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Phase II Contaminant Transport Parameters for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada

Revision No.: 0

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PHASE II CONTAMINANT TRANSPORT PARAMETERS FOR THE GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODEL OF CORRECTIVE ACTION UNIT 98: FRENCHMAN FLAT, NYE COUNTY, NEVADA

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List of Acronyms and Abbreviations

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
A-D	Anderson-Darling
A&E	Architect and Engineer
ADE	Advection-dispersion equation
ASTM	American Society for Testing and Materials
bgs	Below ground surface
BN	Bechtel Nevada
CADD	Corrective Action Decision Document
CAI	Corrective Action Investigation
CAIP	Corrective Action Investigation Plan
CAP	Corrective Action Plan
CAS	Corrective Action Sites
CAU	Corrective Action Unit
CD	Compact disc
CDF	Cumulative distribution function
CI	Confidence interval
CML	Carboxylate-modified latex
CR	Closure Report
DCE	Diffusion Cell Experiment
DDE_F	Data documentation evaluation flag
DEM	Digital elevation model
DFBA	Difluorobenzoic acid
DFN	Discrete fracture network
DoD	U. S. Department of Defense
DOE	U.S. Department of Energy
DQE_F	Data quality evaluation flag
DRI	Desert Research Institute
DTN	Data tracking number
ECDF	Empirical Cumulative Distribution Function
EMI	Electromagnetic Imager

List of Acronyms and Abbreviations (Continued)

EPA	U.S. Environmental Protection Agency
ER	Environmental restoration
ERP	Environmental Restoration Project
ET	Evapotranspiration
F&S	Fenix & Scisson
FEHM	Finite element heat-mass transfer code
FF	Frenchman Flat
FFACO	<i>Federal Facility Agreement and Consent Order</i>
FGE	Forced Gradient Experiment
ft	Foot
FY	Fiscal year
gpm	Gallons per minute
GPR	Ground penetrating radar
HGU	Hydrogeologic unit
HRMP	Hydrology/Radionuclide Migration Project
HSLIS	High-sensitivity liquid <i>in situ</i> particle spectrometry
HST	Hydrologic source term
HSU	Hydrostratigraphic unit
K-S	Kolmogorov-Smirnov
K	Hydraulic conductivity
K _d	Distribution coefficient
Km	Kilometer
Km ²	Square kilometers
kt	Kilotons
L	Length
LaGriT	Los Alamos Grid Toolbox
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
m	Meter
M	Molar
M/S	Meters per second
M&O	Management and Operating
m ² /d	Square meters per day

List of Acronyms and Abbreviations (Continued)

m ³	Cubic meters
m ³ /d	Cubic meters per day
MDC	Minimum detectable concentration
mg/L	Milligrams per liter
mi	Mile
mi ²	Square miles
min	Minute
mL/g	Milliliters per gram
mm	Millimeter
m/s	Meters per second
MT	Magnetotelluric
MTC	Mass Transfer Coefficient
mV	Millivolt
MWAT	Multi-well aquifer test
NDEP	Nevada Division of Environmental Protection
nm	Nanometer
NNSA/NSO	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office
NNSA	National Nuclear Security Administration
NTS	Nevada Test Site
ORP	oxidation-reduction potential
pCi/L	Picocuries per liter
pCi/mL	Picocuries per milliliter
PDF	Probability distribution function
PFBA	Pentafluorobenzoic acid
PM	Pahute Mesa
ppm	Parts per million
PVC	Polyvinyl chloride
QA	Quality assurance
QA/QC	Quality assurance and quality control
QAPP	Quality Assurance Project Plan
R	Cavity radius
REEC	Reynolds Electrical & Engineering Co., Inc.
RELAP	Reactive Transport LaPlace Inversion code

List of Acronyms and Abbreviations (Continued)

RMS	Root mean square
RMSE	Root mean square error
RNM	Radionuclide Migration
RST	Radiological source term
SI	Saturation indices
SNJV	Stoller-Navarro Joint Venture
SSM	Simplified source term model
SWNVF	Southwestern Nevada Volcanic Field
T	Time
TBD	Technical Basis Document
TD	Total depth
TDMS	Technical Data Management System
TDS	Total dissolved solids
TWG	Technical Working Group
UGT	Underground Test
UGTA	Underground Test Area
USGS	U.S. Geological Survey
WIPP	Waste Isolation Pilot Plant
XRD	X-ray diffraction
XRF	X-ray fluorescence
YM	Yucca Mountain
YMP	Yucca Mountain Project
EC	Degrees Celsius
EF	Degrees Fahrenheit
Fm	Micrometer

List of Symbols for Elements and Compounds

Am	Americium
Ar	Argon
C	Carbon
Ca	Calcium
Cd	Cadmium
Ce	Cerium
Cl	Chlorine
Cm	Curium
Co	Cobalt
CO ₂	Carbon Dioxide
CO ₃ ⁻²	Carbonate
Cs	Cesium
Eu	Europium
F	Fluorine
F ⁻	Fluoride
Gd	Gadolinium
HCO ₃ ⁻	Bicarbonate
Ho	Holmium
I	Iodine
K	Potassium
Kr	Krypton
Mg	Magnesium
Na	Sodium
Nb	Niobium
Ni	Nickel
Np	Neptunium
O ₂	Oxygen Gas
Pd	Palladium
Pb	Lead
Pu	Plutonium
Ra	Radium
Ru	Ruthenium

List of Symbols for Elements and Compounds (Continued)

Sb	Antimony
Si	Silicon
SiO ₂	Silicon Dioxide
Sm	Samarium
Sn	Tin
SO ₄ ⁻²	Sulfate
Sr	Strontium
Tc	Technetium
Th	Thorium
U	Uranium
Xe	Xenon
Zr	Zirconium

List of Stratigraphic Unit Abbreviations and Symbols

AA	Alluvial Aquifer
BAQ	Basal Aquifer
BCU	Basal Confining Unit
BLFA	Basalt Lava Flow Aquifer
BOA	Base of Alluvium
BWZ	Base of Tertiary-Age Welded Ash-Flow Tuffs
CA	Carbonate Aquifer
Cbk	Bonanza King Formation
CCU	Clastic Confining Unit
CHZCM	Calico Hills Zeolitized Composite Unit
Kg	Granitic Rocks
LCA	Lower Carbonate Aquifer
LCA3	Lower Carbonate Aquifer-Thrust Plate
LCCU	Lower Clastic Confining Unit
LFA	Lava Flow Aquifer
LTCU	Lower Tuff Confining Unit
LVTA	Lower Vitric Tuff Aquifer
OAA	Older Alluvial Aquifer
Op	Pogonip Group
PCU	Playa Confining Unit
PCU1C	Playa Confining Unit, Upper
Pz	Paleozoic-Age Sedimentary Rocks
Qta	Old Alluvial Deposits
SWNVF	Southwestern Nevada Volcanic Field
TBA	Welded Tuff (also Belted Range Aquifer)
Tbg	Grouse Canyon Tuff
Tc	Crater Flat Group
TC	Tuff Cone
TCU	Tuff Confining Unit
TCB	Bullfrog Containing Unit (also Nonwelded Tuff)
Th	Calico Hills Formation
Tm	Timber Mountain

List of Stratigraphic Unit Abbreviations and Symbols (Continued)

Tma	Ammonia Tanks Tuff
TMA	Timber Mountain Aquifer
Tmab	Bedded Ammonia Tanks Tuff
TM-LVTA	Timber Mountain Lower Vitric Tuff Aquifer
Tmr	Rainier Mesa Tuff
Tmrp	Mafic-poor portion of Rainier Mesa Tuff
Tmrr	Mafic-rich portion of Rainier Mesa Tuff
TM-WTA	Timber Mountain Welded Tuff Aquifer
Tn	Tunnel Formation
To	Older Volcanics
Tor	Redrock Valley Tuff
Tot	Tuff of Twin Peaks
Toy	Yucca Flat Tuff
Tp	Paintbrush Group
Tpt	Topopah Spring Tuff
TSA	Topopah Spring Aquifer
Tu	Volcanics of Big Dome
Tub	Tub Spring Tuff
Tw	Wahmonie Formation
Tx	Tuff Cones, Bullfrog Confining Unit or Belted Range Aquifer
UCA	Upper Carbonate Aquifer
UCCU	Upper Clastic Confining Unit
ULCCU	Upper/Lower Clastic Confining Unit
ULTCU	Upper/Lower Tuff Confining Unit
UTCU	Upper Tuff Confining Unit
VA	Volcanic Aquifer
VCCU	Volcaniclastic Confining Unit
VCU	Volcaniclastic Confining Unit
VTa	Vitric Tuff Aquifer
VU	Volcanics undifferentiated
WCU	Wahmonie Confining Unit
WTA	Welded Tuff Aquifer

1.0 Introduction

This report documents pertinent transport data and data analyses as part of the Phase II Corrective Action Investigation (CAI) for Frenchman Flat (FF) Corrective Action Unit (CAU) 98. The purpose of this data compilation and related analyses is to provide the primary reference to support parameterization of the Phase II FF CAU transport model.

1.1 Project Background

Frenchman Flat is an area within the Nevada Test Site (NTS) that was used by the U.S. Department of Energy (DOE) and the U.S. Department of Defense (DoD) for underground nuclear testing for seven years ([Figure 1-1](#)). Underground nuclear testing on Frenchman Flat began with Operation Whetstone and ended with Operation Grommet (DOE/NV, 2000b). [Figure 1-2](#) shows the location of the nuclear tests conducted at Frenchman Flat that are of interest to the Underground Test Area (UGTA) Project. Tests of interest are those that were detonated in vertical shafts or drillholes in alluvial and volcanic rock. [Table 1-1](#) presents information relative to the 10 underground nuclear tests of interest that were conducted in Frenchman Flat. Five tests were detonated in Area 5 and five tests were detonated in Area 11 of the NTS. All underground nuclear tests conducted in Frenchman Flat, except for two, have yield ranges specified as less than 20 kilotons (kt) (DOE/NV, 2000b). Media contaminated by the underground nuclear tests on Frenchman Flat are geologic formations within the saturated zone or 100 meters (m) or less above the water table. Transport in groundwater is the primary mechanism of migration for the subsurface contamination away from the Frenchman Flat underground nuclear tests.

To address groundwater contamination and ensure the protection of the public and the environment, the DOE, National Nuclear Security Administration Nevada Site Office (NNSA/NSO) is implementing a corrective action investigation of Frenchman Flat. In addition, the NNSA/NSO has established a long-term program to monitor groundwater for the presence of radionuclides.

Since 1996, the Nevada Division of Environmental Protection (NDEP) has regulated NNSA/NSO's NTS corrective action program through the *Federal Facility Agreement and Consent Order* (FFACO) (1996). Section 3.0 of Appendix VI of the FFACO (Revision No. 1, December 2000) defines the corrective action strategy that guides the UGTA Project. In this Appendix, the Frenchman Flat CAU is identified as consisting of 10 Corrective Action Sites (CAS) located in the northern portion of Area 5 and the southern part of Area 11 of the NTS.

Figure 1-1
Location of the Frenchman Flat Corrective Action Unit

Figure 1-2
Location of Underground Nuclear Tests in Frenchman Flat

**Phase II Contaminant Transport Parameters for the Groundwater Flow and
Contaminant Transport Model of CAU 98: Frenchman Flat, Nye County, Nevada**

**Table 1-1
Corrective Action Sites in the Frenchman Flat Corrective Action Unit**

Test Name	CAS Number	Date	Hole Name	UTM Zone 11, NAD 27 (m)	Yield Range (kt)	Hole Depth (m)	Working Point Depth (m)	Working Point HSU	Surface Elevation (m)	Bottom of Hole Elevation (m amsl)
CAMBRIC	05-57-003	05/14/1965	U5e	E 592142.7 N 4075575.354	0.75	305	295	AA	956	651
DERRINGER	05-57-004	09/12/1966	U5i	E 593518.3 N 4081415.398	7.8	648	255	AA	1,040	392
DIAGONAL LINE	11-57-005	11/24/1971	U11g	E 594939.1 N 4081801.575	<20	277	264	AA	1,038	761
DIANA MOON	11-57-003	08/27/1968	U11e	E 595265.3 N 4081581.785	<20	255	242	AA	1,032	777
DILUTED WATERS	05-57-002	06/16/1965	U5b	E 593110.1 N 4074993.954	<20	206	193	AA	943	737
MILK SHAKE	05-57-005	03/25/1968	U5k	E 595267.2 N 4080972.334	<20	276	265	AA	1,021	745
NEW POINT	11-57-002	12/13/1966	U11c	E 594655.9 N 4081579.657	<20	255	239	AA	1,030	775
MINUTE STEAK	11-57-004	09/12/1969	U11f	E 595494.8 N 4081584.415	<20	277	265	AA	1,034	757
WISHBONE	05-57-001	02/18/1965	U5a	E 593719.6 N 4074996.079	<20	191	175	AA	941	750
PIN STRIPE	11-57-001	04/25/1966	U11b	E 594386.2 N 4082708.041	<20	299	296	TM-LTVA	1,093	794

Sources: BN (2004a); DOE/NV (2000a); FFACO (1996)

m = Meters

HSU = Hydrostratigraphic unit

amsl = Above mean sea level

AA = Alluvial aquifer

TM-WTA = Timber Mountain Welded Tuff Aquifer

TM-LVTA = Timber Mountain Lower Vitric Tuff Aquifer

For the UGTA Project, the corrective action strategy includes two major phases: a regional evaluation addressing all CAUs and a CAI process for each of the individual CAUs. The first major phase was completed with the development of the *Regional Groundwater Flow and Tritium Transport Modeling and Risk Assessment of the Underground Test Area, Nevada Test Site, Nevada* (DOE/NV, 1997). The flow and transport model (DOE/NV, 1997) provided the initial basis for determining the magnitude of risk from the source areas on the NTS to potential receptors and a regional context for future individual CAU investigations. The second phase of the CAI process focuses on refining the results of the regional-scale modeling through acquisition and analysis of CAU-specific data, and development of CAU-scale flow and transport models. The CAU-specific objectives are to estimate movement of contaminants utilizing CAU-specific hydrogeologic and transport parameter data and to define boundaries that encompass the extent of contamination.

Figure 1-3 shows the process flow diagram for implementing the corrective action strategy for the UGTA CAUs. The CAU-specific corrective action process includes six major elements: Corrective Action Investigation Plan (CAIP), Corrective Action Investigation (CAI), Corrective Action Decision Document (CADD), Corrective Action Plan (CAP), Closure Report (CR), and long-term monitoring.

- The CAI planning is documented in the CAIP, an FFACO-required document that provides or references all specific information for planning investigation activities associated with CAUs or CASS.
- The CAI includes the collection of new data, the evaluation of new and existing data, and the development and use of CAU-specific groundwater flow and transport model(s).
- The CADD is a required report that documents the CAI. It describes the results of the CAI, the corrective action alternatives considered, the results of their comparative evaluation, the selected corrective action, and the rationale for its selection.
- The CAP is prepared to describe how the selected remedial alternative is to be implemented. The CAP will contain the engineering design and all specifications that are necessary to implement the selected remedial alternative.
- The UGTA strategy has provisions for CAU closure only if the long-term-monitoring alternative is selected. Closure activities include the preparation of a CR, review of the CR by NDEP, and long-term closure monitoring by DOE. The long-term, post-closure monitoring is designed to ensure the compliance boundary is not violated.

The CAI process may be iterative, resulting in several phases of data collection, analysis, and modeling, with assessment of confidence in the results at the completion of each phase. If further data collection, analysis, and modeling are required, a CAIP Addendum will be issued to direct the new phase of activities.

The Phase I CAI for Frenchman Flat with hydrologic and transport data compilation, analysis, and model development was completed in 1999. The Frenchman Flat Phase I CAI planning and work are documented in:

- *Corrective Action Investigation Plan for Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nevada* (DOE/NV, 1999a).
- *Value of Information Analysis for Corrective Action Unit No. 98: Frenchman Flat* (IT, 1997).
- *Underground Test Area Project Corrective Action Unit 98: Frenchman Flat Data Analysis Task, Volume I – Hydrostratigraphic Model Documentation Package*, Rev. 0 (IT, 1998b). This volume documents the

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**Figure 1-3
Process Flow Diagram for the Underground Test Area Corrective Action Units**

development of the Phase I three-dimensional (3-D) hydrostratigraphic framework model for the Frenchman Flat CAU.

- *Underground Test Area Project Corrective Action Unit 98: Frenchman Flat, Vol. II – Groundwater Data Documentation Package*, Rev. 0 (IT, 1999b). This volume presents the Phase I groundwater data incorporated into the groundwater flow and contaminant transport model for the Frenchman Flat underground test area.
- *Underground Test Area Project Corrective Action Unit 98: Frenchman Flat, Vol. III – Groundwater Flow and Contaminant Transport Model Data Documentation Package*, Rev. 0 (IT, 1999c). This volume presents the Phase I groundwater flow and transport model for Frenchman Flat.
- *Evaluation of the Hydrologic Source Term from Underground Nuclear Tests in Frenchman Flat at the Nevada Test Site: The CAMBRIC Test* (Tompson, et al., 1999). This volume presents the Phase I hydrologic source term model for use in the transport model for Frenchman Flat.

Following the completion and documentation of the Phase I work, comprehensive internal and external peer reviews were conducted. The results of these reviews identified and documented deficiencies in the Phase I work.

The external peer review is documented in *External Peer Review Group Report on Frenchman Flat Data Analysis and Modeling Task, Underground Test Area Project, Revision No. 0* (IT, 1999a). Section 2.0 of the peer review document identified key issues of concern. Section 4.0 of the peer review document provided recommended actions to address the key concerns. These recommended actions included general and specific data enhancement and data acquisition needs; incorporation of alternative conceptual models to evaluate potential failure scenarios; changing the modeling approach to one that uses a finite-element platform to better address discrete geologic features (e.g., faults and fracture zones); and the development and application of local-scale uncertainty analysis techniques.

The internal peer review is documented in *Lessons Learned from the Frenchman Flat Corrective Action Groundwater Flow and Radionuclide Transport Model* (IT, 2000b). The lessons learned document concluded that the Phase I Frenchman Flat CAU model was a good first model of groundwater flow and radionuclide transport at the CAU scale. The modeling successfully represented the flow system as defined in the conceptual model and predicted limited radionuclide travel distances. However, the work was not complete and, as recommended by the peer reviews, needed refinement. Section 2.0 of the lessons learned document identified deficiencies in the Phase I Frenchman Flat CAI and provided recommendations to address the deficiencies. [Table 1-2](#) provides a summary of the Phase I CAI deficiencies and recommendations identified in the lessons learned document (IT, 2000b).

Based on the outcome from the external and internal peer reviews, the need for additional work scope (including new data collection and modeling activities),

**Table 1-2
Summary of Lessons Learned from the Frenchman Flat CAU Model Related to Data Analysis**

Topic	Deficiency	Recommendation
Data Analysis	Data analysis does not assess data adequacy	Difficult problem, additional studies would be required
	Justification for transferring data from outside a CAU is lacking	A methodology for justifying data transfer needs to be developed and included in the data analysis
	The statistical treatment of data is not always consistent	Consultation with appropriate subject matter experts will be sought to avoid mistakes in the future
	Hydraulic gradient discussion was missing	This will be added to future data analyses
Sensitivity and Uncertainty Analyses	Range of uncertainty needs to be better documented	The data analysis will be expanded to better assess parameter uncertainty

were identified and an addendum to the Frenchman Flat CAIP was developed. This addendum, *Addendum to Revision 1 of the Corrective Action Investigation Plan for Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nevada* (DOE/NV, 2001), details the new data collection and modeling activities to address the documented deficiencies in the Phase I Frenchman Flat CAI. The new data collection activities identified in the Addendum (DOE/NV, 2001) have been completed. The compilation of both the existing and new data and their analyses are the subject of this document.

1.2 Task Purpose and Scope

The purpose of this report is to analyze and document the relevant information available for the transport parameters that will be used for developing the predictive Frenchman Flat contaminant boundaries. This report will provide the primary reference to support the development of the Phase II Frenchman Flat CAU transport model(s).

Specific task objectives were as follows:

- Compile available transport parameter data and supporting information that may be relevant to the Frenchman Flat CAI.
- Assess the level of quality of the data and associated documentation.
- Analyze the data to derive expected values and estimates of the associated uncertainty and variability.

The scope of this task includes the assessment of data and information relevant to transport parameters for the Frenchman Flat subsurface within the context of unclassified source-term contamination. Data types of interest include matrix and effective porosity, dispersivity, matrix diffusion, matrix and fracture sorption, and colloid-facilitated transport parameters. Descriptions of these data types are provided in [Section 4.0](#).

Data analysis includes: (1) literature searches, (2) data/information compilation, (3) data documentation, (4) data documentation qualification, (5) data quality evaluation, and (6), data assessment and interpretation activities. Data analysis includes the use of scientific software to assist in estimating and visualizing each of the hydrologic data types.

The study area, as described in the CAIP and shown in [Figure 1-4](#), was selected to encompass the Frenchman Flat CASSs and areas immediately downgradient that may be impacted by these CASSs. This area, an intermontane basin within the Basin and Range physiographic region, is located in the southeastern portion of the NTS. The Frenchman Flat area extends from southern Yucca Flat to the southern NTS area, including Mercury. The area of interest to the modeling activities is limited to Frenchman Flat ([Figure 1-4](#)) as the maximum extent of contamination is expected to remain within this area.

Even though the area of interest is limited to the Frenchman Flat area, information considered to be relevant to this task may be obtained from other nearby sites. Nearby sites include other underground test area CAUs, the Yucca Mountain Site, and other sites located within the NTS region. Data transferred from other sites have been documented and justified using methodologies consistent with the *Transferability of Data Related to Underground Test Area Project, Nevada Test Site, Nye County, Nevada* (SNJV, 2004g). A discussion of parameter-specific data transfer techniques is included in each data analysis section where data transfer was utilized.

1.3 CAU Model Documents that Support the Phase II Frenchman Flat CAI

The Frenchman Flat CAU model is documented in a series of reports describing the data analysis and modeling tasks. The CAU model documentation providing information used in this report includes reports from Phase I of the CAI and recent reports developed as part of Phase II.

Phase II reports include:

- *Assessment of Radionuclide Migration from Underground Nuclear Tests in Northern Frenchman Flat, Nevada Test Site* (SNJV, 2004a). This report documents an analysis of potential radionuclide transport pathways in groundwater beneath northern Frenchman Flat.
- *Interpretation of Hydraulic Test and Multiple-Well Aquifer Test Data at Frenchman Flat Well Cluster ER-5-3* (SNJV, 2004d). This report documents the analysis of the hydraulic data collected for Wells ER-5-3, ER-5-3#2, and ER-5-3#3.
- *Transferability of Data Related to the Underground Test Area Project, Nevada Test Site, Nye County, Nevada* (SNJV, 2004g). This report provides a procedure for documenting the transfer and incorporation of data from locations other than the specific area being evaluated. The context of this report provides a method of documenting the

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**Figure 1-4
Location of the Frenchman Flat Study Area and Geologic Model Area**

appropriateness of using non-Frenchman Flat data and information in the Frenchman Flat CAI.

- *Addendum to the Frenchman Flat Hydrogeologic Investigation Wells Drilling and Completion Criteria* (IT, 2001a). This addendum contains two appendices. [Appendix B](#) presents the change from one well to two wells at the central Frenchman Flat location. [Appendix D](#) documents additional work performed at Well Cluster ER-5-3.
- *Alluvial Layering and Distribution of Reactive Phases within Drill Holes ER-5-4 and UE-5n of Frenchman Flat* (Warren et al., 2002). This report presents an analysis of the geologic history of the alluvial deposition into the Frenchman Flat basin.
- *Geostatistical Analysis of Spatial Variability of Mineral Abundance and Kd in Frenchman Flat, NTS, Alluvium* (Carle et al., 2002). This report is a companion modeling report to the Warren et al. (2002) report.
- *Methods for Calculating a Simplified Hydrologic Source Term for Frenchman Flat Sensitivity Studies of Radionuclide Transport Away from Underground Nuclear Tests* (Tompson et al., 2004). This report includes an inventory of radionuclides that are candidates for contaminant transport simulations and radionuclide release conceptualization from the exchange volume and melt glass.
- *Integrated Analysis Report for Single- and Multiple-Well Aquifer Testing at Frenchman Flat Well Cluster RNM-2s* (SNJV, 2004c). This report presents the analysis and interpretation of hydraulic data from the Well ER-5-4 single-well test, the Well ER-5-4 #2 single-well test, and the well cluster RNM-2s multiple-well aquifer test which included the ER-5-4 wells and others.

1.4 Quality Assurance

Quality assurance (QA) measures consistent with the UGTA Project quality assurance project plan (QAPP) (DOE/NV, 2000a) have been used to control quality during the performance of all UGTA data analysis tasks. These measures include data documentation qualification, data quality assessment, checking procedures, software QA, use of standard methodologies, technical and peer reviews, and corroboration through models.

Data Documentation Evaluation

Each data record will be assigned a data documentation multiplier(s) designed to indicate the level of documentation available for that data record. The five levels of data documentation evaluation flags are described in [Section 4.0](#). When data transferability methods are used (see SNJV, 2004g), more detailed data documentation multipliers may be used. Information about data documentation is provided for each parameter prior to an explanation of data analysis.

Data Quality Assessment

The criteria used to assess the quality of the different types of required data are dependent on the type and the intended use of the data. The general procedure includes assigning one or more flags to each record compiled in the dataset, indicating the data quality or suitability of the individual data record for the intended usage. Data-type specific quality evaluation procedures are described in detail in the corresponding section of this document.

Checking Procedures

Various checking procedures were designed for quality control purposes. Checking procedures applicable to the UGTA data analysis include those developed for transcription of data; and generation of figures, tables, logs, and calculations. Data compiled by project personnel are subjected to the checking procedures before inclusion in the appropriate dataset. However, the bulk of the available data are comprised of data gathered and compiled by agencies external to the UGTA project. Internal procedures do not govern other UGTA participants; therefore, their data were subject only to the data transcription checking procedure described here.

Standard Methodologies

Only standard and widely accepted methodologies should be used in the development of the interpretive products. The various methodologies used are too numerous to list here; however, they are described and referenced in the sections of this document which discuss their use in the data analysis process.

Technical and Peer Reviews

The review process constitutes an important measure of product quality, and is used throughout the performance of the data analysis activities. The review process may include internal and external technical reviews. The internal reviews are performed by individuals who are involved in the UGTA project. These reviews may include representatives of Bechtel Nevada (BN), U.S. Geological Survey (USGS), Desert Research Institute (DRI), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), GeoTrans, and the Stoller-Navarro Joint Venture (SNJV). External reviews may be conducted as directed by NNSA/NSO.

