analysis of ESF infiltration tests
4. Deep percolation (present-day and future)	Multiple lines of evidence available for resolution; resolution likely based on data and analyses expected to be provided from ESF, east-west drift, Busted Butte facility, and boreholes
5. Ambient flow in the saturated zone and dilution processes	Methodology under discussion with DOE; resolution possible by LA, but strongly depends on adequacy of Nye County and DOE testing programs for the saturated zone; DOE currently takes no credit for wellbore dilution but could do so

Summary of Subissues	Status of Resolution at the Staff Level
6. Matrix diffusion	Methodology under discussion with DOE; resolution likely based on data from Busted Butte and C-well testing; resolution not important if adequate valley fill occurs along saturated zone flowpaths at 15-20 km; resolution very important if the compliance distance becomes less than 20 km

The following open items are resolved at the staff level. They originally were developed in our review of the DOE TSPA 1995, Site Characterization Analysis (SCA), and various Study Plans (SP). Changes in the overall DOE program has resulted in some of the comments losing validity. Additional information both from DOE and from ongoing work by NRC and CNWRA staff has also become available. As a result, all of these open items are closed with respect to the TSPA-95, SCA, and the SP. However, the technical concerns of some of these issues remain with the NRC staff. Acceptance Criteria in Section 4.0 and the Status of Subissue Resolution in Section 5.0 encompass the NRC staff position on these issues.

TSPA95: Infiltration and deep percolation calculations presented in Chapter 7 of TSPA-95 lack defensibility.

Status: ***Closed***

Basis: The infiltration and deep percolation calculations presented in Chapter 7 of TSPA-95 (CRWMS M&O,1995) were uncertain estimates that were not quantified and not used in the latest PA.

Infiltration estimates documented in Flint and Flint (1994) were used in TSPA-95 which were base primarily on the maximum hydrologic capacity of the matrix material and neglected fracture flow. Two possible infiltration scenario were used in TSPA-95: (1) low infiltration case uniformly distributed between 0.01 and 0.05 mm/yr; and (2) a high infiltration case between 0.5 and 2.0 mm/yr. The high and low rates had an uncertainty factor of 2.

Infiltration is now based on climatic studies which estimates current precipitation at 170 mm/yr and possible wetter climates as high as 500 mm/yr. According to Flint, et al. (1996a), net infiltration currently averages about 6 mm/yr and may have averaged more than 30 mm/yr in some periods over the past 20 kyr. The TSPA-VA Base Case (Andrews, 1998) uses three discrete infiltration rates used as input to the unsaturated zone flow model. The discrete infiltration models are the present (dry, approximately 7 mm/yr), long-term average (approximately 40 mm/yr, and super pluvial (approximately 120mm/yr.) The present infiltration model is calibrated to shallow neutron holes and is used to extrapolate the effects of precipitation changes. The duration and timing of the three TSPA Base Case infiltration cases are as follows: (1) present (dry) - duration of 10 kyr and timing every 100 kyr; (2) long-term average - duration of 90 kyr and timing about 80% of time; and (3) super pluvial - duration of 10 kyr and timing every 300 kyr.

Percolation flux is the volume of water moving downward through the unsaturated zone in a given time period. Percolation flux may travel directly to the saturated zone or a portion may enter the proposed repository as seepage. Percolation fluxes still have large uncertainties (Bodvarsson, et al., 1997a) as they did in TSPA-95. The current analysis is more defensible because a variety of methods to constrain the flux are used, including geochemical analysis, secondary mineral deposits of calcite and opal, borehole temperature data, and various 1D, 2D, and 3D modeling analyses. The TSPA-VA Base Case Unsaturated Zone Flow Model (Andrews, 1998) is calibrated with matric potential, temperature, chloride, ^{36}Cl, perched zones, and pneumatics. The percolation flux varies spatially . Percolation at the repository is discretized into six regions and ranges from the present day climate (4-11 mm/yr), long-term average (31-55 mm/yr), and super pluvial (81-140 mm/yr.)

This was a comment on the now outdated TSPA-95. Therefore this open item is no longer relevant and is closed. However, Acceptance Criteria (1) and (2) in Section 4.4 and the Status of Acceptance Criteria in Section 5.5 address the NRC staffs position on infiltration and percolation.

TSPA95: Dilution factor calculations presented in Chapter 7 of TSPA-95 lack defensibility.

Status: ***Closed***

Basis: The dilution factors in Chapter 7 of the TSPA-95 are mixing of groundwater from two sub-basins and lateral and vertical dispersion over the length of the path length. A dilution factor of 3.5 was used for the mixing of groundwater from 2 sub-basins in the vicinity of groundwater withdrawal. Sub-basin mixing (i.e. dilution) is no longer employed in saturated zone flow and transport modeling. YM is centrally located within the Death Valley groundwater basin and is also centrally located in the Alkali Flat-Furnace Creek sub-basin. The site-scale flow model developed by Czarnecki, et al. (1997) assumed the sub-basin received water as underflow from the adjoining sub-basins (i.e., flux) but did not apply the dilution factor approach.

The dispersive dilution factor (i.e., dose reduction factor) described in TSPA-95 was estimated to be 25. This was applied at 30 km to calculated concentrations at the Amargosa Valley. TSPA-95 recommended the construction of a regional flow model to determine the flow path heterogeneities and sensitivities to the dilution factor. Regional and site-scale flow and transport modeling has been completed. Currently, the TSPA-VA approach uses an effective dilution factor between 1-100 (Andrews, 1998) based the saturated zone expert elicitation. The defensibility of the current dilution factors rests with saturation zone expert elicitation and the uncertainties of their estimates, which were not provided. This is an area of great uncertainty due to the lack of hydraulic data along the flow path describing the degree of heterogeneity. Conservatively though, the TSPA-VA saturated zone model uses no vertical transverse dispersivities.

This was a comment on the now outdated TSPA-95. Therefore this open item is no longer relevant and is closed. However, Acceptance Criteria (1) and (2) in Section 4.4 and the Status of Acceptance Criteria in Section 5.5 address the NRC staffs position on infiltration and percolation.

TSPA95: The lower limit chosen for the “satiated matrix saturation” remains realistically high and not adequately conservative.

Status: ***Closed***

Basis: A DOE letter from Brocoum to Stablein dated April 28, 1998 stated this item was "...closed letter from J. Holonich to R. Milner dated Sept. 15, 1994. The underlying basis of this conc was the "satiated" matrix saturation (σ), used to approximate fracture-matrix flow in the unsaturated zone. At the time of TSPA95, the LBNL-USGS site-scale model used an empirical modification to the equivalent continuum model (ECM) approach. The σ-based formulation was a preliminary method to simulate fracture flow. The current LBNL unsaturated zone flow model now imparts a 3-D dual permeability process model. Thus the "satiated" matrix saturation" (σ) is no longer an issue.