Corroboration of Data Through Models

This step is completed during the development of the groundwater flow and transport model. For example, during the contaminant transport modeling, observations of contaminant movement will be used to help assist and refine the contaminant transport model results. This may be accomplished by modifying the sorption coefficient or porosity in areas where no data are available.

1.5 Document Organization

This document consists of 11 sections and 8 appendices. Summaries of the section contents follow:

- [Section 1.0](#) provides a description of the project background, the purpose and scope of this data analysis task, a description of the documentation supporting this report, and the QA process implemented herein.
- [Section 2.0](#) describes the regional setting, local hydrostratigraphic framework, and detailed descriptions of hydrostratigraphic unit (HSU) mineralogy and radionuclide source term of the Frenchman Flat area. These descriptions are presented to support the analysis of the contaminant transport data presented in this document.
- [Section 3.0](#) provides a brief overview of the modeling strategy proposed for the Frenchman Flat CAU and a more detailed description of the approach that will be used to simulate contaminant transport.
- [Section 4.0](#) presents the general data compilation and analysis approach used to assess the available transport data.
- [Section 5.0](#) defines a stationary probability distribution of matrix porosity per HSU.
- [Section 6.0](#) presents a brief explanation of the role of effective porosity in contaminant transport, outlines available sources of effective porosity, and recommends ranges for effective porosity estimates
- [Section 7.0](#) provides a description of dispersivity data collected at the NTS and sites around the world. Two functions are presented that characterize the uncertainty associated with longitudinal dispersivity values.
- [Section 8.0](#) presents a description of matrix diffusion data applicable to Frenchman Flat HSUs.
- [Section 9.0](#) provides an extensive review and analysis of matrix sorption data that is applicable to Frenchman Flat rocks.
- [Section 10.0](#) provides a basic overview of fracture sorption parameters that have been developed for rocks from other CAUs.
- [Section 11.0](#) defines the colloid-facilitated transport parameters necessary for incorporation colloid transport in the CAU model.
- [Appendix A](#) contains information in support of the hydrostratigraphic model described in [Section 2.0](#) and FF geochemistry data.

- [Appendices D](#) through [H](#) contain descriptions of the datasets and supporting information for various analyses.

2.0 Frenchman Flat Conceptual Model, Physical, Chemical Properties, and Contamination Sources

An overview of the Phase II conceptual model for FF is provided in this section as background for the analyses presented in the later sections of this report. New data collected since 2001 and as recently as the fall 2003 are incorporated into the CAU-scale Phase II FF hydrostratigraphic model. The data better constrain the basin-forming structural features and provide evidence to support the subdivision of several HSUs that were grouped in the Phase I FF hydrostratigraphic model. The revised FF hydrostratigraphic framework includes 72 fault structures and 17 hydrostratigraphic units (compared to the 48 faults and 9 HSUs in the Phase I model). The Phase II FF geologic model is fully documented in the report: *A Hydrostratigraphic Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada* (BN, 2004a).

The following subsections provide a summary of the regional setting for FF and a background of the regional hydrogeologic framework, followed by a short synopsis of regional groundwater occurrence and movement, mineralogy of Frenchman Flat HSUs, and information about the aqueous geochemistry of the aquifers. This section concludes with a summary of the contamination sources and extent.

2.1 Regional Setting

The Frenchman Flat flow system is part of the NTS regional flow system (Figure 2-1), which is part of the Death Valley flow system. A conceptual model of the regional groundwater flow system of the NTS was developed during the regional evaluation (DOE/NV, 1997). Summary descriptions of the NTS regional hydrogeologic framework and groundwater occurrence and movement (as conceptualized in the NTS regional flow model [DOE/NV, 1997]) are presented in this section. This information has been updated from the regional model, where appropriate.

2.1.1 Regional Hydrogeologic Framework

The hydrogeologic framework used in the NTS regional model, which is adapted to create the CAU-scale FF hydrogeologic framework, is based on a conceptual

hydrologic system established for the NTS area by Winograd and Thordarson (1975) and Blankennagel and Weir (1973). This early work was summarized and updated by Laczniaik et al. (1996), and has further been developed by the UGTA Phase I hydrostratigraphic regional modeling team (IT, 1996d).

The rocks of the NTS have been classified using a two-level scheme, in which hydrogeologic units (HGUs) are grouped to form HSUs (IT, 1996d). The HGUs are used to categorize rocks according to their ability to transmit groundwater, which is mainly a function of the primary lithologic properties of the formations, degree of fracturing, and secondary mineral alteration. The complex hydrologic properties of the volcanic rocks of the NTS and vicinity are best addressed in terms of HGUs (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). The concept of HSUs that are made up of groups of similar HGUs is very useful in volcanic terrains because stratigraphic units can differ greatly in hydrologic character both laterally and vertically. The HSUs serve as “layers” in the NTS regional and CAU-scale hydrostratigraphic framework models.

The following subsections summarize the hydrogeologic framework of the NTS, first addressing HGUs, then describing HSUs.

2.1.1.1 Hydrogeologic Units

All rocks of the NTS and vicinity can be classified as one of eight hydrogeologic units, which include the alluvial aquifer, four volcanic HGUs, an intrusive HGU, and two HGUs that represent the pre-Tertiary sedimentary and metasedimentary rocks ([Table 2-1](#)).

2.1.1.2 Hydrostratigraphic Units

Hydrostratigraphic units are groupings of contiguous stratigraphic units that have a particular hydrogeologic character, such as an aquifer (unit through which water moves readily) or confining unit (unit through which water movement is highly impeded). An HSU may contain several HGUs but is defined so that a single general type of HGU dominates (e.g., mostly welded tuff aquifers [WTAs] and vitric tuff aquifers [WTAs] or mostly tuff confining units [TCUs]). Twenty HSUs were defined in the NTS regional HSU model (IT, 1996d).

The regional hydrogeologic framework model covers more than 28,000 square kilometers (km²) of which the Frenchman Flat hydrogeologic framework model makes up only approximately 1 percent. The regional scale model represents a very simplified hydrogeologic framework of the Frenchman Flat area, which is located in the southeastern portion of the NTS. The rocks in this part of the regional model were divided into three Tertiary volcanic HSUs and three pre-Tertiary HSUs. The volcanic rocks east of the NTS were not subdivided and are represented by a single HSU (volcanics undifferentiated [VU]). The older Tertiary sedimentary rocks were included in the Volcaniclastic Confining Unit (VCCU) HSU. The Wahmonie volcanic units were included in the Volcanic

**Table 2-1
Hydrogeologic Units of the NTS Regional Model**

Hydrogeologic Unit	Typical Lithologies	Hydrologic Significance
Alluvial Aquifer (AA) (AA is also an HSU in hydrogeologic models)	Unconsolidated to partially consolidated gravelly sand, aeolian sand, and colluvium; thin, basalt flows of limited extent.	Has characteristics of a highly conductive aquifer, but less so where lenses of clay-rich paleocolluvium or playa deposits are present.
Welded Tuff Aquifer (WTA)	Welded ash-flow tuff, vitric to devitrified	Degree of welding greatly affects interstitial porosity (less porosity as degree of welding increases) and permeability (greater fracture permeability as degree of welding increases).
Vitric Tuff Aquifer (VTA)	Bedded tuff, ash-fall and reworked tuff; vitric	Constitutes a volumetrically minor HGU; generally does not extend far below the static water level due to tendency of tuffs to become zeolitic (which drastically reduces permeability) under saturated conditions; significant interstitial porosity (20 to 40 percent); generally insignificant fracture permeability.
Lava Flow Aquifer (LFA)	Rhyolite lava flows; includes flow breccias (commonly at base) and pumiceous zones (commonly at top)	Generally a caldera-filling unit and/or of local extent; hydrogeologically complex; wide range of transmissivities; fracture density and interstitial porosity differ with lithologic variations.
Tuff Confining Unit (TCU)	Zeolitic bedded tuff with interbedded, but less significant, zeolitic, nonwelded to partially welded ash-flow tuff	May be saturated but measured transmissivities are very low; may cause accumulation of perched and/or semi-perched water in overlying units.
Intrusive Confining Unit (ICU)	Granodiorite, quartz monzonite	Relatively impermeable; forms local bulbous stocks; north of Rainier Mesa, Yucca Flat, and scattered elsewhere in the NTS regional model area; may contain perched water.
Clastic Confining Unit (CCU)	Argillite, siltstone, quartzite	Clay-rich rocks are relatively impermeable; more siliceous rocks are fractured, but with fracture porosity generally sealed due to secondary mineralization.
Carbonate Aquifer (CA)	Dolomite, limestone	Transmissivity values vary greatly and are directly dependent on fracture frequency.

Source: Adapted from IT (1996d) and BN (2004a)

Aquifer (VA) HSU. The HSUs defined for the NTS regional HSU model that are within the Frenchman Flat model area are listed in [Table 2-2](#). These units are listed in approximate order from surface to basement, although some are laterally rather than vertically contiguous, and not all units are present in all parts of the model area.

2.1.2 Groundwater Occurrence

[Figure 2-1](#) is a map depicting the basic characteristics of the NTS regional groundwater flow system including the flow system boundary and general groundwater flow directions. The descriptions provided in this section are based primarily on the data gathered during the regional evaluation (IT, 1996a and c; DOE/NV, 1997). Updates have been incorporated where available.

The following description of groundwater occurrence within the NTS regional flow system is based on the water level dataset compiled during the regional

**Table 2-2
Hydrostratigraphic Units of the Frenchman Flat Area Included
in the NTS Regional Hydrostratigraphic Framework Model**

HSU Layer Number ^a	Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) ^b	Stratigraphic Unit Map Symbols ^c	General Description
20	Alluvial Aquifer (AA) (this term is also used to designate a hydrogeologic unit)	AA	Qay, QTc, Qam, QTa, Qtu, Tybf, Tt	Consists mainly of alluvium that fills extensional basins such as Gold Flat, Crater Flat, Kawich Valley, and Sarcobatus Flat. Also includes generally older Tertiary gravels, tuffaceous sediments, and nonwelded tuffs (where thin) that partially fill other basins such as Oasis Valley and the moat of the Timber Mountain caldera complex.
19	Timber Mountain Aquifer (TMA)	Mostly WTA, minor VTA; TCU within the Tm caldera complex	Tm, Tp	"The uppermost welded tuffs" in the Frenchman Flat model area consists mainly of extra-caldera welded ash-flow tuffs (aquifer-like lithologies). However, the altered intra-caldera equivalent rocks within the Timber Mountain caldera are modeled as confining units.
15	Tuff Confining Unit (TCU)	TCU	Th, Tw, Tc, Tn, To	Mostly zeolitized nonwelded tuffs.
14	Volcanic Aquifer (VA)	WTA, VTA, LFA	Tm, Tp, Tw, Tc	Imprecisely known grouping of volcanic rocks; generally with aquifer-like qualities. Also use as a lumping unit away from the more data-rich NTS.
12	Volcaniclastic Confining Unit (VCCU)	TCU, minor AA, lesser CA	Tgp, Tgw	Complex three-dimensional distribution of zeolitic nonwelded tuff, gravels, mudstones, and limestones. Present in the southern portion of the Frenchman Flat model area.
11	Volcanics undifferentiated (VU)	WTA, TCU, lesser LFA	Potentially includes all Tertiary volcanic units	All Quaternary and Tertiary volcanics outside the NTS proper and the proximal NTS caldera complex.
8	Upper Clastic Confining Unit (UCCU)	CCU	MDC, MDe	Late Devonian through Mississippian siliciclastic rocks. Present in the northeastern corner (CP basin) of the Frenchman Flat model area.
7	Lower Carbonate Aquifer (LCA)	CA	Dg through Cc	Cambrian through Devonian mostly limestone and dolomite. Widespread throughout the Frenchman Flat model area.
6	Lower Clastic Confining Unit (LCCU)	CCU	Cc, Cz, Czw, Zs, Zj	Late Proterozoic through Early Cambrian siliciclastic rocks. Widespread throughout the Frenchman Flat model area.

^aNTS UGTA regional model (IT, 1996d)

^bSee Table 2-1 for definitions of HGUs

^cRefer to Slate et al. (1999) and Ferguson et al. (1994) for definitions of stratigraphic unit map symbols

evaluation (IT, 1996c and DOE/NV, 1997). Within the NTS region, groundwater occurs in alluvial, volcanic, and carbonate materials. Saturated alluvial materials are present in central and southern Yucca Flat, Frenchman Flat, and Jackass Flats on the NTS and in the basins located throughout the flow system. Saturated Tertiary volcanics are present in the western section of the region. The distribution and thickness of AAs and VAs are highly variable throughout the region and are not interpreted to be continuous. In most instances, an AA is confined to a basin by surrounding mountain ranges. In some basins, AAs are discontinuous due to structural controls elevating the bottom of the alluvium above the water table. In general, AAs and VAs are considered depositional elements overlying the regional flow system and only influence regional flow in localized areas. The underlying Lower Carbonate Aquifer (LCA) is the principal aquifer of the NTS regional flow system because of its wide distribution, high

hydraulic conductivity, and potential as a pathway for large-scale transport of contaminants. The LCA forms a nearly continuous aquifer across the region except where interrupted by calderas, truncated by structural controls, or penetrated by intrusive rocks.

Based on the water level dataset compiled during the regional evaluation (IT, 1996c and DOE/NV, 1997), depths to groundwater beneath the NTS and surrounding region vary greatly. Groundwater depths in the southern NTS range from about 23 m beneath upper Fortymile Wash to over 213 m beneath Frenchman Flat, compared to more than 610 m beneath Pahute Mesa in the northern NTS (IT, 1996c and DOE/NV, 1997). Perched groundwater is found locally throughout the NTS and occurs within the TCUs and, to some extent, overlying units. In the regional area highlands, springs emerge from perched groundwater lenses. Regionally, spring discharge rates are low and this water is currently only used by wildlife and one tourist site.

2.1.2.1 Groundwater Movement

Within the NTS regional flow system, groundwater movement is controlled by structural and geologic conditions, and the distribution of recharge and discharge locations.

The general direction of groundwater flow in the NTS regional flow system is from north to south and east to southwest (Figure 2-1). The direction of groundwater flow is locally influenced in areas where structural and geologic conditions have controlled the distribution and thickness of the LCA. In some areas of the NTS regional flow system, groundwater encounters structural and geologic conditions, such as structural highs of the Lower Clastic Confining Unit (LCCU), that promote an upward flow component. The upward flow component may bring water to discharge at the surface in the form of a wet playa or springs. Groundwater flow between basins occurs in the form of subsurface inflow and outflow.

Horizontal hydraulic gradients are generally very low to the east and west of the NTS. In other areas, the prevailing flow direction and hydraulic gradients may locally be influenced by the structural position of geologic units and localized recharge. Structural uplifts of the LCCU and the distribution of the Upper Clastic Confining Unit (UCCU) have caused several of the observed steep gradients within the flow system. Low-permeability sediments along the Funeral Mountains such as the Tertiary Death Valley Section sediments also cause a steep hydraulic gradient between Amargosa Desert and Death Valley.

Groundwater recharge results from precipitation and infiltration at higher elevations and infiltration along stream courses and in playas. Recharge rates and distribution may be estimated. The estimates are, however, uncertain. The recharge model used in the NTS regional flow model was based on a modification of the Maxey and Eakin method (Maxey and Eakin, 1949). Several new recharge models have recently been proposed and are described in Section 6.0 of the Frenchman Flat hydrologic data report (SNJV, 2004e). Groundwater discharges

to the surface in the form of springs, seeps, and evapotranspiration (ET) in several areas. Major areas of natural groundwater discharge include Oasis Valley, Ash Meadows, Alkali Flat, Death Valley, and Penoyer Valley. Estimates of ET have recently been updated by the USGS for the first four areas listed above (Laczniak et al., 2001). Within the NTS region, artificial discharge occurs as groundwater pumpage from drinking water supply wells (public and domestic), agricultural wells, and industrial wells. Public, domestic, and industrial water supply wells for the NTS produce water from the VA, carbonate aquifer (CA) and valley-fill aquifers. South of the NTS, private and public water supply wells are completed in the valley-fill aquifer.

2.2 Phase II Data Collection Activities

The acquisition of new data in the FF basin, which helped constrain interpretations of the structure and stratigraphy in FF, is summarized in the next section. Following a discussion on data acquisition activities, the processes of HSU model development and screening are described, along with a description of the alternative models retained for use in the CAU groundwater flow and transport model. The details for the FF hydrogeologic framework construction may be found in the HSU model report titled: *A Hydrostratigraphic Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Clark, Lincoln, and Nye Counties, Nevada* (BN, 2004a).

A new, revised (Phase II) 3-D hydrostratigraphic framework model including several variations based on alternative interpretations has been built for the Frenchman Flat area (BN, 2004a). Internal and external reviews of the Phase I Frenchman Flat model (IT, 1999a) recommended additional data collection to address uncertainties (IT, 1999a). As a result, the FF CAIP Addendum listed a number of data collection activities that would be implemented to provide data for the Phase II geologic model, including drilling two characterization wells in each of the underground nuclear testing areas, and a seismic geophysical investigation (see [Figure 2-2](#)) (DOE/NV, 2001). These activities were completed as well as several other activities that contributed to the understanding of the geology. The results of these activities, which are incorporated in the new geologic model, constrain the structural framework of the main basin, and indicate more variability in the volcanic and alluvial units as compared to the Phase I Frenchman Flat model. The new data are discussed below, followed by an explanation of the HSUs and key structures identified in FF, which are incorporated in the Phase II Frenchman Flat Hydrogeologic Framework.

A 3-D hydrostratigraphic framework model and alternatives have been built for the Frenchman Flat area (BN, 2004a). The FF hydrostratigraphic framework is much more detailed than the regional hydrostratigraphic framework. Several HSUs have been subdivided compared to the regional framework (i.e., VA in the regional model subdivides into five units: Timber Mountain Welded Tuff Aquifer [TM-WTA], Timber Mountain Lower Vitric Tuff Aquifer [TM-LVTA], Upper Tuff Confining Unit [UTCU], Topopah Spring Aquifer [TSA], and Lower Vitric

Tuff Aquifer [LVTA] in the FF CAU geologic model) and the number of faults is significantly greater in the CAU-scale model.

2.2.1 Phase II Well Drilling

Five new wells were drilled and completed as part of the Phase II Data Acquisition for the Frenchman Flat CAU. The wells were intended to provide confirmatory information and new, detailed information about the geology, hydrogeology, and water chemistry in the immediate vicinity of the two underground nuclear test subareas within Frenchman Flat. Well cluster ER-5-3 (three wells) is located near the northern group of underground tests (UGTs) in Frenchman Flat (Figure 2-2), and well cluster ER-5-4 (two wells) is located near the southern group of UGTs in Frenchman Flat. The purpose and expectations of this drilling initiative are provided in the *Frenchman Flat Hydrogeologic Investigation Wells Drilling and Completion Criteria* (IT, 2000a) and an addendum (IT, 2001a). Information on the well clusters is summarized in the following sections. Data from these wells, combined with the 3-D seismic data, factored prominently in the development of the modified structural model for Frenchman Flat.

2.2.1.1 Well Cluster ER-5-3

Three separate boreholes were drilled at this site on the same drill pad. The overall objective was to penetrate the saturated alluvium, the VA, the TCU, and to reach the LCA. Because of instability problems, the first borehole (Well ER-5-3), was terminated in the TCU before reaching the planned depth of 1,158.2 m. Well ER-5-3#2, was then drilled to 1,732.2 m and reached the LCA. The wells penetrated Quaternary/Tertiary alluvium to the depth of 622.4 m. An 8.5-m (28-foot [ft]) thick basalt flow was encountered within the alluvium near the water table. Tertiary-age tuffs were penetrated to the depth of approximately 1,425.9 m, where the top of the LCA was encountered in Well ER-5-3#2. Well ER-5-3#3 was drilled to a total depth (TD) of 548.6 m and completed in the saturated alluvium for use as an observation well for hydraulic testing.

2.2.1.2 Well Cluster ER-5-4

Well Cluster ER-5-4 is located in central Area 5 of the NTS (Figure 2-2), approximately 1.6 kilometers (km) (1.0 miles [mi]) northwest of the Frenchman Lake playa, near the central underground testing area. The cluster consists of two boreholes drilled 30.5 m (100 ft) apart on the same drill pad.

The wells penetrated 1,120.4 m of Quaternary and Tertiary alluvium, 242.6 m of generally unaltered nonwelded and welded ash-flow tuff of Tertiary age, and 770.5 m of mostly zeolitic nonwelded tuff, also of Tertiary age. Electromagnetic Imager (EMI) log data indicate bedding dips of about 30 degrees to the east-southeast, consistent with the seismic data. The wells encountered a thicker alluvial section and volcanic rock section than expected. Well ER-5-4#2 reached

TD at 2,133.6 m in the Wahmonie Formation and did not reach the older Tertiary sedimentary rocks or Paleozoic rocks as predicted.

2.2.2 Geophysical Investigations

Geophysical data available for the Frenchman Flat area are varied in type and vintage. Geophysical investigations have been conducted in Frenchman Flat since the 1950s and include seismic, resistivity, magnetic, and gravity. In fiscal years (FY) 2001 and 2002, the UGTA Phase II data acquisition initiative included a 3-D seismic survey of the two testing areas ([Figure 2-2](#)), analysis of gravity data using 3-D inversion methods, and a re-analysis of existing aeromagnetic data. A magnetotelluric survey was later conducted in 2003 in Yucca Flat. The two southern transects are relevant to the Frenchman Flat model (BN, 2004a). Geophysical data can be used to better define the nature of the structures within the Frenchman Flat basin and the distribution of the Tertiary-age volcanic units. The Phase II geophysical investigations were designed to better define the structure beneath the two underground test areas, as well as validate and improve the initial 3-D hydrostratigraphic framework model (IT, 1998b) for Frenchman Flat. The geophysical data were also utilized during development of alternative hydrostratigraphic configuration scenarios. The 3-D seismic reflection and magnetotelluric (MT) survey methods are briefly discussed below. More details regarding these and other geophysical investigations employed during development of the Phase II 3-D hydrostratigraphic model can be found in BN (2004a).

2.2.2.1 Three-Dimensional Seismic Reflection

A 3-D seismic reflection survey was conducted in Frenchman Flat to provide subsurface geologic information to better constrain groundwater flow and contaminant transport models. Three seismic horizons were mapped and include from highest to lowest: (1) the base of the alluvial basin-fill deposits (BOA), (2) the base of a zone of Tertiary-age welded ash-flow tuffs (BWZ), and (3) the top of Paleozoic-age sedimentary rocks (Pz). The mapping of these three horizons effectively delineates the extent, thickness, and structural orientation of the alluvial and volcanic aquifers in the vicinity of the seismic survey that encompassed the two testing areas ([Figure 2-2](#)). In addition, mapping of the BWZ and Pz improves constraints on the extent and thickness of the tuff and volcanoclastic confining units that occur between these two horizons. The Pz surface corresponds to the top of the regional carbonate aquifer and thus improves constraints on the depth to and structural orientation of this important aquifer.

Seismic data also revealed the presence of two large and previously unknown structures. A northwest striking fault zone was identified that separates the Frenchman Flat basin proper from a structural platform on the north. In addition, the seismic data in conjunction with drill hole and outcrop data strongly suggest that much of the northern structural platform overlies a detachment fault within the volcanic rocks.

Results from the interpretation of the Frenchman Flat 3-D seismic data allow for much more accurate modeling of HSUs in the survey area. Interpretation results also significantly improves and better constrains the structural model of the basin. The improved accuracy and better constraints provided by the seismic data will allow for more realistic evaluation of the potential for rapid transport of groundwater from the testing horizons to the regional CA.

2.2.2.2 Natural-Source Magnetotelluric

In the fall of 2003, the USGS collected MT data at 52 sites in eight generally west-east transects across Yucca Flat and proximal areas. The southern-most transect stretches from Mid Valley on the west, across CP Basin, and ends just north of Massachusetts Mountain (BN, 2004a). Another transect extends west-east across Yucca Lake in Yucca Flat (BN, 2004a). Data from these two southern profiles were incorporated into the Frenchman Flat model. The MT data were collected primarily to provide insight regarding the pre-Tertiary stratigraphy and structure in Yucca Flat. Of particular interest were the presence and extent of the UCCU and the CP thrust fault (both extend into the northwestern corner of the Frenchman Flat model area).

The MT method is utilized to delineate subsurface formations and units of differing resistivity. Because lithology is the primary factor in determining the resistivity of a unit, MT data can be used to map lithologic units, if sufficiently thick and have significant resistivity contrasts. Because the two primary pre-Tertiary lithologies of interest in constructing hydrostratigraphic models of the Yucca Flat and Frenchman Flat CAUs are thick and have contrasting resistivities (the LCA and Upper Carbonate Aquifer [UCA] carbonate rocks have high resistivities, and the shaley UCCU generally has low resistivity), the MT method seemed promising. Several resistivity layers can be identified in the MT data: (1) high resistivity – LCA (carbonate) and welded tuffs; (2) low resistivity – UCCU and zeolitic tuffs; and (3) intermediate resistivity – unsaturated alluvium. Two structures can also be discerned within the data: CP thrust fault and Cane Spring fault. Furthermore, the occurrence and geometry of the UCCU (combined with other data in the vicinity) is interpreted as the east limb of an asymmetric anticline. The interpretation of the MT survey played a large part in revision of the CP basin area of the geologic model.

2.2.3 HSU Model Development

The approach followed to develop the base HSU model and alternatives is described in SNJV (2004e) (a synopsis is provided in [Appendix A](#)). The HSU geologic model area is described in [Section 1.0](#) and shown on [Figure 1-4](#). The Phase II geologic model area is identical to the Phase I groundwater flow and contaminant transport model footprint for the FF basin and surrounding area.

A preliminary base HSU model was constructed using the conceptual model of the NTS hydrologic system described by Winograd and Thordarson (1975). Further

developments made by Lacznia et al. (1996), IT (1996a, b, and c), Prothro and Drellack (1997a), Gonzales et al. (1998), and BN (2002) were also used in the UGTA base HSU model for Frenchman Flat.

The Frenchman Flat area HSU models were constructed using EarthVision® (Version 7.5, by Dynamic Graphics), a 3-D geologic model building and visualization software package. Input data included drill-hole data, a 3-D seismic survey and MT survey data discussed above, gravity data, magnetic data (both areal and surface surveys), digital elevation model (DEM) data, and outcrop and fault data from surface geologic maps. Where deemed necessary, the data were supplemented with interpretations in the form of “pseudo drill holes,” cross sections, and structure-contour maps. A “pseudo drill hole” is a fictitious data point used to facilitate the automated contouring of data. The data for the pseudo drill holes are obtained from surficial geology maps and/or geologists’ interpretations.