This issue has been resolved and is closed.

SCA: **Comment 15** - Solitario Canyon horizontal borehole activity inadequate to address impact of faults on fluid flow.

Status: ***Closed with respect to SCA Comment 15***

Basis: A DOE letter from Brocoum to Stablein dated April 28, 1998 stated this item was "...closed by a letter from J. Holonich to R. Milner dated Sept. 15, 1994." However, to date no qualitative or quantitative activity has taken place to address the permeability characteristics of the SCF and its impact on groundwater movement. The horizontal borehole activity of the SCF was described in the Site Characterization Plan but was never drilled. Section 3.1 of the SP for Characterization of the Site Saturated-Zone Ground-Water Flow System (8.3.1.2.3.1) detailed a plan to "...1) characterize the hydrologic significance, nature, and implications of the Solitario Canyon fault; and 2) determine whether the fault is a barrier to eastward flow of water in the saturated zone beneath the repository." Several hypotheses were proposed to explain the higher water levels in wells west of Solitario Canyon including "...the fault or fault zone with the canyon acts as a barrier to flow across it because of low-permeability gouge along the f... the fault acts as a barrier to flow because stratigraphic offset juxtaposes a zone of high permeability against a zone of very low permeability..." Pumping tests were to be conducted in the SP's proposed wells installed on west and east of the fault. However the wells were not installed and the pump test never conducted.

Well USW SD-6 has been drilled on Yucca Crest. According to the Borehole USW SD-6, Revision 0, Field Work Package (FWP-SB-97-002), the objectives are to "...allow the collection of critical stratigraphic, structural and rock property characteristics data from the western potential repository block...provide input to the 3-D Geologic Framework Model and hydrologic models..." Hydraulic borehole testing (i.e. pumping and/or bailing of the borehole) is planned for SD-6. The stated objective may not be sufficient to evaluate the effects of the SCF on groundwater movement. In addition to SD-6, the Reimus, et al. (1998) Phase II plan proposed testing of the Yucca Crest domain to obtain hydraulic and transport properties to determine if the Solitario Canyon Fault is a barrier to groundwater flow.

In addition to the work at well SD-6, DOE also plans to test the SCF where it is exposed in the east-west drift. This work will also be reviewed by the staff as results are submitted.

This open item is considered closed with respect to this SP. However, the issue of the SCF remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SCA: **Comment 19** - Activities for the saturated zone flow system are inadequate to characterize boundaries, flow directions, magnitudes, and paths.

Status: ***Closed with respect to SCA Comment 19***

Basis: The NRC staff recognized that since this comment was written in 1991 and the DOE has made significant progress in determining the saturated zone flow characteristics. There are still some areas of high uncertainty related to the saturated zone which may (or may not) impact the TSPA-VA, such as the effects of faulting on groundwater movement, the length of alluvium in the flow path, and the hydrologic properties of the tuff and alluvium. The NRC staff recognizes that values of specified parameters cannot be exactly known because of errors in measurements, spatial and temporal variability in the media and/or practical restrictions in data gathering efforts. It many circumstances it has become more appropriate to express parameter values in terms of probability distributions as opposed to expressing them in terms of deterministic values.

This open item is considered closed with respect to the SCA. However, the issue of the SZ remain a concern to the NRC staff and are addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SCA: **Comment 20** - Current and proposed well locations inadequate for defining the potentiometric surface in the controlled area.

Status: ***Closed***

Basis: The potentiometric surface has been reasonably defined in the so-called "controlled area." However, at the 20 km site-scale, uncertainty remains due to the complex three-dimensional flow system. The greatest uncertainties in the potentiometric surface are 1) the so-called "large hydraulic gradient" north of the potential repository, 2) the "moderate hydraulic gradient" west of the potential repository across Solitario Canyon fault, as defined by Luckey, et al. (1996), 3) the water-table configuration south and southeast of the potential repository, and 4) the carbonate aquifer. The NRC staff recognizes the effort underway to better understand the potentiometric surface in the areas of the large and moderate hydraulic gradient with the current installation of USW SD-6 and WT-24. The Nye County Early Warning Drilling Program should provide potentiometric data in the saturated tuffs and alluvium, and the carbonate aquifer, south and southeast of the potential repository.

This issue has been resolved and is closed. The NRC staff will evaluate the new and updated potentiometric data when it becomes available. See Acceptance Criteria (2), (3), and (4) in Section 4.5 and the Status of Acceptance Criteria in Section 5.5.

SCA: **Comment 21** - No consideration of I-129 and Tc-99 in characterization of saturated hydrochemistry.

Status: ***Closed***

Basis: The NRC requested the that ^{129}I and ^{99}Tc be analyzed in the saturated zone to provide insight into groundwater travel times and the rates of migration of radionuclides in the vadose zone. The ^{36}Cl studies conducted by Fabryka-Martin, et al. (1996b) has provided sufficient analysis of fast pathways in the unsaturated zone. Isotopic age dating of the ground water to support groundwater flow paths has been undertaken by the DOE, although not the specific isotopes of ^{129}I and ^{99}Tc. Carbon-14, ^3H, and elements of the uranium decay series have been analyzed to age date the groundwater. The NRC staff no longer requests ^{129}I and ^{99}Tc be analyzed for to estimate groundwater travel times because other methods have been employed.

This issue has been resolved and is closed.

SCA: **Comment 22** - Inadequate saturated zone hydrology sample collection methods.

Status: ***Closed***

Basis: This comment addressed the isolation of discrete groundwater sampling zones with packers and the hydrochemical analysis. The NRC review of SP 8.3.1.2.3.2, Characterization of the Yucca Mountain Saturated Zone Hydrochemistry, satisfied the requirements to utilize packers and sample perched water. Page 3.2-8 of the SP specified a procedure that should satisfactorily deploy packers to isolate the upper zone of the unsaturated zone. The NRC st-ff request for perched water studies has been conducted in numerous wells. This kind of wo also included in the FWP for both WT-24 and USW SD-6.

This issue has been resolved and is closed.

SCA: **Comment 123** - Inadequate saturated zone hydrology sample collection methods.

Status: ***Closed***

Basis: This comment addressed the effects of ventilation of underground tunnels and the potential for interference with hydrologic testing and determination of baseline conditions. The staff now considers this open item comment to be resolved. Sufficient data on baseline conditions have been obtained and data were collected during the construction of the ESF. Pneumatic monitoring and testing is continuing at various locations in the ESF. As of June 1998 recording of pneumatic data continues at boreholes UZ-4, UZ-5, UZ-7a, SD-12, NRG-7a, and SD-7. Nye County, NV, continues to record pneumatic data in NRG-4 and ONC-1.

This issue has been resolved and is closed.

SCA: **Question 55** - No analysis of potential test interference from water storage facilities.

Status: ***Closed***

Basis: The design plan for the water storage tank, a septic field, and a waste water lagoon have been reviewed and deemed acceptable with regards to potential test interference.

This issue has been resolved and is closed.

SP 831212 Comment 1 - The NRC staff considers that specific attention should be given to the study of surface runoff flows from the west face of YM and in Solitario Canyon.

Status: ***Closed with respect to SP 831212, Comment 1***

Basis: The DOE has done 3D, coupled surface/subsurface flow modeling using the TOUGH2 code of the Wren Wash near SD-9 at the request of the expert elicitation panel (Bodvarsson, 1997a). Wren Wash is located on the east slope of YM and does not evaluate the potential for lateral infiltration from surface runoff on the west slope of YM and/or Solitario Canyon. The NRC recognizes that, according to the April 1998 USGS Monthly Progress Report, page 9, efforts are underway to model surface flow in the Drill Hole Wash, Solitario Canyon, and Dune Wash to compare net infiltration along channel segments and lower side slopes.

In addition, the NRC staff has concerns about the coupling of TOUGH2 and a 3D kinematic overland flow model as described in Chapter 9 of Bodvarsson, et al. (1997a). The fundamental difficulty in the 3D kinematic approach is hidden by the use of an unrealistic Mannings n value of 20 for the modeling in Wren Wash (Bodvarsson, et al., 1997a). Values of Mannings n are less than 1 and an appropriate value for YM is 0.15. Also, the numerical difficulty in coupling the kinematic overland flow model with TOUGH2 could be overcome by use of a diffusion analogy for overland flow.

This open item is considered closed with respect to this SP. However, the issue of coupling TOUGH2 and a 3D kinematic overland flow model remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831214:Comment 1 - The study needs to identify what minimum information and documentation about pre-existing wells will be acceptable to support the use of those wells in calibrating regional models.

Status: ***Closed***

Basis: D'Agnese, et al. (1997) developed and calibrated the regional DVGFS model. Wells contained in the publicly available USGS National Water Information Service (NWIS) data base were used to provide lithologic, hydraulic head, and water-use data for the regional model. Approximately 2,100 wells located in the Death Valley region were utilized in the regional model from the NWIS data base. The USGS NWIS is maintained and operated under strict quality control procedures. Minimum information and documentation exists for the wells in the data base.

This issue has been resolved and is closed.

SP 831214:Comment 2 - The study needs to be updated with respect to available literature on the alternate conceptual models for the regional ground water system. The study plan does not adequately describe the approach for modifying existing conceptual models based on new hydrogeologic data.

Status: ***Closed***

Basis: The DOE has demonstrated that alternative conceptual models are continuously explored as new hydrogeological data becomes available. Each successive YM hydrogeological report incorporates the latest hydrogeologic data and discusses alternative conceptual models if appropriate. For example, Czarnecki, et al. (1997) presented alternative conceptual models to explain the apparent large hydraulic gradient and perched water. The April 1998 USGS Monthly Progress report stated, "Several ongoing efforts continued in the testing of alternative conceptual models and refinement of regional hydrogeologic framework and flow models, etc..." The saturated zone transport model (Zyvoloski, et al., 1997) reviews the ongoing developments of groundwater flow modeling and discusses the issues brought up by the Saturated Zone Expert Elicitation.

This issue has been resolved and is closed.

SP 831214:Comment 3 - Data may be insufficient to adequately construct and calibrate subregional or regional groundwater models.

Status: ***Closed with respect SP 831214, Comment 3***

Basis: A "preliminary" site-scale groundwater flow model was developed by Czarnecki, et al. (1997) and a Death Valley regional groundwater model was developed by D'Agnese, et al. (1997). Without question, the need for sufficient data in groundwater modeling is of paramount importance in order to accurately represent a physical flow system. The authors recognized the need for sufficient data and addressed uses and limitations of the models, additional data needs, and areas for model improvement. According to the USGS Monthly Progress Reports (February-April, 1998), improvements to the models are underway. For instance, the hydrogeologic framework model used in the preliminary site-scale model is incorporating a higher resolution hydrogeologic framework model to sample over a 250-meter by 250-meter grid rather than a 1,500-meter grid. Field data collection is underway at springs in the Death Valley region to support the regional groundwater flow model. Currently, there may be insufficient data to accurately construct and calibrate the groundwater flow models. But the ongoing improvements, refinements, and data collection activities by the DOE demonstrate the desire to accurately model the physical system.

This open item is considered closed with respect to this SP. However, the issue of the groundwater models remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831214:Question 1 - What approaches will be used to evaluate evapotranspiration and recharge on a regional basis?

Status: ***Close with respect to SP 831214, Question 1***

Basis: The refinement of evapotranspiration estimates for the UZ site-scale model (near the repository) could be used to support portions of the regional estimates. Chapter 9 of the unsaturated zone report (Bodvarsson, et al., 1997) described how evapotranspiration was integrated into the Coupled Surface Runoff Model using the TOUGH2 code. All precipitation was modeled as infiltration except when storage capacity of soil is exceeded and runoff occurs. A sub-model then takes changes in soil moisture due to evapotranspiration and net infiltration into account and provides antecedent conditions for the next simulation. The Priestley-Taylor equation was chosen to calculate evapotranspiration. According to the April 1998 USGS Monthly Progress Report, a new evapotranspiration model, which accounts for bare-soil evaporation and utilizes parameters defining vegetation type and density, is being developed to better estimate net infiltration. However, the NRC staff has a strong concern about the adequacy of the TOUGH2 module and feels the modeling is inadequate.

A modified Maxey-Eakin method was employed on a regional basis to produce the initial potential recharge area maps (D'Agnese, et al., 1997). The Maxey-Eakin method is an empirical method which estimates recharge directly from precipitation estimates. It was modified to account for altitude, slope-aspect, rock permeability, and vegetation. These changes are important for the YM site because in Fortymile Canyon Wash, Savard (1994, 1998) found that recharge to groundwater occurs by infiltration along the stream beds. Utilization of an "unmodified" Maxey-Eakin method would have estimated zero recharge along Fortymile Canyon Wash because of its low altitude. The modified Maxey-Eakin method appears to be appropriate for delineating large scale zones of recharge.

This open item is considered closed with respect to this SP. However, the issue of evapotranspiration and recharge remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831228:Question 1 - How will laboratory-scale models and data be used to estimate model parameters in the corresponding site-scale models?

Status: ***Closed***

Basis: Model parameters used the unsaturated zone site-scale flow model were calibrated against actual field data (Bodvarsson, et al., 1997a). Comprehensive model calibration and sensitivity evaluations were performed to incorporate field and laboratory data into the site-scale unsaturated zone flow model.

This issue has been resolved and is closed.

SP 831228:Question 2 - Why have particular modeling strategies been assigned to address particular technical issues?