2.3 General HSU Model

The structural features, HGUs, and HSUs of the base HSU model developed for the Frenchman Flat area are described in the following sections. A two-dimensional (2-D) map of the HSUs at the ground surface is shown in [Figure 2-2](#). [Figure 2-3](#) shows the HSUs interpreted to be present at the water table surface. This surface, which extends across several HSUs, is highly uncertain except in those areas with well data. It is consistent with the contouring of the water table surface as it was implemented in the regional model described in SNJV (2004e).

2.3.1 Structural Features

Geologic structural features are an important part of the hydrologic framework of the groundwater flow system of the Frenchman Flat area. They define the geometric configuration of the flow domain, including the distribution, thickness, and orientation of rock units. The depositional patterns of the geologic units occurring in the area were strongly influenced by paleotopography, including paleovalley and barriers, strike-slip faults (e.g., Rock Valley and Cane Spring faults [[Figure 2-4](#)]) and some normal faults. Faulting, for example, may result in juxtaposition of units with different hydrologic properties. Structures themselves may influence flow patterns by acting as conduits for flow or barriers to flow (BN, 2004a).

The structure of the base HSU model is found in the conceptual model developed by Bechtel Nevada (2004a). BN developed a detailed structural model by integrating this conceptual model and 3-D reflection seismic, gravity, magnetic, and drill hole data. The base HSU model includes a total of 72 structural elements which are typically normal faults (Basin and Range style faults) but also includes several strike-slip and older thrust faults. Only faults that were considered to be

Figure 2-4
3-D Image of Major Fault Structures on Volcanic Aquifer Surface
(Alluvial Sequence not Displayed)

significant were included in the model. These include the larger ones and the ones that seem to form significant structural boundaries.

One significant structural boundary includes the left-lateral Rock Valley Fault System ([Figure 2-4](#)). This set of faults appears to be responsible for the formation of the deep basin (BN, 2004a). In the southern portion of the FF model area, the Rock Valley faults strike northeast southwest. [Figure 2-4](#) is a 3-D image of the main fault structures on the VA surface. In the north portion of the basin, they strike to the north then turn to the west and flare-out into an extensional imbricate fan along the eastern and northern margins of the basin. The space left by the down-dropped fault blocks on the south, east, and north of the fault system has been filled with more than 9,000 ft of mostly Tertiary volcanic rocks and alluvium.

Another significant structural feature is the Cane Spring fault located in the northwest part of the FF model area. The Cane Spring fault separates the main FF basin from the CP basin, which has a hydraulic head significantly higher than the FF basin.

2.3.2 Hydrogeologic Units

The hydrogeologic framework for the NTS model established by Blankennagel and Weir (1973) and Winograd and Thordarson (1975) provided the foundation for most subsequent hydrogeologic studies in the area. As described in [Section 2.1](#), the rocks of the NTS have been classified for hydrologic modeling using a two-level classification scheme in which HGUs are grouped to form HSUs (IT, 1996d). New HGUs and additional detail have been added to the basic framework definition, but the systems developed by these early workers remain the best way to understand the groundwater of the NTS region. The HGU scheme used for CAU-scale modeling includes eight HGUs as mentioned in [Section 2.1.1.1](#), [Table 2-1](#).

2.3.3 Hydrostratigraphic Units

Brief descriptions of all the HSUs used to construct the Frenchman Flat model are provided in [Table 2-3](#). They are listed in approximate order from surface to basement, although some are laterally rather than vertically contiguous, and not all units are present in all parts of the model area.

[Table 2-4](#) shows the correlation of Frenchman Flat HSUs with HSUs from earlier hydrostratigraphic models for this region. These correlated units have been updated and revised to include mineralogy, a necessary component for generalizations between units when assessing transport parameters. [Figure 2-2](#) is a map showing a plan view of the surficial hydrostratigraphy for the Frenchman Flat model area. [Figure 2-5](#) shows a northeast-southwest hydrostratigraphic cross section (C-C'), along the general flow direction, and an west-east hydrostratigraphic cross section (B-B') (perpendicular to the general groundwater flow direction). Both of these cross sections are from the Frenchman Flat 3-D

Table 2-3
Hydrostratigraphic Units of the Frenchman Flat Hydrostratigraphic Framework Model
 (Page 1 of 2)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) ^a	Stratigraphic Unit Map Symbols ^b	General Description
Alluvial Aquifer (AA, AA3, AA2, AA1) (this term is also used to designate a hydrogeologic unit)	AA	Qay, QTc, Qai, QTa, Tt	Consists mainly of alluvium that fills extensional basins. Also includes generally older Tertiary gravels, and very thin air-fall tuffs (e.g. Tt). AA, AA1, AA2, and AA3 are equivalent hydrogeologically except for position relative to other HSUs embedded within the alluvial section (see Figure 2-5).
Playa Confining Unit (PCU2T)	PCU	Qp	Clayey silt and sandy silt forms the Frenchman Flat playa (dry lake).
Basalt Lava Flow Aquifer (BLFA)	LFA	Tybf	Several (possibly dissected) basalt flows recognized in the middle of the alluvial section of the northeastern Frenchman Flat. Possibly related to other basalt flows in Nye Canyon.
Older Alluvial Aquifer (OAA, and OAA1)	AA	QTa	Older, denser, zeolitized alluvium recognized only in northern Frenchman Flat. OAA and OAA1 are equivalent except for position; the OAA is above the BLFA and the OAA1 is stratigraphically beneath the BLFA (see Figure 2-5).
Older Playa Confining Unit (PCU1U and PCU1L)	PCU	QTp	Deep, subsurface playa deposits in the deepest portion of Frenchman Flat. Recognized in Well ER-5-4#2 and with 3-D seismic data. The PCU1U and PCU1L are similar except for position (see Figure 2-5).
Timber Mountain Welded Tuff Aquifer (TM-WTA)	Mostly WTA, minor VTA	Tma, Tmab, Tmr	Consists mainly of extra-caldera welded ash-flow tuffs of Ammonia Tanks Tuff and Rainier Mesa Tuff. Unit occurs mostly in north and central Frenchman Flat. Prolific aquifer when saturated.
Timber Mountain Lower Vitric Tuff Aquifer (TM-LVTA)	VTA	Tma, Tmab, Tmr, Tmrh, Tp, Th	Defined to include all unaltered (non-zeolitic) nonwelded and bedded tuffs below the welded Tmr and above the level of pervasive zeolitization. The presence of the welded Tpt (see TSA) complicates this general description.
Upper Tuff Confining Unit (UTCU)	TCU	Tmr (lower most), Tmrh, Tp	Relatively thin TCU above the TSA. Grouped with the LTCU where the TSA is not present.
Topopah Spring Aquifer (TSA)	WTA	Tpt	The welded ash-flow lithofacies of the Topopah Spring Tuff in Massachusetts Mtn/French Peak area and north-central Frenchman Flat.
Lower Vitric Tuff Aquifer (LVTA)	VTA	Th	Relatively thin VTA unit below the TSA. Grouped with the TM-LVTA where TSA is not present.
Lower Tuff Confining Unit (LTCU and LTCU1)	TCU, minor WTA	Th, Tw, Tc, Tn, To	Generally includes all the zeolitic nonwelded and bedded tuffs in southeastern NTS. May include all units from base of Tmr to top of Paleozoic-age rocks. The Tw stratigraphic interval grades/interfingers laterally (westward) into the WCU (see below). Zeolitic bedded tuffs stratigraphically below the WCU (e.g. Tc, Tn, and To) are classified as the LTCU1 in order to address the operation requirements of the EarthVision® modeling software.
Wahmonie Confining Unit (WCU)	TCU, minor LFA	Tw (Twu, Twm, Twl, Twis)	Mixture of lava flows, debris flows, lahars, ash-flows, and air-falls. Typically zeolitic, argillic, or hydrothermally altered. Grades/interfingers laterally with the LTCU.

Table 2-3
Hydrostratigraphic Units of the Frenchman Flat Hydrostratigraphic Framework Model
 (Page 2 of 2)

Hydrostratigraphic Unit (Symbol)	Dominant Hydrogeologic Unit(s) ^a	Stratigraphic Unit Map Symbols ^b	General Description
Volcaniclastic Confining Unit (VCU)	TCU, minor AA and CA	Tgp, Tgw	Older Tertiary sedimentary rocks of variable lithologies including silts, clays, limestones, gravels and tuffaceous units. Present in southeastern half of Frenchman Flat.
Lower Carbonate Aquifer-Thrust Plate (LCA3)	CA	Dg through Cc	Cambrian through Devonian, mostly limestone and dolomite, rocks that occur in the hanging wall of the Belted Range thrust fault. Present only in the northwest corner (CP basin) of the model area.
Upper Clastic Confining Unit (UCCU)	CCU	Mc, MDe	Late Devonian through Mississippian siliciclastic rocks. Present only in the northwest corner (CP basin) of the model area, northwest of the Cane Spring fault and southwest of the Topgallant fault.
Lower Carbonate Aquifer (LCA)	CA	Dg through Cc	Cambrian through Devonian mostly limestone and dolomite. Regional carbonate aquifer present throughout the model area.
Lower Vitric Tuff Aquifer (LVTA)	VTA	Th	Relatively thin VTA unit below the TSA. Grouped with the TM-LVTA where TSA is not present.
Lower Clastic Confining Unit (LCCU)	CCU	Cc, Cz, CZw, Zs, Zj	Late Proterozoic through Early Cambrian siliciclastic rocks. Hydrologic "basement" present at great depth in the model area.

^aHydrogeologic units: See Table 4-3 in BN (2004a) for definition of hydrogeologic units.

^bStratigraphic units: See Tables 4-1 and 4-2 in BN (2004a) for definition of stratigraphic units.

**Table 2-4
Correlation of Hydrostratigraphic Units of the Frenchman Flat Model and Earlier UGTA Models**

Hydrostratigraphic Unit ^a	Symbol This Report	Correlation with Phase I Frenchman Flat HSU Model ^b	Correlation with NTS Phase I Regional Model ^c	Correlation with Yucca Flat Model ^d	Correlation with Pahute Mesa/Oasis Valley Model ^e
Playa Confining Unit	PCU2	AA ^f	AA ^f	PCU	NP
Alluvial Aquifer	AA			AA	AA
Basalt Lava Flow Aquifer	BLFA			BLFA	YVCM
Older Alluvial Aquifer	OAA and OAA1			NP ^g	NP
Older Playa Confining Unit	PCU1			NP, PCU	NP
Timber Mountain-Welded Tuff Aquifer	TM-WTA	TMA ^f	TMA, TC, VA ^f	TM-WTA	TMA
Timber Mountain-Lower Vitric Tuff Aquifer	TM-LVTA			TM-LVTA	PVTA, CHVTA
Upper Tuff Confining Unit	UTCU			UTCU ^d (YF-UCU) ^h	UPCU, LPCU
Topopah Spring Aquifer	TSA			TSA	TSA
Lower Vitric Tuff Aquifer	LVTA			LVTA	PVTA, CHVTA
Lower Tuff Confining Unit	LTCU	TCU	BCU, VCCU	LTCU ^d (YF-LCU) ^h	CHCU, CFCU, BFCU, PBRCM ⁱ
Wahmonie Confining Unit	WCU	WCU		NP	NP
Volcaniclastic Confining Unit	VCU	VCCU	VCCU	NP	NP
Lower Carbonate Aquifer-Thrust Plate	LCA3	NP	LCA3	LCA3	LCA3
Upper Clastic Confining Unit	UCCU	NP	UCCU	UCCU	UCCU
Lower Carbonate Aquifer	LCA	PreT ^f	LCA	LCA	LCA
Lower Clastic Confining Unit	LCCU		LCCU	LCCU	LCCU

^aIf correlative to more than one HSU, all HSUs are listed.

^bSee IT (1998b) for explanation of initial Frenchman Flat model nomenclature.

^cSee IT (1996a) for explanation of the UGTA Phase I HSU nomenclature.

^dDocumentation for final Yucca Flat model is in progress.

^eSee BN (2002) for explanation of Pahute Mesa/Oasis Valley HSU nomenclature.

^fNot subdivided.

^gNP = Not present.

^hSee Gonzales et al. (1998) for explanation of the Yucca Flat HSU nomenclature.

ⁱMinor embedded ash-flow tuffs may have better aquifer properties than the bulk of this HSU.

Figure 2-5
West-to-East and Northeast-to-Southwest Hydrostratigraphic Cross Sections
Through the Frenchman Flat Area

framework documentation package (BN, 2004a), where additional cross sections and detailed information regarding this CAU-scale model can be found. [Figure 2-6](#) shows a fence diagram of the entire FF geologic model viewed from the southeast. [Figure 2-7](#) shows an enlarged view of the fence diagram for the central FF testing area, and [Figure 2-8](#) shows an enlarged view of the northern FF testing area, both from the same angle as the main view. The test locations are indicated on [Figure 2-7](#) and [Figure 2-8](#).

As can be seen from the information presented in this section, the Frenchman Flat hydrostratigraphic framework model (BN, 2004a) includes considerable structural detail and stratigraphic enhancement over the NTS regional HSU model (IT, 1996d). The total number of HSUs increased from 9 to 17; most of the increase affected the Quaternary-Tertiary alluvial section and the Tertiary volcanic section. The single AA in the regional model has been subdivided into five HSUs. The two Tertiary volcanic HSUs in the southwestern NTS area and the single VU HSU outside the NTS (of the NTS regional HSU model) were subdivided into eight HSUs for the Frenchman Flat model. Except for geometry details, the four pre-Tertiary HSUs remain as initially defined.

2.4 Mineralogy of Hydrostratigraphic Units and Aqueous Geochemistry

Transport parameters are closely tied to the chemical environment in which transport occurs. For example, matrix sorption (discussed in [Section 9.0](#)) is dependent on both the solid (rock) and water chemistry to control immobilization of contaminants. This section contains a detailed description of the mineralogy for each of the HSUs present on FF and an overview of the major-ion aqueous geochemistry of FF. This information is intended to provide background for the transport parameter analyses presented in [Section 5.0](#) through [Section 11.0](#).

2.4.1 Mineralogy of Hydrostratigraphic Units

The nature and distribution of mineral phases in groundwater systems can exert a significant influence on water composition (e.g., major ion chemistry, pH) and the mobility of contaminants of concern. Reactive minerals are expected to occur in four distinct settings within the Frenchman Flat CAU. These include minerals in alluvial deposits, minerals within volcanic and carbonate rock matrices, minerals occurring as coatings on fracture surfaces in fractured volcanic and carbonate rocks, and colloids (fine-grained mineral particles) mobile in groundwater. On average, volcanic units in the Southwestern Nevada Volcanic Field (SWNVF) show fairly consistent mineralogy that tends to vary as a function of style and intensity of alteration (Warren et al., 2003).

2.4.1.1 Alluvium

The principal HSU of concern with respect to mineralogy in Frenchman Flat is the alluvium, because 9 of the 10 nuclear test detonations on Frenchman Flat occurred

Figure 2-7
Enlarged View of the Central Testing Area on the Frenchman Flat Fence Diagram
Solid Black Spheres Indicate Cavity Locations
(The sphere size is not proportional to cavity radius)

Figure 2-8
Enlarged View of the Northern Testing Area in Frenchman Flat
Solid Black Spheres Indicate Cavity Locations
(The sphere size is not proportional to cavity radius)

in this HSU. Additionally, during Phase I modeling activities, no radionuclides from the alluvial tests were predicted to move out of the AA during the 1,000-year transport simulations. The majority of mineralogic analyses of the rocks present in the Frenchman Flat CAU have focused on the alluvial layers that occupy the center of the Frenchman Flat basin, where several drill holes have been sampled. The alluvial materials are comprised of detritus that has been generated from upland source areas. These source areas were elevated during dynamic, structural-deformation events. Deposition into the basin tends to occur as alluvial fan deposits. These deposits are associated with intermittent or ephemeral drainage systems. The deposited alluvium tends to have heterogeneous grain sizes and mineral composition that depend on the source area of the detritus.

Extensive X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses were conducted by Warren et al. (2002) on the 3,722-ft thick alluvium sequence encountered in the ER-5-4 borehole. The alluvium at the ER-5-4 well consists of 12 lithologically, mineralogically, or chemically distinct layers that are primarily vitric in nature with little evidence of *in situ* alteration. Warren et al. (2002) found that minerals within the alluvium are partitioned among three components (phenocrysts, lithics, and matrix), but only the minerals present in the matrix material are expected to interact with groundwater. Highly reactive clay minerals in the smectite group provide the majority of internal surface area available for interaction with groundwater; however, zeolite minerals occur mostly in lithic fragments and shards, thus limiting the available surface area for interaction with groundwater (Warren et al., 2002). Potentially reactive glass fragments are widely available as reactive surfaces, as is calcite in deeper alluvial layers. Transition metal (e.g., iron and manganese) oxides occur as minor constituents within alluvial rocks but provide a relatively high likelihood of interaction with contaminants.

Chemical analyses and mineralogic analyses of other drill holes on Frenchman Flat show that many of the alluvial layers are extensive across the basin, but there are significant changes in alluvial layer thicknesses (Warren et al., 2002). Although many layers are continuous, the chemistry present at each drill hole is most strongly related to the rocks exposed within the most proximal structurally high source area according to the model presented by Warren et al. (2002). For example, at ER-5-3 and nearby drill holes, alluvium is consistent with material derived from regional ash-flow tuffs exposed in the Massachusetts Mountains to the north of the Frenchman Flat basin. The alluvium has been further subdivided into playa confining units (PCUs) and older AAs (OAAs) based on chemical and hydrologic properties of these layers.

2.4.1.2 Playa Confining Unit (PCU2T, PCU1U, and PCU1L)

Frenchman Lake is a prominent playa near the center of Frenchman Flat (Slate et al., 1999). The playa deposits are mainly clayey silt, but they may also contain interbeds of sand and pumice. The playa deposits behave as an aquitard due to the abundance of silt and clay (Winograd and Thordarson, 1975). The playa deposits that compose the Frenchman Lake playa are designated PCU2T in the hydrostratigraphic framework model ([Table 2-3](#); BN, 2004a). Two older

PCUs (PCU1U and PCU1L) are defined in the subsurface based on 3-D seismic data and drill hole samples from Well ER-5-4#2 (NNSA/NSO, 2004b). Because the playa deposits are separated by coarser alluvium, they are designated as separate EarthVision[®] layers in the framework model. The spatial relationship of the PCU2T and the older PCUs with the AAs is shown in the cross sections in [Figure 2-5](#).

Polygonal desiccation cracks are commonly found on dry surfaces, indicating a significant presence of clay. These sediments include up to 50 percent illite and montmorillonite; other mineral constituents include feldspar, quartz, calcite and to a lesser extent, clinoptilolite. The hydraulic and chemical characteristics of the three playa deposits are assumed to be similar.

2.4.1.3 Older Alluvial Aquifer (OAA and OAA1)

Because of the importance of the AA in Frenchman Flat, several studies specific to the alluvial section were undertaken during the Phase II modeling effort to determine whether these deposits could be subdivided on the basis of hydrogeologic characteristics (Subsection 2.4.8 in BN, 2004a). One of the units examined was a denser alluvium in northern Frenchman Flat recognized by Carr et al. (1975), Miller and Healey (1986), and others. This older, denser alluvium has been differentiated as a separate HSU for the Frenchman Flat framework model and is called the older alluvial aquifer (OAA) ([Table 2-3](#)). This unit is limited in extent and generally centered around the UGTs in northern Frenchman Flat (BN, 2004a).

Recent XRD data from Well Cluster ER-5-3 have shown that this “older, denser” alluvium has undergone low-grade zeolitic alteration (Warren et al., 2002; NNSA/NSO, 2004a). The original vitric constituents in the alluvial matrix have been altered to the zeolite, clinoptilolite. The OAA averages a little more than 25 percent clinoptilolite but may vary from 12 to 40 percent ([Table 2-5](#)). Other potentially reactive minerals present in the OAA include smectite clay (7.3 percent) and calcite (6.1 percent). Also, due to its tuffaceous nature, minor amounts of mafic minerals, biotite (1.6 percent), hematite (0.3 percent) and hornblende (0.3 percent) are present. Whole rock mineral abundances from XRD analyses are summarized in [Table 2-5](#). Major element oxide content from XRF analyses are presented in [Table 2-6](#).

The OAA1, which occurs below the Basalt Lava Flow Aquifer (BLFA), and the OAA, which is above the BLFA, are hydrogeologically and mineralogically equivalent. This subdivision was necessary to satisfy operational requirements of the EarthVision[®] modeling software. The relationship among the various alluvial HSUs is depicted in [Figure 2-5](#).

Table 2-5
XRD Analyses of Selected Drill Hole Samples From Frenchman Flat
 (Page 1 of 2)

Source of original data: Warren et al. (2003), WoldeGabriel (2004)

HSU	Stats	SM	KA	ZC	ZM	ZA	TR	CR	OP	QZ	KF	PL	FS ¹	GL	HM	BT	HN	CC	CX	Total ^a
OAA	Avg	7.3	0.1	25.6	0.0	0.0	0.0	2.9	5.6	10.1	--	--	33.1	4.6	0.3	1.6	0.3	6.1	0.0	97.5
	Std Dev	4.3	0.1	9.8	0.0	0.0	0.0	2.4	5.0	2.9	--	--	7.9	9.9	0.2	0.4	0.2	3.3	0.0	2.4
	Count	10	10	10	10	10	7	10	10	10	--	--	10	10	10	10	10	10	10	10
	Max	15.5	0.4	40.1	0.0	0.0	0.0	8.0	13.9	14.8	--	--	47.7	27.6	0.6	2.0	0.6	12.9	0.0	101.9
	Min	1.2	0.0	12.2	0.0	0.0	0.0	0.8	0.0	5.5	--	--	26.9	0.0	0.0	1.0	0.1	2.8	0.0	95.1
BLFA	1 Spl	21.3	2.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	--	--	49.3	0.0	0.6	0.0	0.0	0.0	19.4	94.5
TM-WTA	Avg	2.1	0.0	0.0	0.0	0.0	1.9	3.9	0.0	23.6	32.7	31.2	62.9	4.5	0.7	1.3	0.1	0.2	0.0	99.8
	Std Dev	2.4	--	--	--	--	2.8	3.1	--	6.9	0.9	3.2	--	4.2	0.1	0.7	0.1	0.3	--	0.4
	Count	4	1	1	1	1	2	4	1	4	3	3	1	3	4	4	2	3	1	4
	Max	5.5	0.0	0.0	0.0	0.0	3.9	8.0	0.0	32.7	33.7	34.4	62.9	8.4	0.8	2.0	0.1	0.6	0.0	100.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	18.1	32.1	27.9	62.9	0.0	0.6	0.6	0.0	0.0	0.0	99.2
TM-LVTA	Avg	2.9	--	--	--	--	--	14.9	--	17.2	33.9	29.1	--	--	0.7	1.3	--	--	--	100.0
	Std Dev	0.4	--	--	--	--	--	1.8	--	1.2	0.8	0.2	--	--	0.1	0.1	--	--	--	0.0
	Count	2	--	--	--	--	--	2	--	2	2	2	--	--	2	2	--	--	--	2
	Max	3.2	--	--	--	--	--	16.1	--	18.0	34.4	29.3	--	--	0.7	1.4	--	--	--	100.0
	Min	2.7	--	--	--	--	--	13.6	--	16.3	33.3	29.0	--	--	0.6	1.2	--	--	--	100.0
UTCU	Avg	3.9	0.0	64.5	4.2	0.0	0.0	0.0	4.3	5.4	--	--	20.8	0.0	0.0	0.3	0.1	0.7	0.0	104.0
	Std Dev	1.8	0.0	13.8	5.9	0.0	0.0	0.0	0.1	3.5	--	--	13.3	0.0	0.0	0.4	0.1	1.0	0.0	0.4
	Count	2	2	2	2	2	2	2	2	2	--	--	2	2	2	2	2	2	2	2
	Max	5.2	0.0	74.2	8.3	0.0	0.0	0.0	4.3	7.9	--	--	30.2	0.0	0.0	0.5	0.1	1.4	0.0	104.2
	Min	2.6	0.0	54.7	0.0	0.0	0.0	0.0	4.2	2.9	--	--	11.4	0.0	0.0	0.0	0.0	0.0	0.0	103.7
TSA	Avg	1.7	0.0	7.1	0.0	0.0	0.0	2.0	0.6	7.0	--	--	44.5	33.5	0.3	2.1	0.0	0.0	0.0	98.5
	Std Dev	2.3	0.0	4.0	0.0	0.0	0.0	2.8	0.8	9.9	--	--	37.7	47.4	0.4	0.2	0.0	0.0	0.0	0.8
	Count	2	2	2	2	2	2	2	2	2	--	--	2	2	2	2	2	2	2	2
	Max	3.3	0.0	9.9	0.0	0.0	0.0	4.0	1.1	14.0	--	--	71.1	67.0	0.5	2.2	0.0	0.0	0.0	99.0
	Min	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	--	--	17.8	0.0	0.0	1.9	0.0	0.0	0.0	97.9

Table 2-5
XRD Analyses of Selected Drill Hole Samples From Frenchman Flat
 (Page 2 of 2)

Source of original data: Warren et al. (2003), WoldeGabriel (2004)

HSU	Stats	SM	KA	ZC	ZM	ZA	TR	CR	OP	QZ	KF	PL	FS ¹	GL	HM	BT	HN	CC	CX	Total ^a
LTCU (argillic)		76.1	--	--	--	--	--	--	--	1.4	0.5	3.7	--	15.4	--	--	--	2.8	--	100.0
LTCU (typical)	Avg	6.8	--	23.6	10.9	--	--	2.2	7.7	4.5	8.8	27.6	--	--	0.5	8.3	0.3	0.5	--	100.0
	Std Dev	3.6	--	13.6	9.1	--	--	1.4	5.4	2.5	4.6	7.9	--	--	0.3	5.1	0.2	0.5	--	0.0
	Count	27	--	15	13	--	--	15	15	15	15	15	--	--	13	15	14	10	--	15
	Max	15.0	--	63.3	34.8	--	--	6.6	24.2	10.1	22.3	35.4	--	--	1.1	18.9	0.7	1.5	--	100.0
	Min	0.7	--	6.2	1.5	--	--	0.6	2.0	0.9	3.5	9.9	--	--	0.1	0.5	0.1	0.1	--	100.0

HSUs

AA = Alluvial Aquifer
 OAA = Older Alluvial Aquifer
 BLFA = Basalt Lava Flow Aquifer
 TM-WTA = Timber Mountain Welded Tuff Aquifer
 TMLVTA = Timber Mountain Vitric Tuff Aquifer
 UTCU = Upper Tuff Confining Unit
 TSA = Topopah Spring Aquifer
 LTCU = Lower Tuff Confining Unit
 WCU = Wahmonie Confining Unit

Mineralogy

SM = smectite
 KA = kaolinite
 ZC = clinoptilolite
 ZM = mordenite
 ZA = analcime
 TR = tridimite
 CR = cristobalite
 OP = opal-CT
 QZ = quartz
 KF = potassium feldspar
 PL = plagioclase
 FS = feldspar, undifferentiated
 GL = glass
 HM = hematite
 BT = biotite
 HN = hornblende
 CC = calcite
 CX = clinopyroxene

Statistics

Avg = Average
 Std Dev = Standard deviation
 Count = Number of samples
 Max = Maximum value
 Min = Minimum value
 FS¹ = KF + PL

^a Total percent of rock mineralogy accounted for by minerals listed in this table.