Status: ***Closed***

Basis: A complete discussion of the various modeling strategies has been provided in Bodvarsson, et al. (1997a). The modeling strategies described include fracture/matrix interactions, single-continuum models, effective continuum models, dual-continuum models, etc.

This issue has been resolved and is closed.

SP 831228:Question 3 - Is the method used by Cacas, et al. (1990) for the determination of fracture network hydraulic aperture distributions applications applicable for unsaturated flow?

Status: ***Closed***

Basis: The fracture network hydraulic aperture distribution as described in SP831228 was not utilized in the unsaturated zone flow model prepared by Bodvarsson, et al. (1997a). There were primarily sources of "raw" fracture parameter data sets used in the unsaturated zone flow model. Fracture permeabilities were developed by air injection testing (LeCain, 1997), fracture frequencies and intensities were calculated from boreholes (Rautman, 1996), and fracture locations, trace lengths, and orientations were obtained from Detailed Line Surveys in the Exploratory Study Facility. Inverse modeling was relied upon for the determination for each sublayer in the LBNL model (Bandurraga and Bodvarsson, 1997).

This issue has been resolved and is closed.

SP 831228:Question 4 - How can one build confidence in conceptual models if every time a conceptu model is refuted by experimental data, the experiment is redesigned as inappropriate or not sensitive enough to capture the essence of the model?

Status: ***Closed***

Basis: The majority of components in the unsaturated zone site-scale flow model used extensive data available from field studies at YM. According to Bodvarsson, et al. (1997a) the available data included saturations, in-situ and core sample water potentials, saturated conductivities and desaturation curves, core sample bulk property measurements, pneumatic monitoring, temperature data, air permeability test results, geochemical analysis, and perched water body testing.

This issue has been resolved and is closed.

SP 831228:Question 5 - What modeling strategies will be used to address technical issues for flow studies?

Status: ***Closed***

Basis: This open item was written to address technical issues related to the following: 1) conditions under which flow within fractures in the unsaturated zone is likely to occur; 2) the nature of channeling processes and the implications of channeling for the transport of water and radionuclides; and 3) models which describe the effect of stress changes on the permeability and relative permeability of rough-walled natural fractures. The unsaturated zone site-scale flow model evaluated (Bodvarsson, et al., 1997a) considered seven numerical modeling methods (e.g. fracture only, effective continuum model, dual permeability, etc.) and the associated physical processes.

This issue has been resolved and is closed.

SP 831229:Comment 1 - Solitario Canyon fault as a water infiltration pathway.

Status: ***Closed with respect to SP 831229, Comment 1***

Basis: The potential for the Solitario Canyon and SCF to provide sources of infiltrating water that impact the repository performance exists. The impact to repository performance has not been adequately evaluated to date.

This open item is considered closed with respect to this SP. However, the issue of SCF as a water infiltration pathway remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831229:Question 1 - Evaluation of wetting front instabilities for modeling the Yucca Mountain hydrologic regime.

Status: ***Closed with respect to SP 831229, Question 1***

Basis: The issue of concern with this comment is the "role of the Paintbrush tuff nonwelded unit (PTn)" on the hydrologic system. The current conceptual model by Bodvarsson, et al. (1997a) assumes that when water enters the PTn, the relatively high matrix permeabilities and porosities and low fracture densities greatly attenuate infiltration fluxes. The fracture-matrix interactions in the unsaturated zone transport model (Robinson, et al., 1997) has led to fast paths in the PTn fault-zone properties. The unsaturated zone expert panel concluded that lateral diversion might occur over a few meters to tens of meters, but diversion would not be expected to occur over a much larger scale (Geomatrix, 1997). The NRC staff endorses use, in PA, of the assumption that general lateral diversion does not occur above the repository, as this conservatively passes all net infiltration generated within the repository footprint to the repository horizon.

This open item is considered closed with respect to this SP. However, the role of the PTn on the hydrologic system remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831229:Question 2 - Obtaining hydraulic parameters for fractures.

Status: ***Closed***

Basis: Chapters 6 and 7 of Bodvarsson, et al. (1997a) provide an acceptable description of how the fracture hydrologic properties were obtained from site data.

This issue has been resolved and is closed.

SP 831229:Question 3 - Measurement of local water gradients in fractures to infer net moisture flux rates.

Status: ***Closed***

Basis: According to Bodvarsson, et al. (1997a), "...available saturation and water potential measurements...from specific fractures are not representative of conditions in the complex fracture networks at Yucca Mountain. Therefore, no "measured" fracture saturation or water potential data were used in the calibration effort." Inverse modeling procedures found in Chapter 7 of Bodvarsson, et al. (1997a) adequately describe the methods used to obtain water potential in fractures.

This issue has been resolved and is closed.

SP 831229:Question 4 - Calibration of hydrologic sub-models using experimental perturbations.

Status: ***Closed***

Basis: This was a clarifying question about the scope of work at analog sites and the study plans since been canceled. Therefore the question is no longer relevant.

SP 831229:Question 5 - Evaluation of modeling the non-Darcian flow regime in specific fault zones.

Status: ***Closed with respect to SP 831229, Question 5***

Basis: A DKM modeling approach was used for the unsaturated zone flow (Bodvarsson, et al., 1997a). In this approach, the fracture and matrix systems are treated separately as two parallel, overlapping, and continuous media with interactions at each location. All major faults (i.e. Solitario Canyon, Iron Ridge, Ghost Dance, Abandoned Wash, and Dune Wash Faults) are explicitly incorporated in the GFM of the UZ flow model.

The DKM does not address non-Darcian flow. Alternative conceptualization for flow in faults, e.g. sheet or rivulet flow, need to be analyzed.

This open item is considered closed with respect to this SP. However, the issue of non-Darcian flow remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831233:Comment 1 - Hydrochemical data should be used to support conceptual and numerical groundwater models for the unsaturated zone.

Status: ***Closed***

Basis: Chapter 14 of the unsaturated zone flow model by Bodvarsson, et al. (1997a) adequately describes the integration of the chemical database with the hydrologic database. The premise is that hydrochemical data, when combined with hydrologic data, provide relevant information for validating the unsaturated flow and transport models. The hydrochemical analysis by Yang, et al. (1996a, 1996b) provided the framework for the Bodvarsson, et al. (1997a) unsaturated zone flow model and the Robinson, et al. (1997) unsaturated zone transport modeling.

This issue has been resolved and is closed.

SP 831233:Question 1 - Which hydrologic codes may be used to model complex heterogeneities in the saturated zone?

Status: ***Closed with respect to SP 831233, Question 1***

Basis: To date, the Finite Element Heat Mass Nuclear-Transfer Code (FEHMN) by Zyvoloski, et al. (1997) was used to model in the site-scale saturated zone by Czarnecki, et al. (1997.) FEHMN has the capability (Czarnecki, et al., 1997) to model the site-scale complex heterogeneity including the ability to 1) simulate 3D transient ground-water flow and heat transport, including 3D representation of spatially variable permeability, porosity, and thermal conductivity, and 2) permit specification of dual permeability and porosity representing both fracture and matrix flow. The numerical model used in the Death Valley regional groundwater model calibration by D'Agnese, et al. (1997) was MODFLOWP (Hill, 1992). This model code is an adaptation of the USGS 3D, finite-difference modular ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988; Hill, 1992) in which non-linear regression is used to estimate flow-model parameters that result in the best fit to measured hydraulic heads.

However, it is the understanding of the NRC staff that the 3D site-scale saturated zone modeling has been simplified to a 1D flow and transport model. The DOE Peer Review Panel (page 35, 1998) stated, "The current treatment of the saturated zone flow and transport at Yucca Mountain is not acceptable." But the panel also noted on page 37, "The Panel believes that a numerical approach based on a streamtube formalism, well-resolved near the plume and with a correct representation of dispersion and retardation, is feasible and should be pursued (provided that a good description of the heterogeneity from field data is available)...The Panel believes that a separate model is needed for the case in which a small number of waste packages may have failed. The revised flow and transport modeling code and results have not been received nor reviewed yet by the NRC staff.

This open item is considered closed with respect to this SP. However, the issue of hydrologic model codes remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831233:Question 2 - What methods will be used to incorporate "soft" information in analysis of hydrologic parameters?

Status: ***Closed with respect to SP 831233, Question 2***

Basis: The key hydrologic parameters are characterized in the form of either probability distributions or deterministic bounding values. These parameters include transmissivity, hydraulic gradient, porosity, effective aquifer thickness, permeability, and hydraulic conductivity. The 3D site-scale SZ flow model (Czarnecki, et al., 1997) used the independent parameter estimation software called PEST (Watermark Computing) to estimate the hydrologic parameters. PEST used a nonlinear least-squares regression to estimate parameters.

However, it is the understanding of the NRC staff that the 3D site-scale SZ modeling has been simplified to a 1D flow and transport model. The revised flow and transport modeling code and results have not been received nor reviewed yet by the NRC staff.

This open item is considered closed with respect to this SP. However, the issue of site-scale SZ modeling remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831233:Question 3 - How will site saturated-zone hydrologic modeling be integrated with other site characterization activities?

Status: ***Closed with respect to SP 831233, Question 3***

Basis: Recommendations for future site characterization activities have been made by several au (e.g. Altman, et al., 1996, Luckey, et al., 1996, and Czarnecki, et al., 1997) to improve the saturated zone flow models. Reimus, et al. (1998), in a draft report, present an approach to "...build on and augment the present state of knowledge of the SZ..." The NRC staff do not know if the Reimus, et al. (1998) Three Phase Testing Plan will be implemented.

The DOE Peer Review Panel stated, "The current treatment of saturated zone (SZ) flow and transport at Yucca Mountain is not satisfactory....The lack of field data presents a major difficulty. There is a broad area along the projected SZ flow path from Fortymile Wash to the Amargosa Valley, 10 km or more in length, with no boreholes."

This open item is considered closed with respect to this SP. However, the issue of adequate site characterization and hydrologic modeling remains an area of concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831233:Question 5 - How will upper and lower boundary conditions be selected for a three-dimensional groundwater model at the scale of the controlled area?

Status: ***Closed with respect to SP 831233***

Basis: Constant head boundary conditions are specified in the site-scale 3D SZ flow model by Czarnecki, et al. (1997). However, it is the understanding of the NRC staff that the 3D site-scale saturated zone modeling has been simplified to a 1D flow and transport model. The revised flow and transport modeling code and results have not been received nor reviewed yet by the NRC staff.

This open item is considered closed with respect to this SP. However, the issue of the site-scale 3D SZ flow model remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831233:Question 6 - If additional multiple-well sites are not constructed, how will DOE demonstrate the fracture network models represent the saturated groundwater system in portions of the controlled area beyond the vicinity of the C-well complex?

Status: ***Closed with respect to SP 831233, Question 6***

Basis: Because of the lack saturated zone characterization, Reimus, et al. (1998) recommended more multiple-well tests at three sites. A recent Peer Review Panel (DOE, 1998a) also stated "...the lack of field data presents a major difficulty. There is a broad area along the projected SZ flow path from Fortymile Wash to the Amargosa Valley, 10 km or more in length, with no boreholes." The NRC staff believes that the testing proposed by Reimus, et al. (1998) could, if implemented, significantly improve understanding of the hydrogeologic system.

This open item is considered closed with respect to this SP. However, the issue of SZ site characterization remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831521:Comment 2 - Planned thermal scanner flight data may not provide sufficient areal coverage to characterize regional properties.

Status: ***Closed***

Basis: This was a clarifying question about the scope of work at analog sites and the study plans have since been canceled. Therefore the question is no longer relevant. The NRC staff considers the site-scale properties more important than the regional scale properties.

This issue has been resolved and is closed.

SP 831521:Question 6 - Will tracer isotopic compositions be determined for analog deposits comparable to those in trench 14?

Status: ***Closed***

Basis: This was a clarifying question about the scope of work at analog sites and the study plans have since been canceled. Therefore the question is no longer relevant.

This issue has been resolved and is closed.

SP 831522 Comment 1 - There appears to be a gap in documentation of groundwater modeling work under this study.

Status: ***Closed with respect to SP 831522, Comment 1***

Basis: The NRC staff was concerned that there would be little documentation of the elaborate process of selecting and rejecting conceptual models and developing modeling parameters to simulate the YM region, based on available field data. Quality assurance audits have not verified the scientific notebook process has been followed and that the documentation is available.

This open item is considered closed with respect to this SP. However, the issue of groundwater modeling QA documentation remains a concern to the NRC staff and is addressed in this IRSR under the Section 4.0 Acceptance Criteria and the Section 5.0 Status of Acceptance Criteria.

SP 831522:Question 1 - How will the work in regional surface water and saturated zone modeling be integrated with the site unsaturated modeling?

Status: ***Closed***

Basis: This open item was developed during the staff review of DOE's SP. The question is no longer relevant because it is a clarifying question about unclear language in a study plan that DOE has canceled. We also believe the site-scale modeling is more important than the regional scale surface water modeling.

This issue has been resolved and is closed.

SP 831522:Question 2 - How will infiltration be simulated under the surface water modeling activity?

Status: ***Closed***

Basis: This open item was developed during the staff review of DOE's study plan. The question is no longer relevant because it was a clarifying question about unclear language in a study plan that DOE has canceled. We also believe the site-scale modeling is more important than the regional scale surface water modeling.

This issue has been resolved and is closed.