Table 2-6
XRF Analyses of Samples from Selected Drill Holes in Frenchman and Yucca Flats (in percent)

(Page 1 of 2)

Source of Original Data: Warren et al. (2003), WoldeGabriel (2004)

HSU	Statistics	Na ₂ O %	MgO %	Al ₂ O ₃ %	SiO ₂ %	P ₂ O ₅ %	K ₂ O %	CaO %	TiO ₂ %	MnO %	Fe ₂ O ₃ %	FeO %	LOI %	Total %
AA	Avg	2.61	2.04	13.87	60.51	0.17	3.11	6.34	0.55	0.08	3.23	0.75	6.08	99.58
	Std Dev	0.66	0.93	1.98	5.71	0.04	0.55	3.85	0.14	0.02	0.87	0.32	4.40	0.60
	Count	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	54.00	55.00	55.00
	Max	3.48	4.93	15.93	68.97	0.24	4.28	22.15	0.79	0.12	5.67	1.41	22.83	100.73
	Min	0.51	0.86	7.11	38.09	0.05	1.57	2.83	0.28	0.04	1.53	0.16	2.24	96.87
Ash Fall (in AA)	1 Spl	3.45	0.87	13.28	68.63	0.05	4.81	1.54	0.26	0.08	2.09	0.75	4.05	100.06
BLFA	1 Spl	3.25	7.20	16.10	46.20	0.45	1.05	9.88	2.00	0.15	6.64	2.66	2.85	98.70
OAA	Avg	2.67	1.42	11.71	62.20	0.08	3.38	6.69	0.34	0.08	2.09	0.34	8.17	99.35
	Std Dev	0.47	0.38	1.10	3.09	0.02	0.46	2.40	0.09	0.01	0.57	0.12	2.22	0.34
	Count	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00
	Max	3.25	1.95	13.48	65.98	0.12	4.11	11.92	0.52	0.10	3.16	0.56	12.36	99.99
	Min	1.97	0.86	9.79	55.52	0.05	2.54	3.02	0.23	0.06	1.29	0.12	5.09	98.93
TM-WTA	Avg	3.62	0.00	12.65	75.63	0.01	5.33	0.44	0.15	0.07	0.84	0.02	0.54	99.42
	Std Dev	0.60	0.14	0.29	1.03	0.00	0.20	0.12	0.04	0.01	0.23	0.04	0.14	0.01
	Count	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Max	4.05	0.10	12.85	76.36	0.01	5.47	0.53	0.18	0.08	1.01	0.04	0.64	99.43
	Min	3.20	-0.10	12.44	74.90	0.01	5.18	0.36	0.11	0.06	0.68	-0.01	0.44	99.42
TM-LVTA	Avg	3.74	0.20	12.89	72.86	0.02	4.75	1.07	0.19	0.07	1.01	0.04	2.46	99.42
	Std Dev	0.19	0.17	0.64	2.98	0.03	1.05	0.58	0.09	0.01	0.43	0.05	3.06	0.13
	Count	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
	Max	3.91	0.37	13.97	76.20	0.08	5.77	1.91	0.34	0.09	1.73	0.11	8.29	99.63
	Min	3.34	-0.06	12.04	68.97	-0.01	2.69	0.48	0.11	0.05	0.66	-0.01	0.45	99.26

Table 2-6
XRF Analyses of Samples from Selected Drill Holes in Frenchman and Yucca Flats (in percent)

(Page 2 of 2)

Source of Original Data: Warren et al. (2003), WoldeGabriel (2004)

HSU	Statistics	Na ₂ O %	MgO %	Al ₂ O ₃ %	SiO ₂ %	P ₂ O ₅ %	K ₂ O %	CaO %	TiO ₂ %	MnO %	Fe ₂ O ₃ %	FeO %	LOI %	Total %
UTCU	Avg	3.54	0.34	12.50	67.78	0.03	3.37	1.98	0.20	0.06	1.25	0.03	7.93	99.14
	Std Dev	0.48	0.20	0.26	2.35	0.02	0.43	1.02	0.07	0.01	0.56	0.05	1.44	0.43
	Count	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Max	3.95	0.63	12.88	70.85	0.05	3.67	3.44	0.28	0.08	2.05	0.10	9.28	99.62
	Min	2.96	0.19	12.31	65.41	0.01	2.73	1.13	0.11	0.05	0.75	-0.01	6.16	98.69
TSA	Avg	3.93	0.21	14.30	69.22	0.02	6.19	0.80	0.29	0.09	1.25	0.25	2.66	99.33
	Std Dev	0.69	0.06	0.49	1.47	0.01	1.57	0.43	0.04	0.00	0.14	0.24	2.53	0.36
	Count	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Max	4.41	0.25	14.64	70.26	0.03	7.30	1.11	0.32	0.09	1.35	0.43	4.45	99.58
	Min	3.44	0.17	13.95	68.18	0.02	5.08	0.50	0.27	0.09	1.16	0.08	0.88	99.08
LTCU	Avg	3.34	0.86	14.87	66.13	0.12	3.48	3.02	0.32	0.07	2.31	0.40	4.34	99.48
	Std Dev	0.69	0.70	2.34	3.80	0.07	0.92	1.36	0.16	0.02	1.03	0.24	1.60	0.45
	Count	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	27.00	28.00	28.00
	Max	6.18	3.66	22.60	74.31	0.23	5.79	5.47	0.58	0.12	3.78	0.74	7.59	100.80
	Min	1.70	0.13	11.24	61.11	-0.01	1.82	0.73	0.08	0.02	0.69	-0.01	1.16	98.63
LTCU/WCU (Tw only)	Avg	3.18	1.11	15.33	64.69	0.16	3.42	3.71	0.40	0.07	2.76	0.50	3.89	99.49
	Std Dev	0.45	0.71	1.58	3.29	0.05	0.87	0.97	0.13	0.02	0.86	0.20	1.56	0.47
	Count	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.00
	Max	3.61	3.66	17.21	74.31	0.23	5.79	5.47	0.58	0.12	3.78	0.74	7.46	100.80
	Min	1.70	0.26	11.24	61.11	0.06	2.02	1.94	0.08	0.04	0.69	0.05	1.16	98.63

Statistics

Avg = Average

Std Dev = Standard deviation

Count = Number of samples

Max = Maximum value

Min = Minimum value

HSUs

AA = Alluvial aquifer

BLFA = Basalt lava flow aquifer

OAA = Older alluvial aquifer

TM-WTA = Timber Mountain welded tuff aquifer

TM-LVTA = Timber Mountain lower vitric tuff aquifer

UTCU = Upper tuff confining unit

TSA = Topopah Spring aquifer

LTCU = Lower tuff confining unit

Tw only = ~ WCU - Wahmonie confining unit

2.4.1.4 Basalt Lava Flow Aquifer (BLFA)

Basalt was encountered within the alluvial section beneath the northern portion of Frenchman Flat (BN, 2004a). The thickness of basalt ranges from 9.1 m at Well Cluster ER-5-3 to 25.9 m at UE-5i. The depth to the basalt ranges from 268.2 m at UE-5i to 289.6 m at UE-5k, which places the basalt near the water table, particularly at Well Cluster ER-5-3 and UE-5k. Surface magnetic data suggest that the basalt is not a single continuous flow, but instead occurs as three separate and isolated occurrences (Carr et al., 1975; BN, 2004a). The basalt flow(s) are presented as a separate HSU called the BLFA (Table 2-3). The relationship of the BLFA with the various alluvial aquifers is shown in Figure 2-5.

Whole rock mineralogy (XRD data), major chemical constituents (XRF data), and phenocrysts (petrographic data) for the BLFA are summarized in Table 2-5, Table 2-6, and Table 2-7, respectively. Note that the single sample of BLFA was significantly argillized (21.3 percent smectite; Table 2-5). Smectite-filled vesicles are described in the detailed lithologic log for Well ER-5-3 (NNSA/NSO, 2004a). This clay content is considered anomalously high with respect to the entire HSU. The lower portion of the basalt is also reported to be calcareous. Clinopyroxene and olivine are relatively abundant and biotite, hematite, and orthopyroxene occur in less amounts (Table 2-5 and Table 2-7).

2.4.1.5 Timber Mountain Welded Tuff Aquifer (TM-WTA)

The unaltered volcanic rocks immediately beneath the alluvium of the Frenchman Flat geologic model area are divided into two Timber Mountain HSUs depending upon degree of welding (i.e., TM-WTA and TM-LVTA; Table 2-3). The spatial relationship of the TM-WTA and other volcanic HSUs is shown in Figure 2-5.

The TM-WTA is not an extensive HSU in Frenchman Flat, being generally confined to the north-central and northwestern portions of the model area, and west of the basin-forming faults (BN, 2004a). Lithologically, the TM-WTA consists mostly of vitric to devitrified welded ash-flow tuff and lesser amounts of vitric and nonwelded (i.e., unaltered), ash-flow tuff and bedded tuff. Stratigraphically, these include the Rainier Mesa Tuff (Tmr) and younger Ammonia Tanks Tuff (Tma), both formations of the Timber Mountain Group.

The Tma consists of nonwelded to moderately welded rhyolitic ash-flow tuff. The rocks contain abundant phenocrysts of sanidine, quartz, and sodic plagioclase, with less abundant biotite, and clinopyroxene, and accessory sphene, zircon, and apatite (Warren et al., 2003). The Tma can usually be divided into a mafic-rich upper part and a mafic-poor lower part (Table 2-7). Lithic fragments of the underlying Tmr are common. In most places, the Tma is separated from the underlying Tmr by a 1.5- to 9.1- m (5- to 30-ft) thick bedded tuff, called the bedded Ammonia Tanks Tuff (Tmab). The Tmab is typically vitric and slightly calcareous. However, the detailed lithologic log for Well ER-5-3 notes zeolitic pumice within the Tmab (NNSA/NSO, 2004a).

Table 2-7
Petrography and Mineralogy of Geologic Units in the Frenchman Flat Model
(Page 1 of 3)

Stratigraphy and Hydrogeology					Lithic Fragments ¹		Total Felsics ¹ (relative %)				Phenocrysts ² (% by volume)									
HSU ³	Strat ⁴	Lith ⁵	Lith. Rel. ⁶ %	HGU ⁷	Total Lithics	Lithic Lithology	% Total Felsic	QZ	KF	PL	QZ	KF	PL	BT	HN	Cpx	Opx	OL	Sph	Total % Pheno
PCU2T	Qp	slt, cl	100	PCU																
AA	Qta	ss	70	AA																
		g	30																	
OAA	Qtc	ss	70	AA																
		g	30																	
BLFA	Tybf	bs	100	LFA							0	0	8.58	0.103	0.0007	1.39	0.026	4.72	0	14.81
OAA1	QTC	ss	70	AA																
		g	30																	
PCU1U&L	QTp	slt, cl	100	PCU																
TMWTA	Tmar	pwt	5	VTA	3	wt, lava		8	54	38	2.66	12.75	7.39	1.2	0.005	0.44	0.004	0.01	0.03	24.52
		wt	25	WTA	3	wt, lava	13	8	54	38	2.66	12.75	7.39	1.2	0.005	0.44	0.004	0.01	0.03	24.52
		pwt	5		3	wt, lava	13	8	54	38	2.66	12.75	7.39	1.2	0.005	0.44	0.004	0.01	0.03	24.52
	Tmap	pwt	5	VTA	3		12	18	65	17	3.97	11.58	2.41	0.39	0.002	0.094	0.007	0	0.014	18.46
	Tmab	bed	5	VTA							6.14	13.02	4.09	0.089	0.85	0.05	0.05	0.003	0.007	24.29
	Tmrr	nwt	5		0.4						3.28	9.98	9.36	1.037	0.37	0.204	0.208	0.0007	0.00	24.25
		wt	20	WTA	0.4						3.28	9.98	9.36	1.037	0.37	0.204	0.208	0.0007	0.00	24.25
	Tmrp	wt	30		0.3		8	40	44	16	4.79	5.14	2.28	0.109	0.004	0.009	0	0	0	12.33
TMLVTA	Tmrp	nwt	45	VTA	0.3						4.79	5.14	2.28	0.109	0.004	0.009	0	0	0	12.33
	Tmrh	bed	25		4						2.38	3.56	3.30	0.05	0.08	0.049	0.008	0.005	0.006	9.43
	Tp		15		4						0.23	3.73	1.15	0.05	0.03	0.018	0	0	0.039	5.25
	Thp		15		4						1.1	1.05	0.53	0.056	0.003	0	0	0	0	2.74
UTCU	Tmr	nwt	10	TCU							4.79	5.14	2.28	0.109	0.004	0.009	0	0	0	12.33
	Tmrh	bed	60		4						2.38	3.56	3.30	0.05	0.08	0.049	0.008	0.005	0.006	9.43
	Tp		30																	
TSA	Tpt	wt	100	WTA	1.6						0.08	0.44	0.75	0.046	0.0004	0	0.003	0.0003	0	1.32

Table 2-7
Petrography and Mineralogy of Geologic Units in the Frenchman Flat Model
 (Page 2 of 3)

Stratigraphy and Hydrogeology					Lithic Fragments ¹		Total Felsics ¹ (relative %)				Phenocrysts ² (% by volume)									
HSU ³	Strat ⁴	Lith ⁵	Lith. Rel. ⁶ %	HGU ⁷	Total Lithics	Lithic Lithology	% Total Felsic	QZ	KF	PL	QZ	KF	PL	BT	HN	Cpx	Opx	OL	Sph	Total % Pheno
LVTA	Thp	bed	80	VTA							1.1	1.05	0.53	0.056	0.003	0	0.005	0	0.005	2.74
	Twlb		10								0.8	0.49	18.83	2.3	1.752	0.005	0.18	0.011	0	24.37
	Tc		10								1.27	4.36	4.73	0.06	0.02	0.01	0.13	0.002	0.0001	10.6
LTCU	Tmr	nwt	2	TCU							4.79	5.14	2.28	0.109	0.004	0.009	0	0	0	12.33
	Tmrh	bed	5								2.38	3.56	3.30	0.05	0.08	0.049	0.008	0.005	0.006	9.43
	Tp		5		4						0.23	3.73	1.15	0.05	0.03	0.018	0	0	0.039	5.25
	Thp		10		4						1.1	1.05	0.53	0.056	0.003	0	0.005	0	0.005	2.74
	Twlb		30								0.8	0.49	18.83	2.3	1.752	0.005	0.18	0.011	0	24.37
	Tc		30								1.27	4.36	4.73	0.06	0.02	0.01	0.13	0.002	0.0001	10.6
	Tcb										3.62	5.75	2.73	0.34	0.05	0.004	0	0	0.006	12.5
		pwt	5	LFA	2	lava	6	32	48	22	1.92	2.88	1.32	0.15	0.031			0	0	2.88
	Tn4	bed	5	TCU							2.22	3.14	7.08	0.547	0.599	0.15	0.0002	0.0341	0.0005	13.77
	To		5								0.92	5.38	7.34	0.43	0.03	0.03	0		0.03	14.15
	Tor	pwt	3			pw ash-flow	14.6	3.1	37.1	59.9	0.45	5.41	8.75	0.586	0.1837	0.025	0	0	0.015	15.42
WCU	Twm	la, fb	20	WTA							0.04	0	23.1	1.396	0.2992	4.56	4.036	1.086	0	34.56
	Twlb	bed	80	TCU							0.8	0.49	18.8	2.3	1.8	0.02	0.001	0.01	0	24.37
	Tws	bed	80								0.76	0.18	14.04	2.1487	0.213	0.002	0.0466	0	0	17.4
		la, fb	20	LFA							0.76	0.18	14.04	2.1487	0.213	0.002	0.0466	0	0	17.4
VCU	Tgp	ss, cl	60	CCU																
		ls	5	CA																
		g	5	AA																
		bed	30	TCU																
	Tgw	ss, cl	78	CCU																
		ls	10	CA																

Table 2-7
Petrography and Mineralogy of Geologic Units in the Frenchman Flat Model
 (Page 3 of 3)

Stratigraphy and Hydrogeology					Lithic Fragments ¹		Total Felsics ¹ (relative %)				Phenocrysts ² (% by volume)									
HSU ³	Strat ⁴	Lith ⁵	Lith. Rel. ⁶ %	HGU ⁷	Total Lithics	Lithic Lithology	% Total Felsic	QZ	KF	PL	QZ	KF	PL	BT	HN	Cpx	Opx	OL	Sph	Total % Pheno
VCU cont.		g	2	AA																
		bed	10	TCU																
UCCU	Mc	ss	30	CCU																
		ar	70																	
LCA	PZ	ls	70	CA																
		dol	30																	

Data Sources: Stratigraphy and Hydrogeology, BN (2004a); Lithics, felsics, phenocrysts, Warren et al. (2003)

¹ Lithic fragment and phenocryst content abstracted from an earlier unpublished version of Warren et al. (2003)

² Phenocrysts: Phenocrysts are relatively large and conspicuous mineral crystals in generally nondescript matrix or groundmass of a volcanic rock.

³ HSU = Hydrostratigraphic units from BN, 2004a

⁴ Strat = Stratigraphic Unit

⁵ Lith = Lithology - a general physical description or type of rock

⁶ Lith Rel % = Relative percent of the various lithology types represented in a particular HSU

⁷ HGU = Hydrogeologic unit

The Tmr is a compound cooling unit of nonwelded to densely welded, rhyolitic to quartz-laticite ash-flow tuff. The unit contains 15 to 30 percent phenocrysts, mainly sanidine, quartz and sodic plagioclase, together with less abundant biotite, clinopyroxene (in the upper part only), and accessory apatite, zircon and monazite (Warren et al., 2003). Lithic fragments of aphanitic rhyolite are scarce to rare. The Tmr can usually be divided into a mafic-rich upper portion (Tmrr) and a mafic-poor lower section (Tmrp).

Fracture-filling minerals in the TM-WTA, as reported in various lithologic logs include calcite, clay and possibly zeolite. Whole rock mineralogy (XRD data), major chemical constituents (XRF data), and phenocrysts (petrographic data) are summarized in [Table 2-5](#), [Table 2-6](#), and [Table 2-7](#), respectively.

2.4.1.6 Timber Mountain Lower Vitric Tuff Aquifer (TM-LVTA)

The TM-LVTA includes all unaltered bedded, ash-fall, reworked tuff, and nonwelded ash-flow tuff units present above the level of pervasive zeolitization in Frenchman and Yucca Flats. However, where welded Topopah Spring Tuff (Tpt), which forms the TSA, is present, unaltered nonwelded tuffs below the TSA are grouped within a separate HSU called the LVTA. Welded tuffs are included in the TM-WTA (described separately). Stratigraphically, the TM-LVTA typically includes formations and members of the Timber Mountain (Tm) and Paintbrush Group (Tp), but may also include units within the Calico Hills Formation (Th), and uppermost Wahmonie Formation (Tw). Older units are generally zeolitized, and are therefore categorized as confining units and placed with the Lower Tuff Confining Unit (LTCU) (see discussion below).

The TM-LVTA has a slightly larger distribution than the TM-WTA. Some TM-LVTA rocks are present beneath the alluvium throughout most of the northern and central portions of Frenchman Flat, although this unit is absent in areas where it has been removed by erosion over major structural highs. These include the western (Wahmonie Hills area) and eastern portions of Frenchman Flat. The TM-LVTA is also not present in portions of northern Frenchman Flat where stratigraphically equivalent rocks are zeolitic and are classified as a separate HSU called the UTCU. The relationship of the TM-LVTA with other volcanic HSUs is shown in [Figure 2-5](#).

In Frenchman Flat, the TM-LVTA units are saturated in the deep central portion of the basin. The TM-LVTA exhibits significant interstitial porosity, ranging from about 20 to 40 percent. However, because these lithologies tend to be poorly to moderately indurated, fractures are not common. Therefore, although interstitial porosity is high, its transmissivity may not be great.

The XRD data presented in [Table 2-5](#) reflect the petrographic data summarized in [Table 2-7](#). Major chemical constituents (XRF data), and phenocryst (petrographic data) information for the TM-LVTA are given in [Table 2-6](#) and [Table 2-7](#), respectively.

2.4.1.7 Upper Tuff Confining Unit (UTCU)

The zeolitized nonwelded tuffs that overlie the Tpt in north-central Frenchman Flat are designated as the UTCU ([Table 2-3](#)). Stratigraphically, the UTCU may include units from the base of the welded Rainier Mesa Tuff to the top of welded Tpt. The areal extent of the UTCU is limited in the Frenchman Flat basin, occurring only beneath the northern portion of the basin (BN, 2004a). The UTCU is also present in the southern portion of the Yucca Flat basin immediately above the TSA. Where the TSA is not present, but zeolitic rocks equivalent to the UTCU are present, the zeolitic rocks are assigned to the LTCU. The spatial relationships of the UTCU with other volcanic HSUs is shown in [Figure 2-5](#).

The clinoptilolite content of the UTCU averages 64 percent clinoptilolite but may vary from 55 to 74 percent ([Table 2-5](#)). Other potentially reactive minerals present in the UTCU include mordenite (4.2 percent), smectite clay (3.9 percent), biotite (0.3 percent) and hornblende (0.1 percent) and calcite (0.7 percent). Whole rock mineralogy (XRD data), major chemical constituents (XRF data), and phenocrysts information (petrographic data) for the UTCU are given in [Table 2-5](#), [Table 2-6](#), and [Table 2-7](#), respectively.

The hydrologic and chemical/mineralogical properties of the two tuff confining units (the UTCU and the LTCU [see discussion in this section]) are considered to be essentially identical. For comparison, mineral abundances for the three TCU subdivisions (defined in Prothro, 2004) in Yucca Flat are summarized in [Table 2-8](#).

Prothro (1998) conducted an analysis of fractures in core from the tuff confining unit (TCU) in Yucca Flat. The TCU of Yucca Flat is considered to be analogous to the UTCU and the LTCU in Frenchman Flat due to similarities in stratigraphy, lithology, and alteration. Prothro (1998) noted that almost all fractures observed were either coated or filled with some type of secondary mineral, and that zeolite and metallic oxides (iron and manganese oxides) were the two most common minerals. Typical fracture-filling/coating minerals for the TCU in Yucca Flat include zeolite, metallic oxides, crystalline quartz and chalcedony, calcite, and clay.

2.4.1.8 Topopah Spring Aquifer (TSA)

The TSA consists of a single WTA composed of welded ash-flow tuff of the Yucca/Frenchman Flat lobe of the Tpt ([Table 2-3](#)). The TSA is highly transmissive but is limited in areal extent. The unit is saturated in the deeper north-central portion of Frenchman Flat and has a distribution similar to that of the TM-WTA (BN, 2004a). The relationship of the TSA with other volcanic HSUs is shown in [Figure 2-5](#).

The Tpt is a densely to moderately welded rhyolitic ash-flow tuff. Phenocrysts include scarce to common sanidine and plagioclase, common biotite, and lesser clinopyroxene ([Table 2-7](#)). There is a characteristic 5-m thick black vitrophyre (glassy) near the top; a lithophysal zone below the vitrophyre is also common.

Table 2-8
XRD Analyses of Selected Drill Hole Samples from Yucca Flat TCU Study (Prothro, 2004)

HSU	Stats	SM	KA	ZC	ZM	ZA	TR	CR	OP	QZ	KF	PL	FS	GL	HM	BT	HN	CC	Total
LTCU	Avg	6	<1	55	2	0	1		10	3	8	10		1	0	2	<1	<1	<101
	Std Dev	8.0	0.1	15.2	4.0	0.0	0.9		6.2	2.4	4.2	5.0		8.8	0.0	1.7	0.6	2.4	
OSBCU	Avg	12	<1	32	1	1	1		5	10	17	19		0	<1	3	<1	<1	<105
	Std Dev	9.3	0.1	15.8	1.4	3.2	1.1		5.0	8.8	9.0	6.9		0.0	0.1	1.7	0.6	0.1	
ATCU	Avg	58	1	1	0	<1	0		0	17	11	6		0	<1	2	<1	1	<100
	Std Dev	14.7	2.1	2.2	0.0	0.6	0.0		0.0	6.6	6.1	5.0		0.0	0.5	1.5	2.7	2.4	

Explanation

HSUs

LTCU = Lower Tuff Confining Unit

OSBCU = Oak Springs Butte Confining Unit

ATCU = Argillic Tuff Confining Unit

Mineralogy

SM = smectite

KA = kaolinite

ZC = clinoptilolite

ZM = mordenite

ZA = analcime

TR = tridimite

CR = cristobalite

OP = opal-CT

QZ = quartz

KF = potassium feldspar

PL = plagioclase

FS = feldspar, undifferentiated

GL = glass

HM = hematite

BT = biotite

HN = hornblende

CC = calcite

Statistics

Avg = Average

Std Dev = Standard deviation

The lithophysal cavities are generally lined with euhedral cristobalite, tridimite, and feldspar crystals.

Fracture-filling minerals in the TSA, as reported in various lithologic logs, include quartz, calcite, clay and possibly zeolite. Whole rock mineralogy (XRD data), major chemical constituents (XRF data), and phenocrysts (petrographic data) for the TSA are given in [Table 2-5](#), [Table 2-6](#), and [Table 2-7](#), respectively.