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ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE: UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS

Division of Waste Management
Office of Nuclear Material
Safety & Safeguards
U.S. Nuclear Regulatory Commission

Revision 2
June 1999

Volume II
(Attachments)

ATTACHMENT A

DRAFT FIGURES ILLUSTRATING ELEMENTS OF THE NRC STAFF'S TOTAL SYSTEM PERFORMANCE ASSESSMENT

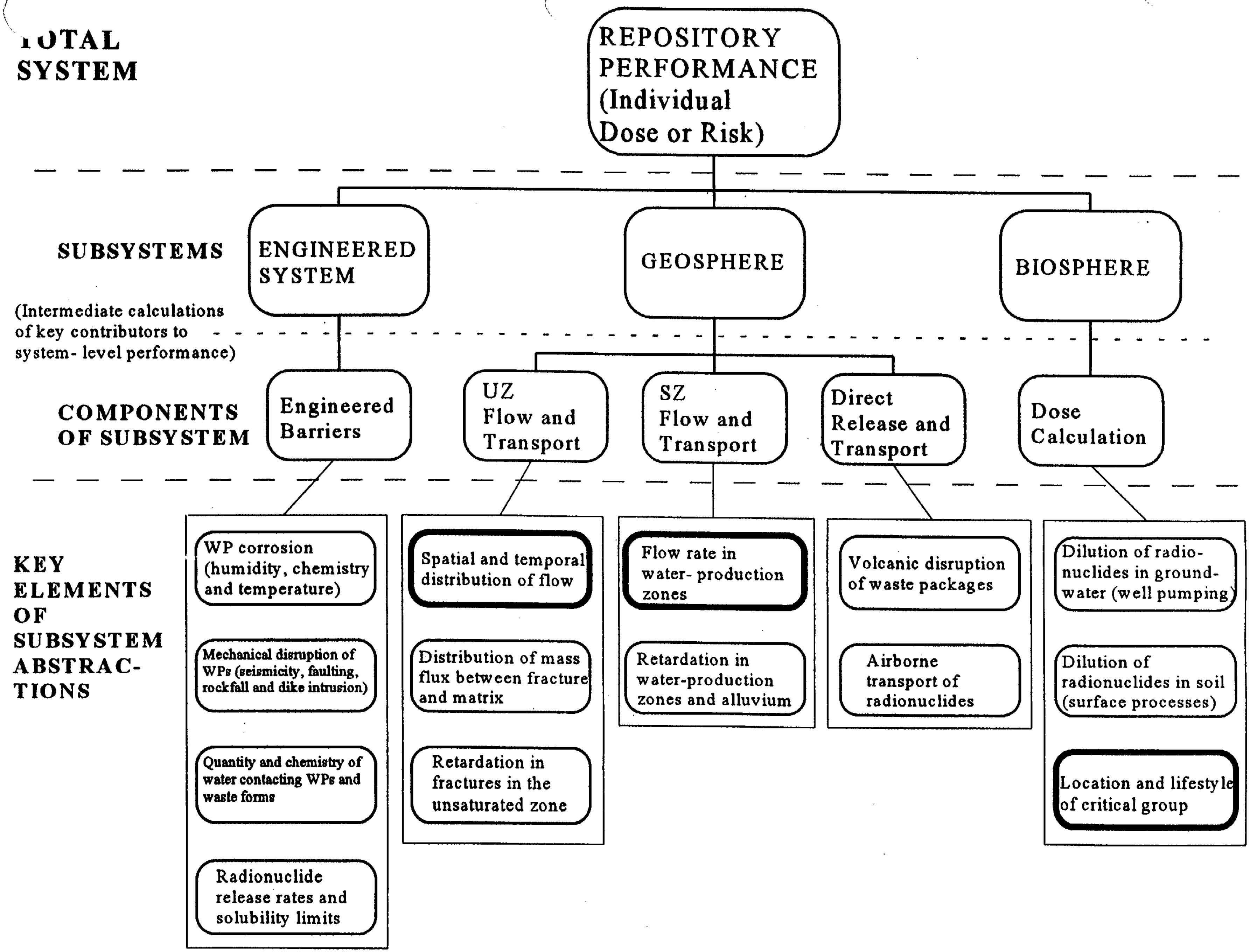

Figure A-1. Flowdown diagram for total system performance assessment. The USFIC subissues on climate change & hydrologic effects provide input to the highlighted elements.