2.4.1.9 Lower Vitric Tuff Aquifer (LVTA)

The LVTA includes all unaltered bedded, ash-fall, reworked tuff, and nonwelded ash-flow tuff units below the TSA and above the level of pervasive zeolitization in Frenchman and Yucca Flats (BN, 2004a; [Table 2-3](#)). The LVTA is only differentiated where the TSA is present; these rocks would otherwise be included in the TM-LVTA ([Figure 2-5](#)). Overlying welded tuffs are included in the TSA WTA (described separately). The LVTA has a distribution similar to the TSA. However, the LVTA is not present beneath portions of northern Frenchman Flat because equivalent units are zeolitic and assigned to the LTCU.

Stratigraphically, the LVTA may include formations and members of the Calico Hills Formation (Th), Wahmonie Formation (Tw), and Crater Flat Group (Tc). Older units are generally zeolitized, and are therefore categorized as confining units and assigned to the LTCU. These two stratigraphic units are petrographically distinctive. The Th is relatively quartz-rich and mafic-poor, and the Tw is quartz-poor and mafic-rich.

There are no XRD or XRF analyses specifically of the LVTA in the Frenchman Flat dataset. However, the TM-LVTA contains similar (unaltered) stratigraphic units. Chemistry and mineralogy for the TM-LVTA (as presented in [Table 2-5](#) and [Table 2-6](#)) may be used as a first approximation for the LVTA.

2.4.1.10 Wahmonie Confining Unit (WCU)

One of the unique aspects of the hydrogeology of the Frenchman Flat is its proximity to the Wahmonie volcanic center. The highlands associated with this volcanic center form the western boundary of the Frenchman Flat physiographic basin. The Wahmonie Formation, including the Sayler Member, consists mainly of rhyodacitic and dacitic lava flows, flow breccias, ash-flow tuff, ash-fall tuff, and reworked tuff (Poole et al., 1965). The lava and breccia flows are interpreted to be restricted in areal extent, but the ash-flow and ash-fall tuffs likely have a much wider distribution. Lavas and flow breccias are inferred to be more abundant in the western third of Frenchman Flat, whereas ash-fall and reworked tuffs are the primary Wahmonie units found in the central and eastern parts of the basin (Warren, 1995).

As with the overlying and underlying bedded tuffs, the Wahmonie nonwelded tuff units tend to become zeolitized where saturated, thus behaving hydrologically as a

confining unit. Closer to the volcanic source, some of the rocks are argillized due to hydrothermal alteration, and not hydraulically conductive (Warren, 1995). However, some of the lava flows may remain vitric to devitrified and may be transmissive.

The Wahmonie Formation is divided into two HSUs based on distance from its source area. Wahmonie rocks in the central and eastern parts of the basin (east of Water Well UE-5c, [Plate 1](#)) are included within the LTCU (see discussion below) and less commonly as the LVTA if not zeolitic (see discussion above). West of UE-5c (closer to the Wahmonie center), the heterogeneous group of Wahmonie rocks is classified as a “leaky” confining unit and designated as the WCU.

Phenocrysts in the WCU include rare quartz, abundant plagioclase, conspicuous biotite, and minor hornblende, orthopyroxene, clinopyroxene, and olivine, and trace apatite ([Table 2-5](#)). Plagioclase and orthopyroxene increase and biotite decreases upward in the section (Warren et al., 2003).

There were no XRD data (whole rock mineralogy) specifically representing the WCU. Major oxide values from XRF analyses presented in [Table 2-6](#) represent the Tw stratigraphic unit in central Frenchman Flat and not necessarily the WCU.

2.4.1.11 Lower Tuff Confining Unit (LTCU)

The LTCU is an important hydrogeologic layer over much of the NTS because it separates the volcanic aquifer units from the underlying regional LCA. The LTCU is generally present in the northern and central portions of the model area. It is absent over the major structural highs, where the volcanic rocks have been removed by erosion. Almost all zeolitized tuff units in Yucca and Frenchman Flats are grouped within the LTCU, which comprises mainly zeolitized nonwelded tuff. The lower part of the section contains several zeolitized and devitrified nonwelded to partially welded ash-flow tuff units, such as Bullfrog Tuff. Other older ash-flow tuff units such as the Yucca Flat Tuff (Toy), and Redrock Valley Tuff (Tor) may also be present. Stratigraphically, the LTCU may include all the Tertiary volcanic strata from the top of the Paleozoic rocks to the base of the Rainier Mesa Tuff. The strongly argillized older tuff and paleocolluvium that directly overlie the Paleozoic rocks, in some places, are also included. However, the older Tertiary sedimentary rocks in southern Frenchman Flat and the Wahmonie Formation in the western Frenchman Flat are not included in the LTCU. These two units are differentiated as separate HSUs and are described separately.

The LTCU and the LTCU1 are hydrogeologically and chemically equivalent except for their positions relative to the WCU. The zeolitic bedded tuffs stratigraphically beneath the WCU in the western portion of the Frenchman Flat geologic model are labeled the LTCU1. This subdivision was necessary to address operational requirements of the EarthVision[®] geologic modeling software.

The LTCU averages about 24 percent clinoptilolite but may vary from 6 to 63 percent ([Table 2-5](#)). Also present are the zeolite, mordenite (10.9 percent) and

smectite (6.8 percent), both of which also have broad ranges. Other potentially reactive minerals present in the LTCU include biotite (8.3 percent), hematite (0.5 percent), hornblende (0.3 percent), and calcite (0.5 percent). Whole rock mineralogy (XRD data), major chemical constituents (XRF data), and phenocrysts (petrographic data) for the LTCU are summarized in [Table 2-5](#), [Table 2-6](#), and [Table 2-7](#), respectively. For comparison, mineral abundances for the three TCU subdivisions in Yucca Flat (Prothro, 2004) are summarized in [Table 2-8](#).

Prothro (1998) conducted an analysis of fractures in core from the TCU in Yucca Flat. The TCU of Yucca Flat is analogous to the LTCU in Frenchman Flat due to similar stratigraphy, lithology, and alteration. Prothro (1998) noted that almost all fractures were coated or filled with some type of secondary mineral, with many fractures containing more than one type of secondary mineral. Typical fracture-filling/coating minerals for the TCU in Yucca Flat include zeolite, metallic oxides, crystalline quartz and chalcedony, calcite, and clay. Prothro (1998) reported that zeolite was observed in 48 percent of the fractures examined and metallic oxides were observed in 37 percent of the fractures. Of the metallic oxides, iron oxides appeared to be the most common with manganese oxide being less common. Crystalline quartz was the third most common secondary mineral observed (in 14 percent of the fractures).

Additional mineralogical and isotopic details for the LTCU in Yucca Flat are available in Dickerson et al. (2004). These investigators used micrographic (scanning electron microscopy-energy dispersion spectroscopy [SEM-EDS]) and isotope ratio analytical methods to characterize secondary minerals occurring in both the rock matrix and fractures of the TCU beneath Yucca Flat. The secondary minerals identified, in approximate order of decreasing abundance are clinoptilolite, illite/smectite, erionite/mordenite, alkali feldspar, silica, calcite, analcime, and secondary manganese and iron oxides.

2.4.1.12 Volcaniclastic Confining Unit (VCU)

The Tertiary sedimentary rocks that are exposed south and southwest of Frenchman Flat are divided into two formations: Rocks of Winapi Wash (Yount, 1996) and the younger, more extensive Rocks of Pavits Spring (Hinrichs, 1968; Barnes et al., 1982). These units consist of a diverse assemblage of interbedded volcanic and sedimentary rocks deposited primarily in lacustrine and fluvial environments. Specific lithologies include ash-flow tuff, ash-fall tuff, and reworked tuff; shale; tuffaceous sandstone and argillaceous sandstone; siltstone and mudstone; conglomerate; and lesser limestone (Hinrichs, 1968; Barnes et al., 1982). The Tertiary sedimentary rocks are probably present beneath most of southern and central Frenchman Flat, but pinch out in the northern portion of the basin (Prothro and Drellack, 1997b).

The Tertiary sedimentary rocks as a whole are believed to behave as a confining unit because of their tuffaceous character, which has a tendency to become zeolitized below the water table, and the abundance of fine-grained clastic rocks (Prothro and Drellack, 1997b). In outcrop, these rocks also appear argillized. The presence of rocks that tend to act as aquifers (limestone and coarser clastic rocks

that support their classification as a “leaky” confining unit) also adds mineralogic and chemical diversity to this HSU.

Fracture-filling minerals in the VCU, as reported in various lithologic logs include calcite, silica, clay, and zeolite. There are no XRF or XRD data easily accessible for the VCU at the time of this investigation.

2.4.1.13 Lower Carbonate Aquifer (LCA)

The LCA consists of thick sequences of Middle Cambrian-age through Upper Devonian-age carbonate rocks (Table 2-3; Winograd and Thordarson, 1975; BN, 2004a). This HSU serves as the regional aquifer for most of southern Nevada, and locally may be as thick as 5,000 m (Winograd and Thordarson, 1975; Cole, 1992 and 1997). Based on the current structural model (BN, 2004a) the LCA beneath Frenchman Flat is Pogonip Group (Ordovician) and older; therefore, it is mostly limestone (CaCO_3), with minor dolomite ($\text{CaMg}(\text{CO}_3)_2$) and much less chert and quartzite (SiO_2).

Deformation related to the west-vergent CP thrust fault has placed these older LCA rocks over younger rocks of the UCCU, and over stratigraphically equivalent LCA rocks. This geometry is only present in the northwest corner of the Frenchman Flat model – under CP basin, north of the Cane Spring fault. The position of these rocks above the UCCU requires that they be distinguishable in the geologic model from the regional aquifer (LCA). The rocks of the Lower Carbonate Aquifer-Thrust Plate (LCA3) are stratigraphically equivalent; therefore, they are hydrogeologically and chemically similar to the LCA.

Detailed information about fracture geometry and fracture-filling minerals in LCA core samples from Wells ER-6-1 and ER-6-2 in southern Yucca Flat is presented in IT (1996e). Due to hydrogeologic similarities, this information is relevant to the Frenchman Flat setting. IT (1996e) found that the fractures in the LCA rocks were generally filled or lined with three types of minerals: iron oxides (limonite and hematite), carbonaceous clays, and carbonate minerals (almost always calcite with rare occurrences of dolomite). They also note that silica cements were rare and restricted to fractures in quartzite lithologies. Another observation was that most of the fractures were lined or filled with a combination of two or more of these materials.

The detailed lithologic log for Well 3, located in eastern Frenchman Flat, lists fracture-filling minerals in the LCA consistent with the above Yucca Flat data. The fracture-filling minerals in the Well 3 lithologic log include calcite; clay; and manganese, limonite, and hematite stains.

2.4.2 Aqueous Geochemistry

The dissolved constituents in groundwater provide a record of the minerals encountered as water moves through geologic materials and may influence the rate

and extent of molecular-level reactions between contaminants and aquifer materials. To predict contaminant transport, knowledge of major ion chemistry helps to predict the extent of contaminant sorption onto rock surfaces.

2.4.2.1 Major Ion Chemistry

The major ions typically consist of calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), silicon (Si^{2-}) and carbonate (CO_3^{2-}). Other constituents (such as fluoride or boron) are occasionally at concentrations high enough to be considered major constituents of groundwater.

Major ion data from wells within the Frenchman Flat CAU were compiled from the UGTA groundwater quality database, GEOCHEM04.mdb. The dataset compiled for this study area includes several measurements of major ions generated between the years 1957 and 2004 (SNJV, 2004e). Sampling and analytical techniques have varied over this period of time resulting in significant variations in some measurements. For this reason, one representative sample was selected for the evaluations included in this section ([Appendix A](#)). These samples consist of the most recent major ion analyses for each location that meet a charge balance criteria of ± 5 percent. Silicon dioxide (SiO_2) and fluoride (F^-) concentrations, along with pH, temperature, and selected well information (total depths, completion intervals, and HSU sampled) are also listed in [Appendix A](#). Additional information regarding the wells is presented in the recent document *Phase II Hydrologic Data for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada* (SNJV, 2004e). Data Documentation Evaluations and Data Quality Evaluation flags are also provided for these data as described in SNJV (2004e). Further geochemical evaluations of the Frenchman Flat groundwaters, including flow path and groundwater age estimates, are presented in a recent document by Hershey et al. (2004).

Using the dissolved constituents in groundwater, Schoff and Moore (1964), Blankennagel and Weir (1973), and Winograd and Thordarson (1975) identified three distinct hydrochemical water types, or facies, in NTS groundwaters. These include a Na-K- HCO_3 groundwater facies commonly found in volcanic-rock aquifers, a Ca-Mg- HCO_3 facies commonly occurring in Paleozoic carbonate aquifers, and a Ca-Mg-Na- HCO_3 facies assumed to be a mixture of the volcanic and carbonate facies (Schoff and Moore, 1964).

- Na-K- HCO_3 water type - Sodium and potassium together are 60 percent or more of the total cations.
- Ca-Mg- HCO_3 water type - Calcium plus magnesium are 60 percent or more of the total cations. Calcium concentrations are generally slightly greater than magnesium concentrations.
- Ca-Mg-Na- HCO_3 water type (mixed type) - Neither cation pair amounts to as much as 60 percent of the total cations.

Groundwater in volcanic HSUs and the AA gains sodium from reaction with volcanic glass (White et al., 1980). Where wells exist in the alluvial aquifer beneath Frenchman Flat, the alluvium consists primarily of material derived from volcanic bedrock, this is affirmed by the groundwater chemical signature that is similar to that of the volcanic HSUs. The predominant anionic constituent in groundwater (bicarbonate), is derived from incorporation of carbon dioxide (CO_2) gas and dissolution of carbonate minerals.

A Piper diagram is a graphical tool used to represent the relative concentrations of major ions in a groundwater sample or group of samples (Hem, 1985). Ion concentrations are expressed in percent milliequivalents per liter and are used to classify the groundwater as a particular hydrochemical type. A Piper diagram consists of three different component representations of major-ion chemistry. Cation (i.e., Ca^{2+} , K^+ , Mg^{2+} , Na^+) and anion (i.e., Cl^- , SO_4^{2-} , HCO_3^- , and CO_3^{2-}) data are plotted in separate triangles. Both cation and anion data are then projected on to a central diamond-shaped area so that compositional relationships (such as mixing or evolutionary trends) within or between a group or groups of groundwater sample locations can be visually presented.

A Piper diagram for groundwater from the AA, VA, CA of Frenchman Flat is shown in [Figure 2-9](#). Two samples collected near Yucca Mountain, U-25-P #1 and J-13, are also identified in [Figure 2-9](#). These waters were used in the sorption studies described in this document ([Section 9.0](#)) and are included in [Figure 2-9](#) for comparison to Frenchman Flat CAU groundwaters. Two samples collected from Well ER-5-3 are also identified in [Figure 2-9](#). One sample is a composite from two completion zones within the well. The upper completion zone samples groundwater from the AA, and the lower completion zone samples groundwater from the TM-WTA and the UTCU HSUs. Because the majority of the groundwater (97 to 100 percent) flow comes from the lower interval in this well, this sample is designated as representing the volcanic HSUs. The other ER-5-3 sample was collected from only the upper completion zone and is, therefore, identified as a sample representing the AA. These samples are designated as ER-5-3 (composite) and ER-5-3 (upper) in the Piper diagram.

As shown in [Figure 2-9](#), the groundwater from the volcanic HSUs, including the sample from J-13, are primarily the Na-K- HCO_3 water type. Sodium is the dominant cation and HCO_3^- is the dominant anion. Mixed (Ca-Mg-Na- HCO_3) to Na-K- HCO_3 is observed at WW-4 and WW-4a. The Ca-enriched groundwater of water wells WW-4 and WW-4A (CP basin wells) is not representative of the groundwater of volcanic HSUs near the nuclear test holes in Frenchman Flat. The groundwater of the volcanic HSUs plot along a trend line of decreasing Ca plus Mg and increasing Na in the Piper diagram ([Figure 2-9](#)). The greatest percentages of Ca plus Mg relative to the total cation concentration of the water sample are observed in the groundwaters of wells WW-4 (42 percent) and WW-4A (43 percent); the next greatest are observed for wells ER-5-3 (26 percent) and UE-PW-3 (34 percent); and the lowest are observed in UE-11a (13 percent), UE-5c WW (11 percent), and ER-5-4#2 (0.3 percent). This trend appears to correspond with the particular volcanic HSU sampled. For instance, two of the groundwater samples plotting at the lower end of the trend (UE-5c WW and ER-5-4#2) are sampled from the LTCU. These samples are clearly dominated by

Na (> 85 percent) with very little Ca or Mg present. This unit consists primarily of zeolitized tuffs. Conversely, the primary HSU sampled for the other wells is the TM-WTA, which consists primarily of nonzeolitized, welded tuffs. The deepest well of the volcanic HSUs, ER-5-4#2, also has the greatest amount of sulfate relative to the total anion concentration (25 percent) and may, therefore, be classified as a Na-HCO₃-SO₄ water type.

The Na-K-HCO₃ water type is also observed in the majority of the groundwater of the AA (Figure 2-9). The relative percent of SO₄²⁻ is also greatest in the two deepest wells of the AA, ER-5-4 (29 percent) and WW-5B (25 percent). The groundwater of these wells may be classified as a Na-HCO₃-SO₄ water type.

Alteration products of volcanic rocks and alluvium derived from volcanic rocks include mineral phases with high cation exchange capacities (e.g., montmorillonite and zeolites) (Borg et al., 1976 and White et al., 1980). Based on the ion exchange series for montmorillonite presented in Fiero et al. (1974), Ca and Mg may be preferentially removed from groundwater and replaced with Na. Another possible explanation for the observed cation trend in FF CAU AA and VA may be precipitation of mineral phases such as carbonates, and the phases discussed above, montmorillonite and zeolites. Claassen (1985) attributed a similar cation trend in tuffaceous aquifer groundwater to precipitation of montmorillonite and clinoptilolite (a zeolite). Thus, the observed differences in cation chemistry within the Frenchman Flat AA and volcanic-HSU groundwaters may result from reactive mineral phases (e.g., smectite group clays [such as montmorillonite] or zeolites) in the aquifer. Saturation indices (SI) for calcite and dolomite, for a selected set of groundwaters, are listed in Appendix A (Hershey et al., 2004). A negative SI indicates undersaturation and a positive value indicates oversaturation.

In general, the groundwaters of the LCA included in this study (ER-5-3#2, TW-3, and TW-F) are of the mixed Ca-Mg-Na-HCO₃ type. This mixed type groundwater suggests some degree of intermingling between groundwaters of the AA or volcanic HSUs and groundwater in the underlying CA.

Differences in total dissolved solids (TDS) within the AA are also observed (Hershey et al., 2004). The most dilute alluvial groundwater has a TDS of about 200 milligrams per liter (mg/L) (calculated as total concentration of Ca, Mg, Na, K, Cl, SO₄, SiO₂ and ½ HCO₃+CO₃ [Hounslow, 1995]) while the most concentrated alluvial groundwater has a TDS of about 570 mg/L (Hershey et al., 2004). While a clear trend is not observed between sampling depth and TDS, the greatest TDS is observed in the deepest alluvial well, ER-5-4 (Hershey et al., 2004).

In the volcanic HSUs, similar to groundwater in the alluvium, there are notable differences in TDS (Hershey, et. al., 2004). The TDS of the dilute groundwater samples are approximately 270 to 290 mg/L TDS with a couple somewhat higher (UE-5c WW = 336 mg/L; UE-11a = 373 mg/L) and one substantially higher (ER-5-4 #2 = 754 mg/L). Also, similar to the AA, the TDS is significantly greater in the deepest well, ER-5-4 #2.

The calculated TDS of the LCA groundwater of Frenchman Flat is in general greater than that in the alluvial and volcanic HSU groundwaters (Hershey et al., 2004). The TDS for wells ER-5-3 #2 (northern Frenchman Flat), TW-F (western Frenchman Flat), and TW-3 (eastern Frenchman Flat) are 708, 415, and 436 mg/L, respectively (Hershey et al., 2004). Although a greater TDS is observed in the deepest well, ER-5-3 #2, similar TDS concentrations are observed in shallower wells of southern Yucca Flat (WW-C1, TDS = 683 mg/L and WW-C, TDS = 663 mg/L).

The chemistry of the groundwater of Frenchman Flat, in general, reflects a relatively oxidizing environment; nitrate and dissolved oxygen are present, and iron and manganese are generally low (IT, 1999c). LANL performed an *in situ* measurement of the oxidation-reduction potential (ORP) in the groundwater of WW-5a at depths ranging between approximately 220 and 250 m. The measured ORP values ranged between 251 and 300 millivolts (mV) reflecting oxidizing conditions (Finnegan and Thompson, 2001). The ORP values measured *in situ* in southeastern Yucca Flat (completed in the LCA), ER-6-1, were 276, 266, 143, and 144 mV at depths of 473, 473, 498, and 504 m, respectively (Finnegan and Thompson, 2002). Although a decreasing trend in ORP relative to depth may be present, all reported values reflect an oxidizing environment.

The pH of the groundwater within Frenchman Flat are reported in [Table A.2-1](#). In general, the pH of the LCA (6.67 – 7.85) is near neutral and slightly lower than the AA and volcanic HSUs. These values reflect the well-buffered groundwater within the LCA. The pH of the groundwaters of the volcanic HSUs (7.39 – 8.7) are relatively similar to those of the AA (7.9 – 9.29). The 9.29 pH observed for the AA reflects a single sample from Well ER-5-3 Upper and appears to be unusually high relative to all other FF AA water samples.

2.5 Contamination Sources and Extent

This section includes summary descriptions of the sources and extent of the radioactive contamination present at the Frenchman Flat CAU.

2.5.1 Contamination Sources

This section describes the sources of radioactive contamination present at the Frenchman Flat CAU. Brief descriptions of the underground nuclear tests, the radiologic source term, the hydrologic source term, and the simplified hydrologic source term are provided. Full details on the hydrologic source term is the subject of a separate report.

2.5.1.1 Underground Nuclear Tests

Ten underground nuclear tests were conducted in Areas 5 and 11 at the NTS ([Table 1-1](#)). [Figure 2-10](#) shows the name and date of the ten underground tests as

well as the HSU in which each test was conducted, in addition to the name and date, the estimated cavity radius (R) is also presented (in meters). Three of the tests were located just northwest of Frenchman Playa at boreholes U5a, U5b, and U5e (Plate 1). The seven remaining underground tests were conducted in the northern portion of the basin near the Massachusetts Mountains at borehole locations U5i, U5k, U11b, U11c, U11e, U11f, and U11g (Plate 1). The location of nuclear tests is shown in Figure 1-2.

Of these 10 underground tests, only one, the CAMBRIC test at U5e, was detonated below the water table (Figure 2-10). The remaining nine tests were detonated from 15 to 62 m above the water table. Pawloski (1999) reports that cavity radius (R_c) is a function of the announced yield, such that

$$R_c = \frac{70.2y^{1/3}}{(hp_b)^{1/4}} \quad (2-1)$$

where y is the test yield (kt), h is the working point depth (m), and ρ_b is the bulk density (grams per cubic centimeter [g/cm³]) of the overlying materials. Based on the maximum value of the announced test yield (DOE/NV, 2000b), the test cavities are expected to be less than 43 m in diameter, suggesting that some test cavities may extend to the water table. Hoffman (1979) reported a cavity diameter of 21.8 m for the CAMBRIC test. All tests on Frenchman Flat were conducted within 100 m of the water table and will be modeled as saturated source areas, which is considered a conservative assumption.

2.5.1.2 Radiologic Source Term and Potential Contaminants

The most recent inventory of the radiologic source term may be found in an unclassified report titled, *Nevada Test Site Radionuclide Inventory, 1951-1992* (Bowen et al., 2001). The inventory includes radionuclides produced by the 828 underground nuclear tests conducted at the NTS between 1951 and 1992. The inventory was subdivided into five areas roughly corresponding to the UGTA CAUs. The inventory for Frenchman Flat was reported as a total inventory for all 10 nuclear tests (see Table 2-10). The inventory includes tritium, fission products, actinides, and activation products. This inventory also provides an estimate of radioactivity remaining underground after nuclear testing completed in 1992. Bowen et al. (2001) published an estimate for the accuracy of the various groups of radionuclides in the inventory (Table 2-9). The accuracies depended on a number of factors, but most especially on the source of the information.

The source term inventory does not include all of the radionuclides produced during a nuclear test. Bowen et al. (2001) developed criteria to exclude radionuclides that are not considered to be of interest from a risk assessment perspective. Radionuclides were excluded from the inventory if they have half-lives of less than 10 years (with the exception of europium [Eu]-154 at 8.6 years), and if their abundance was so low that they do not present a significant

Table 2-9
Estimated Accuracies for Individual Radionuclides within Radionuclide Groups Reported by Bowen et al. (2001)

Radionuclide Group	Individual Radionuclide Accuracy
Unspent fuel materials	~20% or better
Fuel activation products	~50% or better
Residual tritium	~300% or better
Activation products	~ a factor of 10
Fission products	~10% to 30% for most of the fission products

risk to human health. A detailed description of the criteria for inclusion of radionuclides in the inventory may be found in Bowen et al. (2001).

The list of radionuclides with inventories corrected to September 23, 1992, the date of the last underground nuclear test at the NTS, for Frenchman Flat is provided in [Table 2-10](#). This list serves as the preliminary list of potential contaminants for the Frenchman Flat CAU. This list supersedes all previous lists supplied for Frenchman Flat.

To minimize the computational effort involved in generating the source term values, the 43 radionuclides considered in the inventory were combined into three sets of basis species. Basis species are radionuclides representing a group of radionuclides having similar partitioning and transport behavior. The three groups are as follows:

- Tracers: all non-sorbing radionuclides that partitioned in different ratios between the melt glass and the exchange volume and colloids
- Sorbing Radionuclides without consideration of daughter product production
- Radionuclides with daughter products of concern and their associated daughter products

2.5.2 Radionuclides in Frenchman Flat Groundwater

Available radionuclide data from wells within the Frenchman Flat CAU were compiled from the UGTA groundwater quality database, GEOCHEM04.mdb. The dataset compiled for this study area includes radionuclide activity measurements generated during 1,505 recorded sampling events at 20 different wells. A sampling event is defined as a particular date of sampling with the earliest event reported within the dataset dated 1957. The primary agencies providing data to the database include SNJV, LANL, LLNL, USGS, DRI, IT/Shaw, and BN. Each agency typically analyzes for a different suite of radionuclides. Tritium activities are generally reported by all agencies. Information regarding each of the wells included in this dataset is presented in

Figure 2-10
Hydrostratigraphic Cross Sections Showing Each Underground Nuclear Test Conducted in Area 5 and 11 at the Nevada Test Site

**Table 2-10
Radionuclide Inventory for Frenchman Flat CAU**

Radionuclide	Curies^a	Atoms^a
Tritium	1.744E+05	3.620E+24
Carbon-14	6.653E+01	6.405E+23
Aluminum-26	7.035E-03	8.413E+21
Chlorine-36	8.907E+00	4.516E+24
Argon-39	6.166E+00	2.794E+21
Potassium-40	1.649E+00	3.527E+27
Calcium-41	6.542E+01	1.135E+25
Nickel-59	1.634E+00	2.092E+23
Nickel-63	1.679E+02	2.828E+22
Krypton-85	1.285E+02	2.329E+21
Strontium-90	1.879E+03	9.109E+22
Zirconium-93	1.118E-01	2.825E+23
Niobium-93m	0.000E+00	0.000E+00
Niobium-94	6.968E-01	2.347E+22
Technetium-99	1.167E+00	4.189E+23
Palladium-107	1.949E-02	2.135E+23
Cadmium-113m	2.991E+00	7.104E+19
Tin-121m	1.646E+01	1.525E+21
Tin-126	8.193E-02	3.450E+22
Iodine-129	4.542E-03	1.201E+23
Cesium-135	1.362E-01	5.277E+23
Cesium-137	5.045E+03	2.555E+23
Samarium-151	2.949E+02	4.471E+22
Europium-150	9.859E-03	5.979E+17
Europium-152	7.569E+02	1.726E+22
Europium-154	2.622E+02	3.796E+21
Holmium-166m	2.024E+00	4.092E+21
Thorium-232	1.196E-01	2.821E+27
Uranium-232	1.027E-02	1.208E+18
Uranium-233	1.334E-03	3.578E+20
Uranium-234	4.316E-01	1.788E+23
Uranium-235	8.570E-03	1.016E+25
Uranium-236	2.995E-03	1.181E+23
Uranium-238	9.507E-02	7.159E+26
Neptunium-237	1.379E-02	4.969E+22
Plutonium-238	3.232E+02	4.775E+22
Plutonium-239	1.415E+03	5.744E+25
Plutonium-240	3.489E+02	3.855E+24
Plutonium-241	4.408E+03	1.069E+23
Plutonium-242	2.882E-02	1.821E+22
Americium-241	5.022E+02	3.661E+23
Americium-243	0.000E+00	0.000E+00
Curium-244	0.000E+00	0.000E+00
Total	1.901E+05	7.158E+27

^aDecay corrected to September 23, 1992 (date of last underground nuclear test)

Source: Modified from Bowen et al. (2001)

[Appendix A](#). Additional data may be found in a recent report prepared by SNJV (2004e).

This discussion of radionuclides in groundwater is divided into data related to the CAMBRIC RNM project and data from wells unrelated to the CAMBRIC experiment. All activity concentration data given in the following sections are presented as the concentration at the time of sampling; no data were decay corrected to the time of detonation. Also, no classified data are presented or discussed in the following sections.

2.5.2.1 CAMBRIC Radionuclide Migration Project

The CAMBRIC Radionuclide Migration (RNM) project was initiated in 1974 to provide data on the migration of radionuclides away from the site of the CAMBRIC underground nuclear test. One well, RNM-1, was slant-drilled through the radioactive debris and cavity formed by the CAMBRIC test. Another well, RNM-2S, was installed 91 m south of the center of the CAMBRIC detonation point. Groundwater flow from the detonation point to Well RNM-2S was induced by pumping Well RNM-2S from October 1975 to August 1991 (Bryant, 1992). Pumping was necessary to produce an artificial gradient so that water would move to Well RNM-2S in a reasonable length of time. Approximately 1.7×10^7 cubic meters (m^3) of water were discharged during this radionuclide migration experiment (Finnegan and Thompson, 2002).

A multi-well aquifer test (MWAT) was later conducted (April 10, 2003 to November 11, 2003) in order to acquire data for use in estimating hydraulic properties of the AA in the vicinity of RNM-2s (SNJV, 2004c). RNM-2S was pumped continuously for a period of 75 days at an average rate of 595.5 gallons per minute (gpm). Groundwater characterization samples were collected from well RNM-2s by SNJV, LLNL, and LANL at the beginning and again at the end of this test.

2.5.2.2 Well RNM-1

Groundwater samples were periodically collected from five isolated zones within Well RNM-1 during 1974 and 1975, approximately 10 years after the detonation. The zones were: below the cavity (zone 1), lower cavity (zone 2), upper cavity (zone 3), chimney area (zone 4), and periphery of chimney (zone 5). [Table 2-11](#) presents average radionuclide concentrations in groundwater from these sampling zones. Bryant (1992) reported that no radioactive constituents were detected in groundwater below the bottom of the cavity (Zone 1). Radionuclide concentrations in cavity groundwater (Zones 2 and 3) were substantially elevated ([Table 2-11](#)). Concentrations of cesium (Cs)-137, krypton (Kr)-85, strontium (Sr)-90, and tritium were also elevated in groundwater samples from the chimney area and periphery of the chimney (Zones 4 and 5). Although elevated, concentrations in the chimney area and periphery were lower compared to concentrations found in the cavity. Antimony (Sb)-125, plutonium (Pu)-239, and

ruthenium (Ru)-106 activities were below detection in groundwater samples from the chimney and periphery (Table 2-11).

**Table 2-11
Radionuclide Concentrations in Groundwater at Well RNM-1**

Water Source	Sample Date(s) ^a	Antimony-125 (pCi/L) ^b	Cesium-137 (pCi/L)	Iodine-129 (pCi/L)	Krypton-85 (pCi/L)	Ruthenium-106 (pCi/L)	Strontium-90 (pCi/L)	Plutonium-239 (pCi/L)	Tritium (pCi/L)
Lower Cavity (Zone 2)	9/6/1974	2.2 x 10 ⁺³ filtered ^c	5.9 x 10 ⁺² filtered ^c	5.3 ^{d, e}	no data	3.6 x 10 ⁺³ filtered ^c	no data	6.3 ^{d, e}	1.9 x 10 ⁺⁹ ^d
	9/6/1974	1.4 x 10 ⁺³ unfiltered	6.1 x 10 ⁺² unfiltered		no data	4.0 x 10 ⁺³ unfiltered	4.0 x 10 ⁺³ unfiltered		
	11/5/1974	4.2 x 10 ⁺³	6.7 x 10 ⁺²	8.1 ^d	1.6 x 10 ⁺⁵ ^d	4.0 x 10 ⁺³	2.9 x 10 ⁺³	1.3 ^d	5.3 x 10 ⁺⁹
Upper Cavity (Zone 3)	4/29/1975	9.8 x 10 ⁺²	1.5 x 10 ⁺³	2.9 ^d	2.3 x 10 ⁺⁵ ^d	1.9 x 10 ⁺³	2.6 x 10 ⁺³	1.2 ^d	3.7 x 10 ⁺⁹
Chimney Area (Zone 4)	8/7/1975 - 8/8/1975	not detected ^d	3.7 x 10 ⁺²	4.6 x 10 ⁻³ ^d	1.6 x 10 ⁺⁴	not detected ^d	1.8 x 10 ⁺³	not detected ^d	7.5 x 10 ⁺⁷
Periphery of Chimney (Zone 5)	8/14/1975	not detected ^d	8.2 x 10 ⁺¹	1.6 x 10 ⁻³ ^d	3.1 x 10 ⁺³	not detected ^d	8.2 x 10 ⁺¹	not detected ^d	2.8 x 10 ⁺⁷

^aData source is Hoffman et al. (1977) unless otherwise noted

^bPicocuries per Liter

^cFiltered through a 1-micrometer filter in the field (Hoffman et al., 1977)

^dInformation reported in Bryant (1992)

^eData from 9/5/1974 to 9/6/1974 Zone 2 samples not differentiated into filtered and unfiltered

Radionuclide data, provided by LANL, are presented in Figure 2-11. Figure 2-11 shows the temporal change of radionuclide concentrations in Well RNM-1 groundwater samples from the chimney and periphery zones (Zones 4 and 5) during the pumping of RNM-2s. Except for the first sample (from 1975), which was from Zone 4 only, samples were composites of both zones. Tritium and Kr-85 concentrations decreased several orders of magnitude over the period of pumping (1975 to 1991); to a lesser extent, Cs-137 and Sr-90 concentrations also decreased (Figure 2-11). Only small changes in concentrations were observed at RNM-1 once the pump in RNM-2s was stopped. At this time, the tritium and Kr-85 concentrations were near the analytical detection limits (Finnegan and Thompson, 2001). The slight increase in tritium levels following 1991 (Figure 2-11) most likely reflects the higher level of uncertainty associated with the measurement of low concentrations.

2.5.2.3 Well RNM-2S

Figure 2-12 shows radionuclide concentrations in groundwater at Well RNM-2S as a function of time. These data were provided by LANL and LLNL. Tritium, Kr-85, chlorine (Cl)-36, Ru-106, and iodine (I)-129 were transported in groundwater from the CAMBRIC test area. These radionuclides are all known to be relatively mobile in the groundwater environment. Tritium forms tritiated

**Figure 2-11
Radionuclide Concentrations in Groundwater at Well RNM-1**

water and should ideally move at the same velocity as groundwater. Krypton is a dissolved gas, and the other radionuclides are generally present in groundwater as anionic constituents.

Maximum tritium concentrations were observed at Well RNM-2S in late 1980, and peak concentrations were observed in mid-1981 to 1982. The breakthrough and the maximum concentration of Cl-36 in RNM-2S are reported to have occurred before that of tritium (Ogard et al., 1988) (see also Figure 7-6). This early arrival is attributed to anion exclusion, which effectively prevents anionic constituents from entering into dead-end pore spaces and the intragranular porosity of aquifer materials (Ogard et al., 1988). Anion exclusion also keeps the anions more in the center of pores, where groundwater velocities are greater. The relative breakthrough of Ru-106 is difficult to assess based on the few number of data points available (Figure 2-12). The dominant aqueous ionic form of Ru-106, RuO_4^- , is anionic and therefore likely to migrate in groundwater (Buddemeir and Isherwood, 1985). The ratios of Ru-106 to tritium were reported to be nearly the same for samples collected at both RNM-1 and RNM-2S, which suggests that Ru-106 and tritium traveled at the same rate from the CAMBRIC cavity to RNM-2S (Bryant, 1992).

The radionuclides Cs-137, Pu-239, Sb-125, and Sr-90 were not detected in Well RNM-2S groundwater, although these radionuclides were present in groundwater samples from the CAMBRIC cavity (Table 2-11). Cesium and Sr are

**Figure 2-12
Radionuclide Concentrations in Groundwater at Well RNM-2S**

generally cations, do not readily form complexes and, therefore, may be sorbed (Borg et al., 1976). Plutonium is typically very insoluble (Bryant, 1992). Apparently these radionuclides are not migrating from the CAMBRIC detonation point or are migrating very slowly.

2.5.2.4 Well UE-5n

UE-5n, an exploratory hole, was drilled approximately 560 m east and south of the RNM-1 hole in March 1976. Although not part of the CAMBRIC RNM experiment, Well UE-5n is located within 100 m of the unlined discharge ditch that was used to transport the water pumped from Wells RNM-1 and RNM-2S to Frenchman Lake. Radionuclides were not detected in UE-5n waters until 1989 and are thought to reflect infiltration of water from the CAMBRIC ditch (Rose et al., 2003). Tritium activities of 1.41×10^5 and 1.35×10^5 picocuries per liter (pCi/L) were measured in samples collected from UE-5n in September of 1999 and April of 2001, respectively. If the April 2001 samples are decay corrected to the time of the September 1999 sampling date, an average activity of 1.49×10^5 pCi/L is obtained. This indicates a slight increase in activity over the period between sampling times (Finnegan and Thompson, 2002). No Kr-85 activity, and very low levels of neptunium (Np)-237 (82 to 84 parts per quadrillion), consistent with those measured in samples collected at RNM-1 and

RNM-2S, were detected in UE-5n groundwaters (Finnegan and Thompson, 2002). The isotopic composition of dissolved uranium in UE-5n groundwaters is consistent with natural abundances (Rose et al., 2003).

2.5.3 Non-CAMBRIC Radionuclide Data

In general, groundwater radionuclide concentrations are low (most likely background) at well locations other than those associated with or impacted by the CAMBRIC RNM project. Analytical uncertainty is relatively high at concentration levels near background; therefore, the radionuclide data are highly variable in groundwater samples from non-CAMBRIC well locations. The variability appears primarily to be an artifact of sampling and/or analysis, rather than related to any physical or chemical process. Also, in many cases, detection limits are too high to quantify radionuclide concentrations.

Bechtel Nevada is the primary agency providing radionuclide data for wells not associated with the CAMBRIC RNM experiment. Routine radiological monitoring is provided by BN for the wells WW-4, WW-4A, WW-5B, WW-5C, UE-5C WW, UE-5 PW-1, UE-5 PW-2, and UE-5 PW-3. The radionuclides measured for the radiological monitoring program include:

- Tritium
- Americium (Am)-241
- Cerium (Ce)-144
- Cobalt (Co)-60
- Cs-134 and Cs-137
- Eu-152, Eu-154, and Eu-155
- K-40
- Lead (Pb)-212
- Pu-238 and Pu-238+239
- Radium (Ra)-226 and Ra-228
- Ru-106
- Sb-125
- Sr-90

Although measured values for radionuclide activities are reported in some cases within the compiled dataset, the values are typically less than the minimum detectable concentration (MDC) and/or the measurement error reported as 2 sigma (2 times standard deviation). Many of the reported data are notably low, but no MDC is reported. All tritium measurements were reported as less than the MDC of approximately 20 pCi/L during the 2003 monitoring events (BN, 2004b). Bechtel Nevada (2004b) reports a general lack of anthropogenic alpha, beta, and gamma emitting radionuclides in groundwater samples collected during the 2003 monitoring events. Although, very low yet detectable concentrations of naturally occurring Ra-226 and Ra-228 were observed, the levels did not exceed U.S. Environmental Protection Agency (EPA) levels of concern or their established maximum contaminant levels for drinking water (BN, 2004b).

In addition to the routine radiological monitoring performed by BN, multiple agencies (SNJV, LLNL, LANL, DRI, USGS, and BN) collected and analyzed groundwater samples from the newly drilled wells, ER-5-3, ER-5-3#2, ER-5-4, and ER-5-4#2. All resulting data were added to Geochem04.mdb.

Well ER-5-3 was drilled and completed during FY 2000 and primarily produces water originating from the TM-WTA HSU (SNJV, 2004e). Well ER-5-3#2, located about 30 m east of ER-5-3, was drilled and completed in FY 2000, and then recompleted in FY 2001. ER-5-3#2 has a single completion zone in the lower carbonate aquifer. Groundwater characterization samples were collected from ER-5-3 and ER-5-3#2 in March 2001 and May 2001, respectively. No radionuclide activity attributed to nuclear testing was detected in either of these wells (Finnegan and Thompson, 2002; Rose, 2003a, Rose, 2003b).

Well ER-5-4 was drilled and completed to a total depth of 1,137.5 m in FY 2001 and produces water primarily from the AA (SNJV, 2004e). ER-5-4 is located in the central portion of Frenchman Flat (approximately 350 m northeast of the emplacement hole for the CAMBRIC test). During drilling, tritium was detected at a depth of approximately 305 m with activities ranging from 4,300 to 5,400 pCi/L (Finnegan and Thompson, 2002). No other fission products or other weapon related radionuclides were observed during this time (Finnegan and Thompson, 2002). Interestingly, the tritium was found at a depth equivalent to the depth of the CAMBRIC test. Characterization samples were collected in July 2001 and analyzed by multiple agencies. Although the interval containing tritium activities was cased off during completion, a detectable amount of tritium (2.5 pCi/L) was measured by LLNL using helium mass spectrometry, which has a detection limit near 1 pCi/L (Rose, 2003c). LANL detected no activity in these samples other than background gamma activity of U-238, U-235, Th-232, and their daughters, and Kr-40; no tritium was detected above the detection limit of approximately 810 pCi/L using liquid scintillation counting (Finnegan and Thompson, 2002).

Well ER-5-4#2 was drilled and completed in FY 2002 approximately 30 m south of ER-5-4 (Shaw, 2003b). ER-5-4#2 was completed to a total depth of 2,133.6 m and produces water primarily from the LTCU. Groundwater characterization samples were collected in November 2002. A tritium activity of 156.8 pCi/L was reported by LLNL but problems with low-level measurements of tritium were experienced in their laboratory during this time. This activity may be due to post-sampling cross-contamination (Rose, 2003d). No activity in these samples other than background gamma activity of U-238, U-235, Th-232, and their daughters, and K-40 were detected by the other agencies (Finnegan and Thompson, 2004).

2.6 Hydrologic Source Term

The hydrologic source term is defined as the radionuclides that are available for transport in groundwater. It represents a portion of the radiologic source term, which includes all radioactive material remaining after a nuclear test.

Detailed process models have been developed by LLNL to simulate the hydrologic source term (HST) (Tompson et al., 1999). These models are designed to simulate the chemical and physical processes that govern the migration of radionuclides from the underground test cavities. These process models have the potential to simulate the release from a specific underground test assuming adequate site-specific data exist.

However, the HST models require large amounts of information and resources. Thus, it is impractical to use them to generate HST for the underground tests on Frenchman Flat. The development of a simplified method was, therefore, necessary.

2.6.1 Simplified Hydrologic Source Term

A Simplified Source Term Model (SSM) was constructed using GoldSim (Golder, 2002a and b). The SSM will be used to generate generic cavity source flux terms for use in the CAU-scale radionuclide transport model of the Frenchman Flat CAU. The generic cavity source flux terms will then be used to derive hydrologic source terms for Frenchman Flat nuclear tests.

The SSM consists of several components representing sections of the detailed process model. The SSM is used to generate a series of generic radionuclide mass flux curves representing the release of radionuclides from the exchange volume and the melt glass. The SSM accounts for radionuclides with different mass partitioning between melt glass and exchange volume. This model approximates the release of radionuclides as tracers or as colloids, but can also simulate the release of reactive radionuclides. Finally, the SSM has the capability to simulate the mass flux of daughter products. SSM simulations account for uncertainty by treating many of the input parameters as random variables.

A normalized inventory of 1.0 is used for each radionuclide considered in the SSM to generate the series of generic radionuclide mass flux curves. Hydrologic source terms specific to each nuclear test or a group of similar tests are then generated using site-specific or group-averaged inventory data. For more details on the HST for the CAU transport model, see the unclassified hydrologic source term and radionuclide data report (Tompson et al., 2004).

3.0 CAU Modeling Approach and Data Needs

The process for achieving the UGTA corrective action strategy includes modeling to predict the maximum extent of contaminant transport within a specified time frame. The use of groundwater flow and transport models to achieve the objectives of the corrective action strategy is specified in Appendix VI of FFACO (1996, 2000). This section presents an overview of the CAU groundwater flow and transport modeling approach, a summary of the groundwater flow modeling approach for Frenchman Flat, and a discussion of the transport modeling approach and transport model data needs for Frenchman Flat. Additional discussion of the modeling approach for Frenchman Flat CAU is included in IT (2001b).

3.1 Overview of CAU Modeling Approach

Underground nuclear testing at the NTS included a total of 908 detonations conducted in shafts and tunnels at depths ranging from 27 to 2,452 m (83 to 4,764 ft) with approximately one-third of these tests conducted near or below the water table (DOE/NV, 1997). Groundwater flow from these sources occurs through diverse and structurally complex rocks (Laczniak et al., 1996). Given the complexity of the system, sources, and processes controlling transport, computer models will be required to meet the objectives of the FFACO strategy. The modeling approach used to develop an integrated 3-D model for flow and transport begins with characterization of the system, development of conceptual models based on assumptions of system processes, and representation of these processes mathematically. Mathematical models representing the system are then implemented on computers.

Integrated 3-D Model

The CAU groundwater flow and transport models will consist of an integrated set of models. Some of these models focus on a small-scale (relative to the CAU) process such as radionuclide release from source regions and others simplifying CAU-scale processes such as reactive transport in fractures to an abstraction for system sensitivity analysis. Combined, the models (referred to as component models) constitute the CAU predictive model. Essential aspects of the processes described by the detailed process models must be accurately represented in the CAU model. This representation must include the uncertainty associated with the process or parameters.

The CAU groundwater flow and transport models will be developed at the CAU scale and will be used to simulate radionuclide concentrations for the 1,000-year timeframe. The integrating numerical model will be a 3-D finite-element flow and

transport simulator that captures the complex geologic structure including units of variable thickness, faults, and offsets, as well as complex transport processes associated with reactive solutes and fractured rock. The CAU groundwater flow model component requires two other component models: the NTS regional groundwater flow model (DOE/NV, 1997) and recharge models (SNJV, 2004e). The CAU contaminant transport model component requires the CAU groundwater flow model and the hydrologic source term model.

Total System Model

The detailed component process models are computationally intensive and are currently not efficient for implementing thorough uncertainty analyses. Therefore, to complement the integrated modeling approach, a modeling platform for dynamic, probabilistic simulations may be used to develop simplified abstraction models that will attempt to reduce the description of the system to capture dominant processes and behaviors in one-dimensional (1-D) models of transport. Using this platform, uncertainty in processes and parameters can be explicitly represented. The simplicity of this approach facilitates a more thorough uncertainty analysis of the governing parameters and processes.

The CAU model approach and the total system model approach complement one another. The total system model results can be used to constrain scenarios to be considered by the CAU model, while the more detailed CAU model can be used to constrain the processes considered and their representation in the total system model. To use the total system transport model, it first must be demonstrated that simplified formulations capture the same general phenomena as the more complex CAU and process models. Then the total system model can be used to efficiently conduct additional sensitivity and uncertainty analyses not feasible with the complex CAU model. However, as computer hardware technology advances, it may become feasible to directly use the CAU process models in the uncertainty analyses. In this case, it will no longer be necessary to develop and use simplified abstraction models.

CAU Model Validation

The process of model validation, as it applies to the CAU model, involves following a modeling protocol - a series of steps which, when followed, builds support in demonstrating that a particular site-specific model is capable of producing meaningful results. Following this protocol increases confidence in the model predictions. To ensure fidelity of the CAU model to the physical system, a 10-step protocol will be utilized. These 10 steps are: (1) establishment of model purpose, (2) development of conceptual model, (3) selection of a computer code and verification of the code, (4) model design, (5) model calibration, (6) sensitivity and uncertainty analyses, (7) model verification, (8) predictive simulations, (9) presentation of model results, and (10) postaudit.

Data Requirements

Data requirements for the CAU groundwater flow and transport models fall into the following three categories:

Groundwater Flow Parameters

Data types required for the groundwater flow model include permeability (or hydraulic conductivity), storage parameters, recharge, lateral boundary fluxes, hydraulic heads, and groundwater chemistry.

Contamination Sources

The underground nuclear testing at the NTS consisting of a total of 908 detonations conducted in shafts and tunnels provide the contaminant source locations. The radiological source term (RST) is the total inventory of radionuclides remaining in the subsurface following an underground nuclear explosion. The radiological source term is distinguished from the HST that describes the part of the radiological source term dissolved in water in the exchange volume (cavity and chimney region). The HST is implemented in conjunction with the transport model to predict the transport of contaminants.

Transport Parameters

Major data types of interest include effective porosity, dispersivity, matrix porosity, matrix diffusion, sorption coefficients, and colloid-facilitated transport parameters. Note that for the purpose of modeling, effective porosity and matrix porosity are considered to be transport parameters rather than hydrologic parameters as they are required input variables in the contaminant transport model.

3.2 Historical and Phase II Modeling Strategy for Frenchman Flat CAU

Unlike the other NTS CAUs, the Frenchman Flat CAI process is in a second iteration of data evaluation. Following a peer review of the Frenchman Flat CAU model (IT, 1999a), DOE and NDEP decided the data for Frenchman Flat were not adequate, and an addendum to the Frenchman Flat CAIP was produced (DOE/NV, 2000a). The addendum described new data to be collected and how the new data would be included in the evaluation of existing/new data. The addendum also addressed modifications to the Frenchman Flat CAU modeling approach.

The modeling approach described in this document enhances and extends the Frenchman Flat CAU model presented by IT Corporation (1999b). The major enhancements and extensions are listed below:

- Incorporate newly collected Frenchman Flat data. This data is derived primarily from two drill hole locations, one (ER-5-3) near the northern group of underground tests and the other (ER-5-4) near the southern group of underground tests. The new data includes geologic unit identification and description within and below the base of the alluvium, surface geophysical data to assess deep basin structure, water-level measurements at several depths to assess vertical hydraulic head

relationships, hydraulic conductivity values from single- and multiple-aquifer tests to improve the hydraulic parameter dataset, and interpretation of reactive mineral distribution in the alluvium to constrain the source term model.

- Expand the assessment of uncertainty to include alternative geologic framework models, alternative conceptual flow models, better documented ranges of uncertainty on parameters, and uncertainty in the hydrologic source term.
- Adopting the FEHM (Finite Element Heat-Mass Transfer) flow and transport code, and significantly refining the model mesh to prevent the grid dilution effects noticed in the Phase I analysis.
- Use local-scale models to improve the accuracy of the transport predictions near the underground tests and allow for a more thorough assessment of uncertainty related to transport away from the underground tests.
- Develop a total system model to facilitate a more thorough analysis of uncertainty in the governing parameters, processes, and conceptual models.

3.3 FF Phase II CAU Groundwater Flow Modeling Approach

The Frenchman Flat Phase II Hydrologic Data Document (SNJV, 2004e) describes the approach used for development of the CAU groundwater flow model and the associated data requirements. The approach, which forms the framework for both the groundwater flow and transport CAU models, is summarized below. The specifics of the CAU transport modeling approach is documented in a later subsection.

The steps for developing the CAU groundwater flow model include:

- Identify simulation objectives
- Define CAU geologic model
- Define parameter distributions for model inputs
- Define CAU flow model boundaries
- Select computer code
- Generate CAU model grid
- Calibrate CAU flow model
- Perform parameter sensitivity analysis
- Prepare model documentation

Simulation Objectives

Simulation objectives that address the UGTA corrective action strategy are defined in Appendix VI of the FFACO (1996, 2000). A flow model for each CAU will be constructed to simulate local 3-D flow, evaluate the range of flow

conditions in the CAU that may be important in determining maximum extent of transport, and provide boundary conditions for transport for predicting contaminant migration from source locations. The contaminant transport model will be used to estimate the lateral extent of radionuclide transport and the deepest affected hydrostratigraphic unit.

Geologic Model

The Frenchman Flat geologic boundaries were chosen such that: (1) they coincide with perceived geologic and hydrologic domains, (2) they include important faults that may impact flow within Frenchman Flat, and (3) the contaminant source areas and perceived migration pathways are included. A base model and four alternative geologic models have been developed for the Frenchman Flat CAU. The Frenchman Flat CAU flow and transport models will be developed within the boundaries of the geologic model.