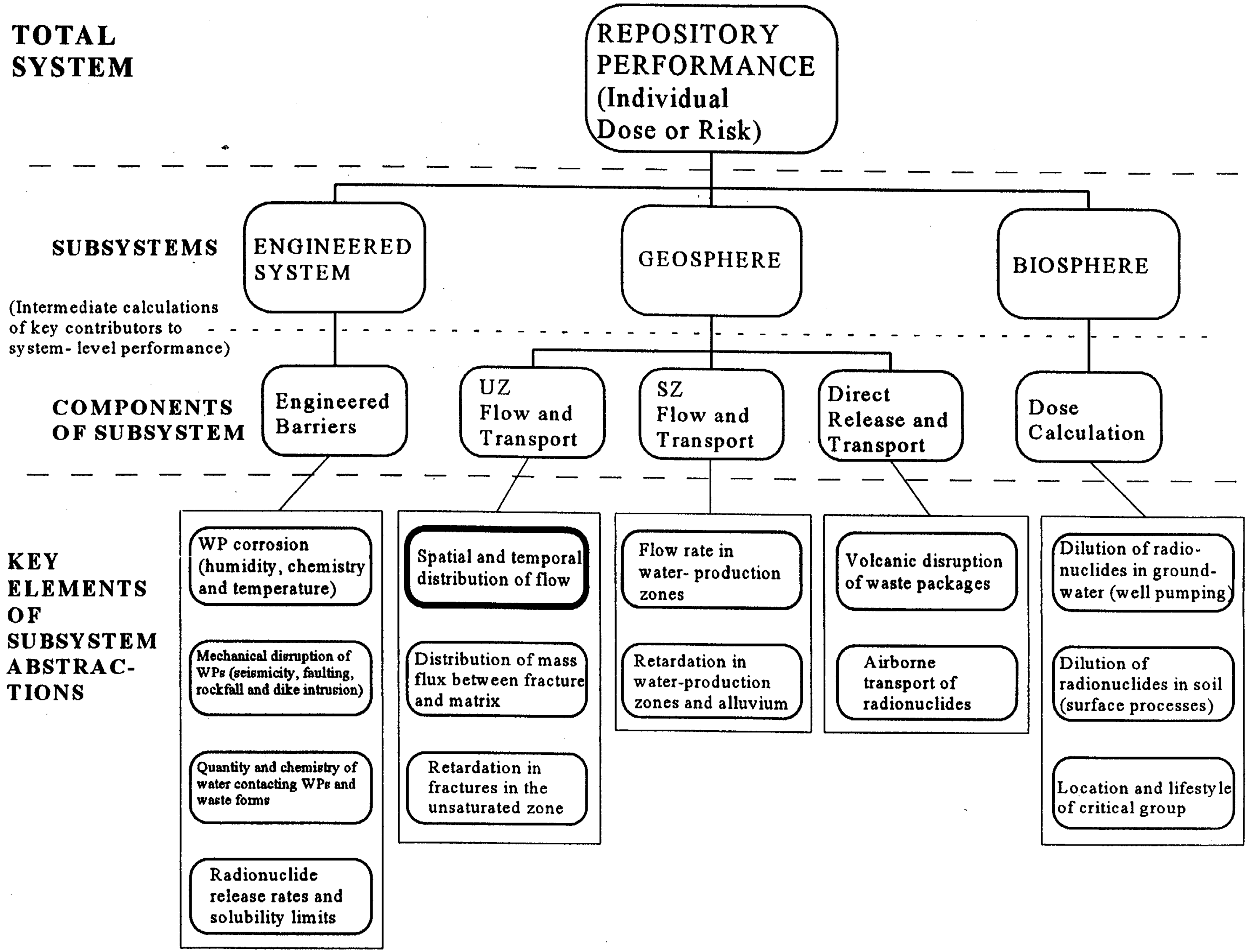

Figure A-2. Flowdown dia[illegible] for total system performance assessment. The U[illegible]IC subissue on shallow infiltra[illegible] providesinput to the highlighted elements.

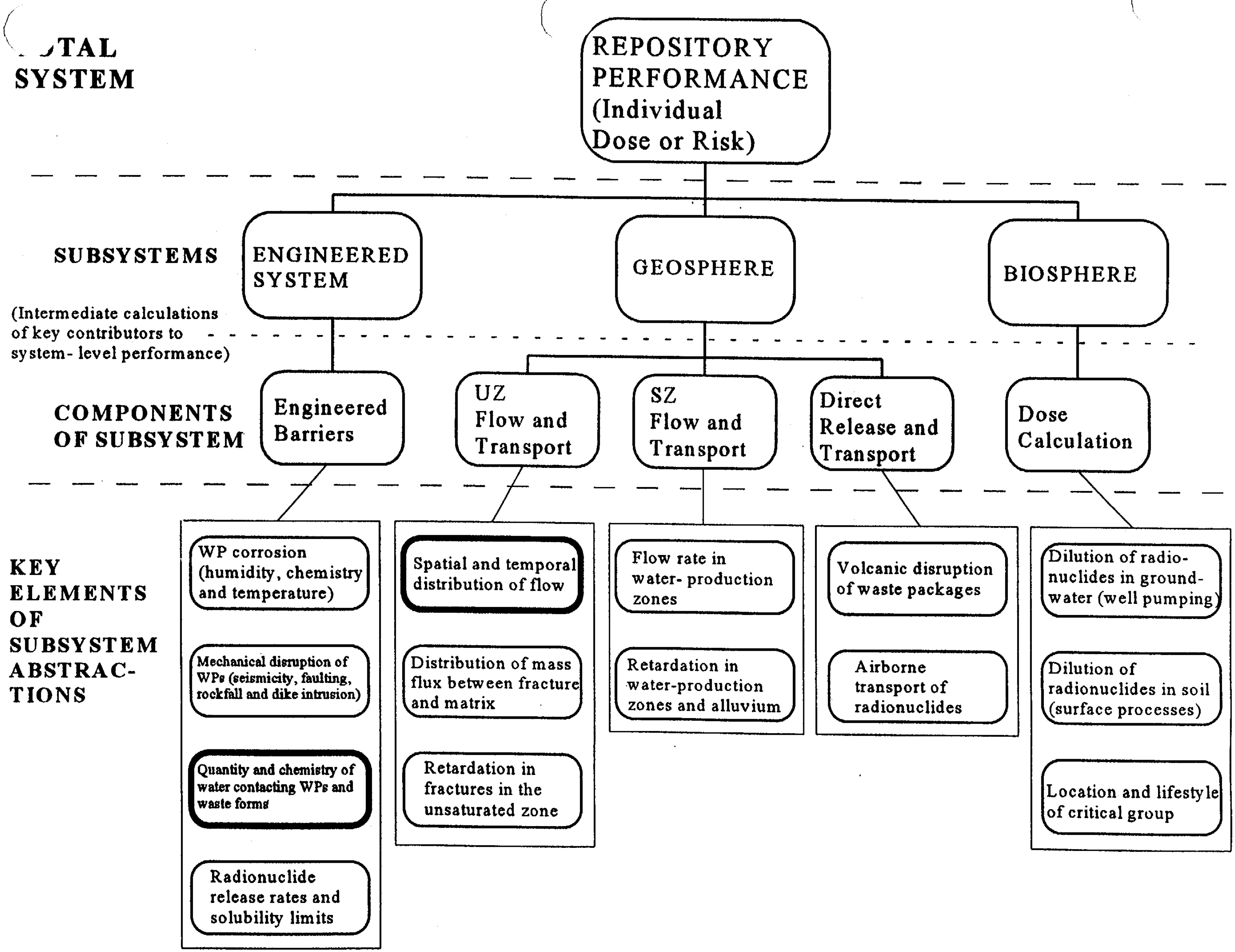

Figure A-3. Flowdown diagram for total system performance assessment. The USFIC deep percolation subissue provides input to the highlighted elements.