Parameter Distributions for Model Inputs

Specific data types needed to support groundwater flow modeling include: hydraulic properties, hydraulic conductivity, groundwater recharge, discharge, lateral boundary fluxes, and hydraulic heads. Parameter distributions were developed based on review and analysis of available data and information.

CAU Model Boundaries

The boundaries of the CAU groundwater flow model were selected to incorporate all relevant sources, important hydrogeologic features, and wells providing hydrologic and geologic information. These boundaries will be similar to the geologic model boundaries, but of more limited extent to the east and south. Lateral boundary conditions will be obtained from the NTS regional groundwater flow model simulations. The recharge models will provide fluxes for the upper model surface. The bottom of the model will be no deeper than the estimated contact between the LCA and the underlying LCCU.

Computer Code

The FEHM code (Zyvoloski et al., 1997), developed by LANL, was chosen for the Pahute Mesa CAU-scale flow and transport model (DOE/NV, 1999b) and has been demonstrated during 2003/2004 to be suitable for development of the calibrated groundwater flow model. The processes of interest for the Frenchman Flat CAU are the same as those of the Pahute Mesa CAU. Therefore, FEHM has been selected for development of the Frenchman Flat CAU flow and transport models.

FEHM simulates 3-D, time-dependent, multiphase, nonisothermal flow, and multicomponent, reactive transport through porous and fractured media. FEHM's finite-element formulation provides an accurate representation of complex 3-D geologic media and structures and their effects on subsurface flow and transport. Inputs to the flow model include the finite-element grid, initial conditions, lateral boundary conditions, recharge, and material properties for HSUs and faults.

Grid Generation

Simulations of flow and transport (including particle tracking), in 3-D domains representing the complex hydrostratigraphy described in the hydrogeologic models will be conducted on finite-element grids. The grids are discrete interconnected tetrahedra which, when connected together, capture the structure of the hydrostratigraphy. The flexibility of finite elements allows for the resolution of the grid to vary spatially so as to capture contaminant source areas and complex structures such as faults with higher resolution than other areas where coarser discretization is sufficient.

A process for transferring hydrogeologic framework model information from an EarthVision[®] model (Dynamic Graphics, 2002) to inputs required by the grid generation software Los Alamos Grid Toolbox (LaGriT) (George, 1997) has been developed, tested, and applied to development of the Pahute Mesa CAU flow model. Calibration efficiency can be increased by keeping the flow model grids coarse, then adding higher resolution to source regions and plume pathways for the transport simulations.

Flow Model Calibration

Calibration consists of determining model parameter values such that simulated heads and fluxes are consistent with observed or target values. The input parameters for the CAU flow model will include the permeabilities of the HSUs and faults in the model domain and fluxes through the top of the model estimated as recharge. Specified observations for the CAU model will include hydraulic heads measured in wells within the model domain and fluxes through lateral model boundaries calculated using the NTS regional flow model. These data provide “targets” for the calibration process. Analysis of geochemical data may be reserved for subsequent model verification to provide independent lines of evidence to support parameters leading to the prediction of groundwater flow and transport.

Sensitivity Analyses

Sensitivity analysis is a systematic process of varying the magnitude of model inputs such as hydraulic conductivity, recharge, and boundary conditions and determining the effect on model outputs such as hydraulic head and flux. Sensitivity analyses conducted during model calibration help identify parameters that have the greatest influence on the variance of model results.

Model Documentation

Documentation for the Frenchman Flat CAU model will include:

- Identification of all components, inputs, and assumptions of the analysis
- Justification of assumptions, simplifications, and parameter ranges and distributions used
- Description of all uncertainties
- Identification of the results of sensitivity analysis

- Description of major alternative model formulations and sensitivity of results to alternatives
- Documentation of final model sufficiently detailed to allow replication of modeling and calculations
- Identification of all significant limitations of the model
- Description of all significant conclusions, limitations, and insights

Data Requirements

Specific data types needed to simulate groundwater flow are: geologic data, hydraulic head data, groundwater recharge estimates, discharge estimates, hydraulic conductivity estimates, and groundwater chemistry data. These data types are the subject of *Phase II Hydrologic Data for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada* (SNJV, 2004e).

3.4 FF Phase II Contaminant Transport Modeling Approach and Data Requirements

This section describes the approach used for modeling the transport of contaminants in the groundwater flow system in the Frenchman Flat area. The associated data requirements are also described.

3.4.1 Modeling Approach

The CAU transport model will be built upon the groundwater flow model using the contaminant transport capabilities of the FEHM code (Zyvoloski et al., 1997). The CAU transport model will then be used to simulate the transport of radionuclides in the aquifer system of Frenchman Flat for the 1,000-year timeframe. The objectives and modeling process are briefly described.

3.4.1.1 Objectives

Using the CAU transport model, concentrations of radionuclides will be calculated for specified points located downgradient from the underground nuclear tests of Frenchman Flat. Simulated concentrations will then be used to estimate the location of the contaminant boundary as defined in the FFACO (1996, 2000).

3.4.1.2 Transport Modeling Process

The transport modeling process will consist of the following steps:

- Identifying radionuclide transport processes at work
- Designing a simulation strategy
- Conducting transport model simulations
- Conducting sensitivity analyses
- Conducting uncertainty analysis

Transport Processes

The Frenchman Flat CAU transport model will need to account for the following processes:

- Advection and dispersion of solutes in the saturated groundwater flow system
- Diffusion of solutes from fractures into matrix material
- Retardation of radionuclides on alluvium and fracture minerals
- Enhanced mobility of contaminants due to colloids
- Retardation of colloids via filtration and attachment to alluvium and fracture walls

Simulation Strategy

The strategy for simulating the transport of radionuclides at the CAU scale will include both a fully-coupled reactive transport methodology for testing concepts, and an abstraction model based on streamline particle tracking. The fully-coupled model will be used to investigate process sensitivity and design parameter ranges for the more efficient particle-tracking model. The particle-tracking model will be suitable for the multiple simulations needed to investigate multiple geologic interpretations and ranges of uncertainty of all other groundwater flow and transport parameters.

Saturated zone transport can be simulated with continuity equations on a finite-element grid, with discrete particle-tracking techniques, or with continuity equations along 1-D grids, mapped to coincide with particle pathways in a 3-D flow field.

Solving the continuity equations in 3-D or along 1-D pathways allows for the greatest flexibility in specifying reactive processes. Fully coupled kinetic and equilibrium reactions describing multicomponent, aqueous-aqueous, and aqueous-solid reactions can be accommodated with a dual-porosity methodology suitable for capturing fracture-matrix interactions. However, such simulations are computationally demanding and may not be appropriate for CAU-scale simulations, particularly when uncertainty is addressed with Monte Carlo-type simulations. Such an approach is useful for testing concepts. Although slightly

more limited in the reactions that can be addressed, the 3-D streamline particle-tracking transport algorithm is significantly more efficient than finite-element solutions of the continuity equations.

The particle-tracking model is a full-, single- or dual-porosity method for simulating transport in porous and fractured rock. It can be used to simulate either single- or dual-porosity transport with: (1) diffusion into the matrix, (2) radionuclide retardation on alluvium and matrix/fracture minerals, and (3) radionuclide reaction with minerals. Fracture properties such as aperture, spacing, and reactivity can vary spatially as can matrix reactivity.

The limitation of the particle-tracking solver compared to the continuity equation solver is that solute-solute reactions cannot be simulated with the particle-tracking model. This means that an abstraction of complex processes such as contaminant-colloid reactions must be developed prior to the simulations. Such an abstraction can be developed with a limited number of simulations of the complete set of continuity equations. It involves identifying the transport parameters associated with a new species (e.g., plutonium-colloid). These parameters govern the retardation and the maximum aqueous concentration. The new species can then be simulated independently, and somewhat conservatively relative to the fully-coupled model. Another limitation of the particle-tracking model is that it is incapable of considering kinetic sorption processes and rate-limited filtration of colloids. Thus, an abstraction will use the fully-coupled process model to justify equilibrium retardation factors for such processes as colloid attachment and detachment to fracture walls, while maintaining conservatism.

Radionuclide Transport Simulations

Deterministic transport simulations will be conducted to predict the movement of contaminants in the groundwater.

First, the finite-element mesh used in the CAU flow model will be evaluated to determine the necessity of further grid refinement around the contamination sources and within the plume domains. Reducing the lateral extent of the model for the purposes of evaluating transport will be assessed. Simple advective particle-tracking simulations using the calibrated CAU flow model will aid in the determination of the appropriate scale for the simulated plumes. Second, a limited number of simulations will be conducted using the finite-element, dual-porosity, reactive transport module (most likely 1-D because of computational limitations) to develop abstractions of complex processes. These simulations will be used to condition and validate parameters that will be used in the dual-porosity, streamline, particle-tracking module of FEHM. They will also be used to condition and validate conceptual models. Third, predictive simulations will be made using the dual-porosity, streamline, particle-tracking module of FEHM.

Important inputs for the transport simulations are: (1) groundwater flux distribution from the flow model, (2) transport parameter distributions, and (3) integrated-source release model parameters from the hydrologic source term modeling.

Sensitivity Analyses

Sensitivity analyses will be performed after the deterministic part of the contaminant transport model is completed. The objective of the sensitivity analyses is to assess the response of the predicted concentration values and contaminant boundary as a result of changes in input parameter values. Results of the sensitivity analyses may also help define monitoring locations and the type of data to be collected for the monitoring network design.

Uncertainty Analyses

Uncertainty analyses will follow the sensitivity analyses. The purpose of these analyses is to quantify the level of uncertainty associated with the CAU-modeling results. The uncertainty of the predicted contaminant concentrations and the location of the contaminant boundary is caused by the uncertainties in the conceptualization of the geologic system and the parameter data used to build the CAU flow and transport models. Transport model result uncertainties caused by uncertainties in the HSU model, calibrated flow model, HST, transport parameter values, or boundary conditions will be evaluated.

The approach to quantifying the uncertainty in the HST and transport parameter values is via the Monte Carlo approach. One Monte Carlo realization will consist of a set of input parameters sampled from their respective probability distributions, and a simulation using FEHM. The probability distribution of model response (contaminant concentrations) is determined from the simulations and provides an assessment of uncertainty in the model predictions. The Monte Carlo method can provide a quantitative measure of the uncertainty in the location of the contaminant boundary.

The contribution to output uncertainty (variance) by an input is a function of both the uncertainty of the input parameter and the sensitivity of the output to that particular input. In general, input parameters identified as important in global sensitivity analyses have both characteristics: they demonstrate significant variance and are characterized by large sensitivity coefficients. Conversely, parameters that do not show up as important per these metrics are either restricted to a small range in the probabilistic analysis, and/or are parameters to which the model outcome does not have a high sensitivity.

Assessment of sources of uncertainty that cannot be described via a probability distribution will be included in a different manner. For example, the alternative interpretations of the HSU model will actually be evaluated using separate models. In this case, the simulation of contaminant concentrations for each alternative provides a quantitative change in a measure, such as the contaminant boundary. Other sources of uncertainty that cannot be described by a probability function will be treated in a similar manner.

3.4.2 Data Requirements

A wide variety of data types are required to simulate radionuclide transport in the groundwater system. The data types needed for the contaminant transport model

include the hydrologic source term and transport parameters including effective porosity, dispersivity, radioactive decay coefficients, distribution coefficients, matrix diffusion coefficients, matrix porosity, a description of the fracture geometry, and a description of colloid-facilitated transport.

Hydrologic Source Term

Potential contaminant sources are the 10 test locations in Frenchman Flat. One of the tests (CAMBRIC) was conducted 77 m below the water table and the other nine tests were located from 15 to 62 m above the water table. Nine of the tests were conducted in alluvium and one test was conducted in the volcanics. In addition, the CAMBRIC RNM distributed contaminants from CAMBRIC Test over an area larger than the original source. Well RNM-2s, completed in south-central Frenchman Flat, was pumped from October 1975 to August 1991 at an average rate of 23 million gallons per month. The pumped waters, containing contaminants from the nearby CAMBRIC test, were discharged to a ditch. The contaminated water seeped to the subsurface from the base of the ditch and from the playa area where the ditch ended.

Two hydrologic source-term datasets will be defined for Frenchman Flat. One source term will be based on unclassified data and will be extrapolated to all underground tests on Frenchman Flat. Later, a classified dataset (based on information from individual tests) will be used to calculate the final location of the contaminant boundary. The radiological and hydrological source term available for modeling in Frenchman Flat (Tompson et al., 1999) consists of the unclassified data from CAMBRIC. More detailed discussion and information on the HST and radionuclide data for Frenchman Flat will be documented in separate reports.

For the unclassified data, the source of radionuclides for the CAU transport model will be abstracted release functions from the underground nuclear test. These will be in the form of mass flux versus time at either: (1) the working point of the tests or (2) the intersection of aquifers with the cavity/chimney systems associated with the tests. For a summary description, see [Section 2.0](#) of this document. For more details, see the unclassified hydrologic source term and radionuclide data report (Tompson et al., 1999).

Transport Parameters

Parameters needed to simulate the radionuclide transport processes at work in the Frenchman Flat flow system include effective porosity, dispersivity, radioactive decay constants, distribution coefficients, matrix diffusion coefficients, matrix porosity, description of the fracture geometry, and colloid-facilitated transport parameters. A general description of the various transport parameters and the approach to developing parameter distributions is given in [Section 4.0](#).

Observed Radionuclide Data

Measurements of radionuclide concentrations in groundwater samples may be useful in evaluating the CAU-model predictions. These data may be used to calibrate the transport model and/or provide further confidence in the simulations. Evidence of radionuclide migration away from test locations, such as was observed during the long-term pumping near the CAMBRIC location, could be compared with simulated results of the CAU model.

4.0 Data Analysis

Data analysis is the process of compiling, assessing, and interpreting available data in preparation for CAU groundwater flow and transport modeling. The data needed for CAU modeling includes a wide variety of types, from numerous sources, that represent a wide variety of measurements and scales of measurement. The process of analyzing the data can be summarized in the following six steps: (1) compilation of existing data for the FF investigation area, (2) transfer of applicable data from outside the FF area, (3) assignment of data quality indicators, (4) assessment of data representativeness and appropriateness for use in CAU modeling, (5) data reduction and analysis, (6) graphical and tabular presentation of results, and (7) discussion of data limitations and the possible impacts to the CAU groundwater flow and contaminant transport model. This document presents data analysis and results used to support the development of a CAU-scale groundwater flow and transport model.

4.1 Data Compilation

The compilation of existing data is a multiple step process of determining needed data, identifying and acquiring available data, and compiling the data into structured databases. As discussed in later sections of this document, certain data types required for CAU modeling are derivative, determined by processing more basic data using models specifically developed for the purpose (e.g., sorption models used to develop sorption coefficients). Data types of interest and data sources are discussed in the following sections.

4.1.1 Data Types

General descriptions of the various types of information needed for modeling are provided in the following sections. The descriptions are followed by explanations pertinent to the different transport parameters of interest to the FF CAU model.

4.1.1.1 Description of Transport Data Types

Information needed to support CAU contaminant transport modeling include porosity (matrix and effective), dispersivity, matrix diffusion, contaminate-rock sorption parameters, and colloid-facilitated transport parameters. Following are brief descriptions of each data type.

Porosity

As stated previously, effective porosity and matrix porosity are required parameters in the CAU models. Porosity, however, can be defined in several different ways depending on the application (Freeze and Cherry, 1979; de Marsily, 1986).

Total Porosity

The total volume of void space divided by the total volume of rock. No other porosity measure can exceed the total porosity.

Bulk Porosity

The bulk porosity is a total porosity measurement and for the purposes of the CAU model can be treated as total porosity. In fractured units, for example, bulk porosity is a sum of matrix and fracture porosity.

Effective Porosity

Also called kinematic porosity by de Marsily (1986), effective porosity is the specific discharge (volumetric flow rate divided by cross-sectional area) divided by the mean flow velocity within a representative elemental volume. From the perspective of transport, adhesive water, dead-end pores, isolated pores, or any other water that does not actively move needs to be excluded from the effective porosity. As a result, the effective porosity is always smaller than the total porosity. As noted above, effective porosity is a key parameter governing the velocity of water, and associated radionuclide migration in the groundwater system.

Fracture Porosity

In fractured geologic units, faults, fissures, cracks, joints, and bedding planes form a complicated network of interconnected planar features through which groundwater flows. Often, the majority of groundwater flow is through the fracture network and not through the matrix material separating the fractures. At the scale of the CAU models, this network of planar features will be modeled as an equivalent porous media characterized by an effective porosity.

Matrix Porosity

The matrix material between fractures is porous. In many cases, the porosity of the matrix is several orders of magnitude larger than the fracture porosity. Although the flow through the matrix is often much smaller than through the fractures, the vast majority of the water volume is in the matrix. Matrix porosity is comprised of effective flow porosity, transport storage porosity, and disconnected storage porosity. If the volume of isolated pores (disconnected storage porosity) in the matrix is small, matrix porosity can become important via the diffusion of solutes between fractures and matrix. In many instances, the total porosity is a good approximation of the matrix porosity.

Dispersivity

The hydrodynamic dispersion of solutes (or particles) in groundwater describes the spreading phenomenon at a macroscopic level by the combined action of mechanical dispersion and molecular diffusion. Dispersion results in transport distances that are greater than those caused by advection alone. The effect of dispersion is quantified and measured in terms of the mechanical dispersion coefficient or dispersivity. The mechanical dispersion coefficient is defined as

$$D_{ij} = A_{ij}v \quad (4-2)$$

where:

- D = Mechanical dispersion coefficient
- A = Macrodispersivity
- i, j = Coordinate directions
- v = Porewater velocity

In the general case, the dispersivity and the dispersion coefficient are second-rank tensors. In most applications, however, only the diagonal terms of the tensor are used.

Matrix Diffusion Coefficient

In fractured rock systems where the primary pathway for groundwater flow is through the fractures, the matrix material is saturated with groundwater that is considered immobile for the purposes of modeling. The amount of immobile water in the matrix is governed primarily by the matrix porosity. In many fractured aquifers, the matrix porosity may be 10 or more times larger than the fracture porosity. Thus, although the bulk of the water travels through the fractures, a very large reservoir of water in the matrix can act to store contaminants temporarily via a process called matrix diffusion. If a contaminant diffuses into the matrix for a period of time, it effectively stops moving relative to the water in the fracture. Therefore, matrix porosity and the matrix diffusion process are necessary for successful modeling of contaminant transport in fractured aquifers of the CAU model.

As noted above, matrix diffusion is one of the parameters that govern the transport of contaminants in fractured aquifer systems. The matrix diffusion coefficient describes the rate at which a particular contaminant will diffuse into the nearby rock matrix. If there are no physical barriers to diffusion, the diffusion coefficient is a function of the diffusion coefficient of the molecule in free water which is primarily related to the size of the molecule. In real aquifer systems, the diffusion coefficient definition is complicated by physical and chemical factors at the fracture matrix interface such as fracture coatings, which may have different chemical constituents than those found in the matrix, thereby possibly increasing or decreasing the number of radionuclides capable of diffusion into matrix pore spaces.

Matrix and Fracture Sorption Parameters

Contaminant sorption is a general term describing a variety of chemical processes that bind (temporarily or permanently) contaminants to rock material. The rock material may be the matrix or fracture minerals. Often this chemical binding is treated mathematically via an equilibrium approach where the amount of contaminant stored on the rock is a function of the concentration in the water. The transfer from the water to the rock is assumed to occur instantaneously and is completely reversible. Matrix diffusion acts to slow the migration of the contaminants with respect to the flowing groundwater. Therefore, sorption acts to temporarily store contaminants and slows the migration of the contaminants with respect to the flowing groundwater.

In the equilibrium approach, the sorption is represented by a distribution coefficient, K_d , defined by the relationship:

$$S = K_d C^b \quad (4-3)$$

where:

- S = Mass of the contaminant adsorbed on the solids per unit bulk dry mass
- C = Contaminant concentration as mass per volume of water
- K_d = Distribution coefficient
- b = Exponent

In many cases, the exponent, b, is set to 1, which leads to a linear adsorption isotherm. Sorption may also be accounted for using retardation factors (R parameters) in the solute transport equation.

Colloid-Facilitated Transport Parameters

Colloids are defined as small particles (less than 1 micrometer) comprised of either organic material or inorganic mineral fragments and secondary minerals of the host rock. Oxides and hydroxides of actinide elements (e.g., plutonium) can also form as colloids (Kersting et al., 1998). Migration of a given nuclide sorbed onto colloids in flowing groundwater is more rapid than that of the same nuclide in solution. Parameters needed to represent colloid-facilitated transport include colloid types, concentrations, and size distribution; radionuclide sorption/desorption rates onto colloids; and colloid filtration rate constants.

4.1.1.2 Supporting Information

The following types of supporting information for each data type and/or data entry are recorded in the documentation, where applicable and available:

- Identification and location information
- Physical information on the location
- Sample information

- Chemical constituents
- Method of data collection or type of test
- Scale of measurement
- Date of data collection
- Stratigraphic unit
- Lithology
- Alteration
- Hydrostratigraphic unit
- Method of data analysis
- Observed parameter value
- Parameter spatial distribution
- Uncertainties
- Any references relating to the data records
- Any noted deficiencies

References to the specific sources of information are provided along with the data. A general description of the data sources is provided in [Section 4.1.2](#).

4.1.2 Data Sources

A great many sources for the data have been identified. Historic data are available in many publications. Much of this data was incorporated in databases developed as part of the NTS regional groundwater flow and transport modeling (DOE/NV, 1997), which were supplemented with additional data compilation that supported the development of the FF CAIP and Addendum (DOE/NV, 1999a and 2001). The data considered in the FF Phase I Data Report have been supplemented with new data collected through UGTA field investigations (conducted in accordance with the FF CAIP Addendum) and additional existing data not previously incorporated.

Data for the Frenchman Flat Area come from numerous organizations including BN, LLNL, LANL, DRI, USGS, SNJV, and the University of Nevada, Las Vegas-Harry Reid Center for Environmental Studies. A large amount of historic data had been gathered under the auspices of previous NTS Management and Operating (M&O) contractors Reynolds Electrical & Engineering Co., Inc. (REECO), Fenix & Scisson (F&S), Holmes & Narver, Architect and Engineer (A&E) contractors (Raytheon), and Environmental Restoration (ER) contractors (IT Corporation and Shaw Environmental).

FF-Specific Data

Data collected from within the FF study area or, more restrictively, from within the FF CAU geologic model area ([Figure 1-2](#)), depending upon the data type and usage, are classified as FF-specific data. These data are directly applicable to the FF CAU and data analysis.

NTS Investigation Area Data

Data and analyses for the NTS and vicinity investigation area are incorporated where applicable. This primarily includes data from other CAUs that have direct

relevance or transferability to FF. The use of this transferred data is discussed and justified in this document.

Yucca Mountain Data

Yucca Mountain is the proposed geologic storage location for commercial and defense high-level radioactive waste in the United States. A great deal of high-quality data has been collected and analyzed during investigations of the Yucca Mountain Site. The Yucca Mountain Project (YMP) is located adjacent to the southern edge of the Pahute Mesa (PM) investigation area. The volcanic geology in the YMP region is similar to the volcanic geology in some HSUs present on Frenchman Flat, but not exactly the same. A process was developed to assess the transferability of YMP data for use in the PM CAU model and further documented in a technical basis document (TBD) (SNJV, 2004g). Some data were incorporated by identifying an equivalent regional HSU and then transferring to the FF CAU through a crosswalk based on similar HSU characteristics ([Section 2.0](#)).

Other Data

Data from more distant locations have been incorporated in the analysis for select purposes. The use of such data is explained and justified in the discussion of data analysis for the particular data type.

4.2 Data Transfer Methodology

It has been proposed that using data from other sites to reduce flow and transport parameter uncertainty is an appropriate approach when developing large-scale models (Freeze et al., 1990), such as that of the FF area. This type of approach incorporates flow and transport parameter data from investigations of similar environments for parameters to be used in modeling of the study area. Utilization of data from other sites can be both a cost-effective and necessary step for a modeling effort. Nearby sites considered as sources of additional data for the Frenchman Flat CAU are other UGTA CAUs, Yucca Mountain, Beatty Low-Level Waste Facility, and sites worldwide where tracer studies have been conducted. Rock genesis and evolution factors that influence flow and transport parameters, general transfer methodology, and the transfer of YMP data are described in this section.

The TBD for data transferability (SNJV, 2004g) was issued in June 2004. It provides a comprehensive discussion of requirements and methodology for data transfer. This document has been incorporated in the FF data analysis process where applicable.

4.2.1 Genesis and Evolution Factors Influencing Flow and Transport Parameters

Numerous factors may influence the flow and transport of groundwater in the subsurface environment in a variety of ways. This section focuses on rock genesis and evolution factors which influence rock characteristics and, therefore, flow and

transport parameters. These factors include the overall geologic history of the area, lithology, alteration, stress history, and groundwater chemical composition.

Geologic History

The geologic history of an area has a significant impact on the flow and transport of groundwater. For example, the depositional environment of a rock can influence things such as the primary porosity of sedimentary rocks or the texture of volcanic rocks. In addition, subsequent structural episodes may increase faulting in a given area that could lead to increased groundwater flow.

Lithology

The specific rock type of a study area has an important impact on the flow and transport of groundwater. Alluvial materials ranging in texture from fine sand to coarse gravels that are well sorted would obviously have different hydraulic properties than an indurated, non-fractured carbonate rock.

Alteration

The alteration of a given rock can play a large factor in the flow and transport of groundwater in the subsurface environment. For example, the formation of zeolitic material in volcanic tuffs can greatly decrease the permeability of a given formation by directly affecting the fracture geometry.

Groundwater Chemical Composition

Groundwater chemistry can play an important role in the flow and transport characteristics of a groundwater flow system. It can have a large impact on everything from mineral dissolution and precipitation reactions to fracture geometry. For example, mineral precipitation or dissolution reactions may govern the rate and extent of radionuclide sorption by changing the availability of ligands available for aqueous complexation reactions in the system.

Transfer Methodology

The use of flow and transport data from other study areas to develop parameter distributions for flow and transport modeling of UGTA CAUs can be justified by examining specific similarities that may exist between various investigation areas. It must be shown that there is a sufficient similarity that exists between the two areas, taking into account the various factors mentioned in the previous subsection. A general approach for the transfer of data from one area to another was used based on the following strategy:

- For each parameter of interest, sites are identified that may contain data of the same type. Under ideal conditions, sites could be found in the same general area that have roughly the same geologic setting. More likely, however, sites will be identified that are located farther away but have similar types of rocks. Under less desirable conditions, data may have to be transferred from locations that have no similarities at all to the original study area other than data was collected there for the specific parameter of interest.