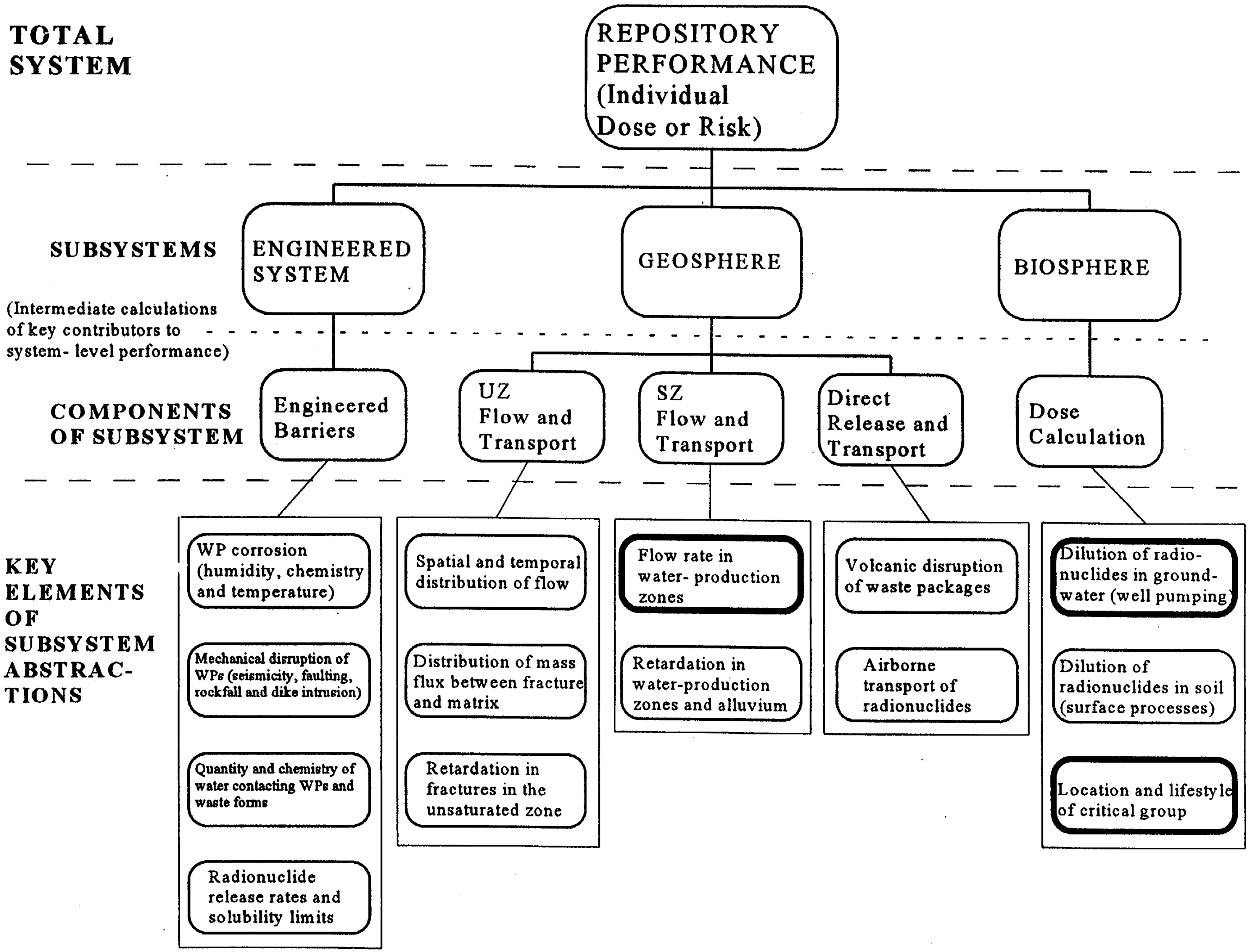

Figure A-4. Flowdown diag[illegible] for total system performance assessment. The USFIC saturated zone [illegible]sue provides input to the highlighted elements.

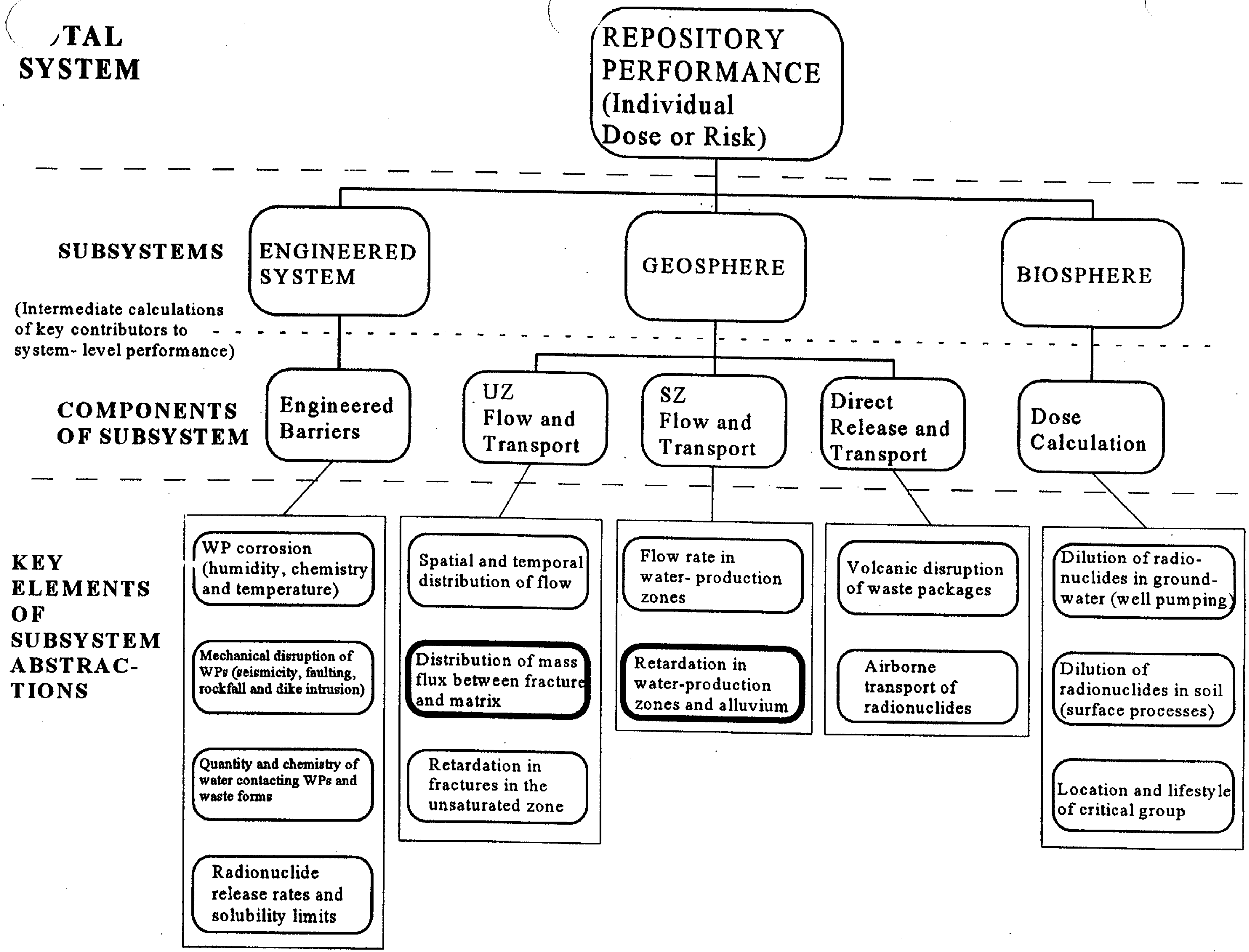

Figure A-5. Flowdown diagram for total system performance assessment. The USFIC matrix diffusion subissue provides input to the highlighted elements.

ATTACHMENT B

INITIAL ASSESSMENT OF DILUTION EFFECTS INDUCED BY WATER WELL PUMPING IN THE AMARGOSA FARMS AREA