- Once the source of the flow and transport parameter data are identified, the factors affecting the specific parameter need to be clarified. If it can be shown that only one factor influences a given parameter, it may make the transfer of data easier to justify. For example, if it can be shown that a parameter is only influenced by lithology, then a comparison of the lithologies of the two HSUs involved in the data transfer would suffice to make a decision.
- Finally, if sufficient data are present in the original study area, a statistical comparison can be made of the data from the other area to see if the two datasets are comparable. If it can be shown that the two datasets have comparable distributions, it would provide further justification for the incorporation of the data into the existing dataset.

4.2.2 YMP Data Transfer

The Yucca Mountain Site Characterization Project has implemented one of the largest hydrologic and geologic characterization studies of volcanic rocks ever conducted. The proximity and similar hydrogeologic environment of the Yucca Mountain Site to Frenchman Flat make it particularly relevant as a source of data for hydraulic properties for similar FF HSUs. A detailed rationale for the transfer of data from the YMP was provided in a technical basis document (SNJV, 2004g). The use of this transferred data was more prominent for Pahute Mesa, and applies to FF primarily with respect to data incorporated in the sorption analyses for the Regional HSUs within the NTS investigation area. A brief summary of the justification for data transfer is presented here:

- Both areas are located in the SWNVF.
- Volcanic rocks in both areas are the result of similar depositional processes.
- Both areas contain similar lithologic units and even lithologic units from the same source area.
- Both areas have experienced similar types of alteration including devitrification and zeolitization of volcanic material.
- Both areas have undergone similar types of regional tectonic stresses resulting in a similarity in the two areas regional fracture orientations.
- Both have similar groundwater chemistry.

As a result of the two areas similarities, the use of flow and transport parameter data from the Yucca Mountain area can be justified in helping to develop parameter distributions for the FF modeling effort. Note that the data are actually transferred on an HSU-by-HSU basis. In others words, data for a given parameter are transferred only between HSUs that have relevant and similar characteristics.

4.3 Qualification of Data and Data Documentation

During evaluation of data for use, both the quality of the documentation for the data source and the quality (suitability) of the data for use are evaluated. These subjects are discussed in detail in the Data Transferability TBD (SNJV, 2004g). The TBD was used for data transfer for the appropriate data analyses in this document; however, dispersivity parameters used a previously established approach.

4.3.1 Data Documentation Qualification

Data documentation provides information on the traceability (or pedigree) of the data. Typically, data collected in the recent past has much better documentation than data collected and reported many years ago. Qualification of the documentation of the data makes it easier to investigate and evaluate the quality of the data used in modeling.

Each data record of a given dataset was assigned a data documentation evaluation flag (DDE_F) value to indicate the level of documentation available for that data record. The process of data qualification ensures that the pedigree of the data is retained for database users. However, it is important to note that the data qualification does not indicate the usefulness of data for Frenchman Flat modeling. Historic data, while often poorly documented by today's standards, are often of high quality and extremely useful in the CAU investigations.

The five levels of data documentation evaluation flags are as follows:

Level 1

Data are collected in accordance with NNSA/NSO Environmental Restoration Project (ERP) QAPPs, approved State of Nevada procedures, and/or participant-specific procedures. This ranking indicates that all supporting documentation for the data is on file and available for review by data users.

Level 2

Data are collected in accordance with approved plans and procedures as required for Level 1, with the exception that one or more documentation requirements may be deficient in some way. Examples of data documentation deficiencies may include lost or destroyed field-data collection forms or data acquired using interim or draft procedures.

Level 3

Data are collected using accepted scientific methodology (e.g., American Society for Testing and Materials [ASTM]), U.S. Environmental Protection Agency [EPA] methods, USGS procedures) and accompanied by supporting and corroborative documentation such as testing apparatus diagrams, field or laboratory notes, and procedures.

Level 4

Data are collected by a participating NNSA/NSO ERP organization or another organization not associated with the NNSA/NSO ERP prior to the issuance and implementation of project-approved standard policies, procedures, or practices governing data acquisition and qualification. The methods of data collection are documented and traceable; however, the validity of data use or compliance with reference procedures is indeterminate. Supporting documentation may or may not exist.

Level 5

Data are obtained under unknown, undesirable, or uncertain conditions. When data documentation is unknown, any available supporting or helpful descriptions of the intended use and conditions of data capture should be described.

4.3.2 Data Quality Evaluation

The data qualification process varies depending on the type of parameter. The criteria used to evaluate the different types of required data are dependent on the type and the intended use of the data. Thus, various criteria are used to assess data quality. The general procedure includes assigning one or more data quality evaluation flags (DQE_F) to each record or group of records compiled in the dataset, indicating the data quality or suitability of the individual data record for the intended usage. The data quality evaluation flags and their definitions depend on the data type. Data-type specific quality evaluation procedures are described in corresponding sections of this document.

4.4 Analysis Methods Used

Methods of analysis used vary depending on the type of transport data considered. See the approach subsections of the analysis sections for information on the specific methods used.

4.5 Data Limitations

Data limitations need to be identified. These limitations may be related to the level of data documentation, the data collection method, the data analysis method, or other factors that may limit confidence in the values. Within the discussion of each dataset, data limitations will be documented.

5.0 Matrix Porosity

The matrix porosity of a geologic medium is a component of the medium's total porosity. The total porosity is the proportion of void space within the total unit volume of the medium at a representative elementary scale. If the medium is porous, the total porosity is equivalent to the matrix porosity of the consolidated medium. Matrix porosity can consist of effective flow porosity, transport storage porosity, and/or disconnected storage porosity. In fractured rock, where a significant permeability contrast exists between fractures and matrix, fracture porosity and matrix porosity distinctly differ, and matrix porosity becomes a distinct component of the total porosity. In this case, the matrix porosity provides a secondary component of porosity (relative to the primary fracture porosity) that is equal to the total void volume within the consolidated matrix divided by the total volume of the matrix at a representative elementary scale. If the proportions of effective flow porosity and/or transport storage porosity in the matrix are large, then the matrix porosity can have a significant impact on transport via diffusive processes.

The objective of this section is to assign a probability distribution of matrix porosity to each Frenchman Flat HSU for use in a CAU-scale flow and contaminant transport model. [Section 5.1](#) discusses the role of matrix porosity in contaminant transport and the methods of porosity measurement. [Section 5.2](#) presents the datasets compiled and the rationale by which the data are evaluated. The data evaluation is presented in [Section 5.3](#). The matrix porosity distributions for each HSU are provided in [Section 5.4](#). Each distribution includes information on the role of matrix porosity with respect to whether the HSU is a porous or fractured medium.

5.1 Role of Matrix Porosity in Contaminant Transport

The role of matrix porosity depends on whether the geologic medium is porous or fractured.

In porous media, water movement occurs through the rock matrix. The flow measured through the network of interconnected pores is a measurement of the effective flow porosity. If the pores are well connected (i.e., if transport storage porosity and disconnected storage porosity are small), the measured effective flow porosity can be used to estimate matrix porosity. Such an estimate of matrix porosity is expected to be slightly less than the total porosity that would contain some volume of isolated pore space. If the medium is poorly connected and effective porosity is small, a large component of the matrix porosity is comprised

of transport storage and/or disconnected storage porosity, in which case diffusive transport would dominate.

In fractured rock material, the portion of the medium that is not fractured is considered the matrix. Under saturated conditions, flow of water is primarily through the interconnected fracture network. The volume of rock that comprises fractures is a small percentage of the total rock volume; the matrix comprises the majority of the rock volume. In this case, the total porosity and matrix porosity are nearly equivalent. The large reservoir of water in the matrix can be extremely important to radionuclide migration. If matrix pores are well connected through both advective and diffusive pathways, a higher radionuclide concentration in fracture water may cause the migration of the radionuclide into the matrix, effectively slowing the rate of transport relative to groundwater flow. The matrix porosity, coupled with the matrix diffusion coefficient, controls the rate of diffusion into and out of the matrix.

5.2 Data Compilation

Matrix porosity data are widely available from boreholes in Frenchman Flat. This section discusses the types of measurements and sources from which the porosity data are derived. The data are evaluated for quality and representativeness of Frenchman Flat hydrogeology. In the case that HSU-specific data are not available from Frenchman Flat, representative data from other areas of the NTS and vicinity are transferred according to an established protocol (SNJV, 2004g). In general, this section presents the compilation and preparation of the matrix porosity data for their evaluation and analysis in [Section 5.3](#) and [Section 5.4](#).

5.2.1 Data Types

Matrix porosity data are available from the analysis of borehole geophysical logs and borehole core samples. The large majority of the data are obtained from geophysical logs.

The measurement methods for geophysical log-derived data are described in detail in Attachment A, Section 2.0 of the document *Transferability of Data Related to the Underground Test Area Project, Nevada Test Site, Nye County, Nevada* (SNJV, 2004g). The measurement methods utilized for the collection of data presented in this section include gamma-gamma logs, neutron logs, acoustic velocity logs, gravimetry logs, and resistivity logs. Each method measures a direct property of the rock formation (e.g., water content) that is used to indirectly estimate the porosity of the volume tested. Total porosity is estimated from the gamma-gamma, neutron, acoustic velocity, and gravimetry logging methods. As discussed in [Section 5.1](#), the matrix porosity is some fraction of the total porosity, the degree to which depends on how fractured, if at all, the medium is. The resistivity logging method provides an indirect measurement of interconnected porosity (the sum of effective flow porosity and transport storage porosity). In porous media, the interconnected porosity differs from the matrix porosity only by

the disconnected storage porosity. In fractured media, the interconnected porosity differs from the matrix porosity by both the fracture porosity and disconnected storage porosity. The sample radius of investigation for the geophysical methods, from the borehole out into the formation, ranges from a few inches to about one foot. Although gravimetry logging has a radius of investigation on the order of tens of meters, the method was rarely utilized during Frenchman Flat logging surveys.

The above-described geophysical methods, with the exception of resistivity logging, provide total porosity. The reported total porosity will be the upper-bound estimate of matrix porosity. In porous media, the total and matrix porosity are equivalent. In fractured media, the total porosity is the sum of the matrix and fracture porosity. Fracture porosity is typically less than 1 percent, whereas matrix porosity may be 25 percent or more. Thus, total porosity is also a reasonable estimator of matrix porosity in fractured rock in most cases.

Porosity measurement methods for core data typically involve the measurement of dry bulk density, grain density, and saturated water content in the laboratory. A discussion of laboratory core measurement is also presented in Attachment A, Section 2.0 of SNJV (2004g). In general, core-derived measurements provide the best estimates of matrix porosity in both porous and fractured media if the sample is at least as large as the matrix representative elementary volume. However, in unconsolidated media (e.g., alluvium), grain radii can range in size from microns to meters, and the sample volume will be, in general, too small to accurately measure matrix porosity. Accordingly, estimates of matrix porosity in unconsolidated media may be highly spatially variable depending on the degree of grain size heterogeneity and anisotropy. Other sources of uncertainty related to core laboratory measurement are incomplete saturation of the sample (underestimate of matrix porosity) and unconsolidation of the sample resulting from both physical disturbance and reduced lithostatic confining pressure in the laboratory (overestimate of matrix porosity).

5.2.2 Data Sources

The porosity dataset is compiled from a large number of publications that report porosity measurements made in Frenchman Flat boreholes or on borehole core samples. The data are current to the end of FY 2003. The porosity data per borehole are categorized with respect to Frenchman Flat HSUs for analysis. Certain Frenchman Flat HSUs were not sampled in any borehole. In this case, the compiled dataset is supplemented with HSU-specific matrix porosity data from the Pahute Mesa CAU¹. The Pahute Mesa data were selected for two reasons. First, corresponding HSUs between Frenchman Flat and Pahute Mesa have been identified as the same or similar with respect to hydrogeologic characteristics (e.g., rock type, deposition, and alteration history). [Table 2-3](#) and [Table 2-4](#) listed

1. Matrix porosity data representative of the Frenchman Flat WCU and VCU HSUs (see [Table 2-3](#) and [Table 2-4](#)) were not measured in Frenchman Flat boreholes and are not defined at Pahute Mesa. Both the WCU and VCU are composed of the TCU HGU; therefore, the UTCU and LTCU HSUs from Frenchman Flat should be used to represent matrix porosity in these units.

the Frenchman Flat HSUs and their corresponding HGU(s) and lithologic descriptions. [Table 5-1](#) provides a geologic crosswalk developed for matrix porosity between Frenchman Flat and Pahute Mesa HSUs (BN, 2004a). Second, the Pahute Mesa data provided a practical source. Pahute Mesa matrix porosities were compiled and published in FY 2003 for the UGTA project (Shaw, 2003a); therefore, the data compilation, evaluation, and quality assurance requirements were pre-completed. The complete matrix porosity datasets, including local Frenchman Flat and transferred Pahute Mesa data, are electronically documented and described in detail in [Appendix D](#).

**Table 5-1
Matrix Porosity Crosswalk between Pahute Mesa
and Frenchman Flat HSUs and HGUs**

Frenchman Flat HSU	Frenchman Flat HGU	Pahute Mesa HSU	Pahute Mesa HGU
AA	AA	AA	AA
OAA	AA	not present	
PCU2T	PCU	not present	
PCU1&U	PCU	not present	
BLFA	LFA	YVCM	LFA, WTA, VTA
TM-WTA	WTA	TMA	WTA
TM-LVTA	VTA	PVTA	VTA
UTCU	TCU	UPCU	TCU
		LPCU	TCU
LTCU	TCU	CFCU	TCU
		BFCU	TCU
		PBRM	TCU, WTA, LFA
TSA	WTA	TSA	WTA
WCU	TCU	not present	TCU, LFA
VCU	TCU	not present	TCU, AA
LCA3	CA	LCA3	CA
UCCU	CCU	UCCU	CCU
LCA	CA	LCA	CA
LCCU	CCU	LCCU	CCU

5.3 Data Evaluation

The matrix porosity data are derived from a variety of different sources, represent a suite of measurement methods, and include measurements from outside of the Frenchman Flat investigation area. It is important to normalize the data before

their analysis, effectively removing the relative emphasis of these factors on the porosity values (see [Appendix B](#) for a general description). A scoring system, utilizing data weights and multipliers, is applied to accomplish this. A detailed description of the protocol for assigning a weight and multiplier to each matrix porosity datum is presented in Attachment A, Section 4.0 of SNJV (2004g). The protocol is explicit and was not modified for this application. A brief summary of the method is presented below.

Each matrix porosity datum is first assigned a composite weight that is representative of the geologic setting. Three individual and independent sub-weights are assigned per datum that characterize, respectively, the representativeness of the sample rock type, the deposition and alteration history, and the structural setting and mechanical alteration. All sub-weights are defined with respect to the specific HSU of interest. The sub-weights are then summed to determine the composite weight.

Each datum is then assigned a composite multiplier that is representative of three factors: the measurement method, the quality of analysis, and data documentation. A sub-multiplier is assigned for each of the three factors, and the composite multiplier is determined as the product of the sub-multipliers. It is the measurement method sub-multiplier that considers the relative quality (i.e., accuracy, uncertainty, scale of measurement) between core and geophysical methods. An explicit protocol is used to define a datum multiplier based on the measurement method and type medium type.

Finally, an overall score is assigned to each datum, equal to the product of the composite weight and the composite multiplier. The rationale for using both weights and multipliers is that the geologic setting relevance and the data quality, which are independent factors, are independently combined to standardize the data. All weights and multipliers assigned to each matrix porosity datum, for both local Frenchman Flat data and those transferred from Pahute Mesa, are listed in [Appendix D](#). Comments are included when the assignment of weights/multipliers may be uncertain; however, the established protocol was followed to ensure reproducible results. The incorporation of the overall score for each matrix porosity datum into probability distributions for each HSU is presented in [Section 5.4](#).

5.3.1 Comparison of Core- and Geophysical Log-Derived Porosity

Core- and geophysical log-derived matrix porosities apply direct and indirect methods of measurement, respectively. The difference between the methods may introduce a measurement bias. Because the population (true) mean matrix porosity for each HSU is unknown, the bias would be defined as an offset in the mean porosity value between the sample measurement methods, and one method would have to be assumed accurate. Further, errors associated with the geophysical log-derived porosity may be larger than those for the core-derived measurements. It is difficult to assess the influence of measurement precision between the methods because the uncertainty would include components of spatial variability and the difference in sample size.

With the exception of in the alluvium (AA), at no sample locations were measurements of matrix porosity obtained using both core and geophysical methods. Core measurements are typically sampled too shallow in boreholes. Of approximately 9,000 porosity measurements made in the AA, about 20 collocated core-geophysical (gravity log) data pairs (using a 1.5-m window) were collected at UE-5n. Although the difference between the paired sample means is significantly different at both 95 and 90 percent confidence levels, this result is expected; the sample statistics are representative of a small sample (less than 0.5 percent of the alluvium data), are of a limited depth interval (about 400 m), and are located in a HSU that has highly spatially variable hydraulic properties in both lateral and vertical orientations. Although an exact comparison between the measurement methods is not possible for the FF data for all HSUs, a small minority of the FF matrix porosity data (approximately 1 percent) is derived from borehole core measurements ([Appendix D](#)). This implies that any bias that may exist as a result of the different methods is averaged, or smoothed, in the HSU-lumped statistics that are used to define the matrix porosity distribution for each HSU. An analysis of both core- and geophysical log-derived matrix porosities from five Pahute Mesa boreholes showed that there is no significant bias in one measurement method over the other (Shaw, 2003a). The Shaw (2003a) analysis also showed that, in general, an offset did not exist between co-located point measurements with depth.

5.3.2 Variability of Porosity with Depth

The intent of this section is to assign a matrix porosity probability distribution to each Frenchman Flat HSU. A probability distribution does not include spatial components of the measured data (i.e., the distribution and its descriptive parameters do not contain any information describing the spatial variability of first- or higher-order statistics of the measured porosity). HSUs are fundamentally defined such that hydrogeologic properties within each are approximately constant with depth and are continuous; therefore, before the assignment of a distribution per HSU, it is important to confirm that spatial trends do not exist that would act to both bias and increase the apparent variability of the measured and estimated probability distribution. As a result of the spatial orientation of porosity measurements in boreholes, the spatial features of the porosity data are considered in the vertical direction only. Data in the horizontal plane are too sparse for a spatial analysis (see [Section 5.5](#)).

Geologic reasoning would suggest that porosity within HSUs of constant lithology may decrease with depth under greater lithostatic pressure. This rationale is particularly appropriate in the alluvium units. The lithology of these units at the time of deposition can generally be described as highly porous and loosely packed (unconsolidated), and would be expected to consolidate with an increase in overburden pressure. However, each HSU, to some degree, has changing geologic units with depth that interrupt the identification of a depth trend.

[Table 2-3](#) lists the Frenchman Flat HSUs and their corresponding HGU(s) and lithologic description. The descriptions are composite in nature, and it is likely that some portion of the matrix porosity data corresponding to each HSU represents lithologies other than what is described in the table. For this reason, the

depth dependency of porosity is examined for the alluvium HSUs only; the remaining HSUs are too heterogeneous for the assessment of depth trends and, in fact, do not show any depth trends that appear to be independent of lithology. Further, it is important to examine data for Frenchman Flat alluvium because of its unique prevalence with respect to NTS hydrogeology (i.e., the OAA is recognized only in northern Frenchman Flat). Although the matrix porosity borehole profiles for the remaining units are not presented in this section, the data are presented in [Appendix D](#) for completeness and are referred to further in [Section 5.4.1](#).

Alluvium

[Figure 5-1](#) shows the AA matrix porosity plotted with depth for each borehole with measurements. Core data are plotted in [Figure 5-1\(a\)](#), and geophysical log-derived measurements in (b). The majority of the porosity data were measured below the water table at approximately 280 m below ground surface (bgs) (SNJV, 2004e); therefore, the geophysical logging techniques provide applicable data for the study of saturated zone transport (SNJV, 2004g). However, the appropriateness of the geophysical method applications in unconsolidated media require scrutiny. Acoustic velocity log-derived porosities are uncertain in unconsolidated media. The component of the acoustic signal that travels through the rock matrix has a more variable velocity than in consolidated rock because of variations in grain size, cementation, and heterogeneous consolidation of the matrix, that results in a slower apparent acoustic velocity. In some cases, the signal may be attenuated to below the receiver detection limit and velocity cycles skipped, resulting in a lower total porosity estimate (Keys, 1990). Because of this measurement uncertainty within alluvium, the acoustic velocity log-derived porosity data are not included in the alluvium matrix porosity probability distributions ([Section 5.4.1](#)) that are to be used in transport modeling. However, because these data do, effectively, contain useful information (e.g., spatial information), they are included in the analysis of matrix porosity descriptive statistics presented below.

Identification of a matrix porosity depth trend is difficult in the alluvium because of the large sub-meter-scale variability in the data that results from the natural, small-scale variability of the alluvium lithology. In general, depth profiles of matrix porosity in hard rock HSUs do not contain such large magnitude variability at this scale ([Appendix D](#)). Although a detailed analysis of matrix porosity variability (identifying the components of the measurement tool uncertainty, sample support, and natural lithologic features of the alluvium) is beyond the scope of this analysis, it generally concluded that variability results from the unconsolidated, complex nature of alluvial deposits. In support of this conjecture, the core-derived data are shown to have a statistically equivalent variance to that of the geophysical log-derived data; core measurements are considered precise point measurements (although their accuracy may be uncertain if the sample volume is less than one that is statistically representative). Results from the variance comparison using an F-test (Davis, 1973) are listed in [Table 5-2](#). The critical F-statistic is 0.91 and the calculated value is 0.52; therefore, the null hypothesis (i.e., that the samples are statistically equal) cannot be rejected.

The shallow (core) measurements do not show a decreasing trend in matrix porosity with depth. Deeper in the alluvium, below 800 m bgs, a decreasing trend

Figure 5-1
Alluvial Aquifer (AA) Matrix Porosity with Depth

**Table 5-2
F-Test: Two-Sample for Variances**

Porosity (%)	Core	Geophysical Log
Mean	38.52	34.17
Variance	30.20	58.52
Observations	695	7201
degrees of freedom	694	7200
F	0.52	
P(F<=f) one-tail	0	
F Critical one-tail	0.91	

is apparent in the data measured in borehole ER-5-4. However, if the data are viewed as a pooled sample representing multiple boreholes, the measurement trends are not apparent. Therefore, in an effective sense, the AA matrix porosity probability distribution will not be misrepresented by a vertical trend when porosity data are used from multiple boreholes. Recall, also, that the data derived from the acoustic velocity logs are not considered in the AA matrix porosity probability distribution.

A comparison of the shallow (core) and deep (geophysical log) porosity arithmetic means show that matrix porosity in the upper AA is on average higher than that in the lower sections. Descriptive statistics and results from the t-test (Davis, 1973) used to test the hypothesis of equal core and geophysical log mean porosities are shown in [Figure 5-2](#) and [Table 5-3](#). Note that the anomalously low matrix porosity values measured between 600 and 700 m in ER-5-4 correspond to a thin, localized lens of silty/clayey sand that are not representative of the AA as a whole. These data are not included in the comparison of the shallow and deep porosity means ([Table 5-3](#)).

In the OAA, there is no apparent trend in porosity with depth. [Figure 5-3](#) shows the OAA matrix porosity plotted with depth for each borehole measured. In borehole ER-5-3, porosity actually increases with depth, indicating that depositional features in the alluvium probably dominate the effects of compaction and consolidation from overburden pressure and/or zeolitization. The core-derived matrix porosities, although few, have a similar magnitude of variation at small-spatial scales to those porosities derived from the geophysical logs, which again supports the conjecture that the large-magnitude, fine-scale variability observed in the measured matrix porosity reflect the poorly-sorted lithology of the alluvium.

5.4 Development of Parameter Distributions

A probability distribution of matrix porosities is assigned to each HSU, the parameters of which are to be used for sampling (e.g., Monte Carlo) of the

**Figure 5-2
Comparison of Shallow (Core-derived) and Deep (Log-derived)
AA Matrix Porosity Summary Statistics**

**Figure 5-3
Old Alluvial Aquifer (OAA) Matrix Porosity with Depth**

**Table 5-3
t-Test: Two Sample Assuming Equal Variances**

Porosity (%)	Core	Geophysical Log
Mean	38.52	34.17
Variance	30.20	58.52
Observations	695	7201
Pooled Variance	56.03	
Hypothesized Mean Difference	0	
df	7894	
t Stat	14.62	
P(T<=t) one-tail	4.41E-48	
t Critical one-tail	1.65	
P(T<=t) two-tail	8.83E-48	
t Critical two-tail	1.96	

distribution as part of the Frenchman Flat CAU-scale flow and transport model input parameter selection. Recall that each porosity datum is assigned a score ([Section 5.3](#)) that effectively standardizes the value with respect to its physical representativeness of the HSU and its measurement quality. To incorporate the scores with the measured matrix porosity data per distribution, the scores are used to define the empirical cumulative probability for each measured porosity datum. To construct an empirical cumulative distribution function (ECDF) from the data and scores, the measured porosity values are sorted in ascending order and their corresponding scores are then summed in cumulative fashion. The cumulative score for each porosity datum is divided by the sum of the scores to obtain an empirical estimate of the cumulative probability for that porosity measurement.

This method brings to consideration an important point regarding the ECDF. The ECDF honors the measured matrix porosity data (e.g., their statistics), while the probability of obtaining a given porosity datum (from random measurement of the HSU) is dependent on the measurement method and the heterogeneity of lithology within the HSU of interest. The method would also permit the direct construction of a matrix porosity probability density function (PDF) using the relative sum of scores (empirical PDF) for each binned matrix porosity.

After defining the ECDF for each HSU, BestFit ([Appendix C](#)) was used to fit a cumulative distribution function (CDF) to the data. The fit is based on an empirical statistic. The fitting algorithm minimizes the root mean squared error (RMSE) between the ECDF and CDF; therefore, the (fitted) distribution parameters do not always reproduce the (measured) data statistics. The advantage of this method is that, in most cases, the shape of the complete distribution, including the tails, is honored. Each HSU is characterized by a sufficiently large dataset that the ECDF is relatively smooth and well defined over the entire range

of measured matrix porosities; the fitted distribution does not require the interpolation of probabilities between matrix porosity values. The disadvantage of this method is that the certainty of a statistical goodness-of-fit test (e.g., the Kolmogorov-Smirnov) becomes questionable in some cases because the fitted distribution is dependent on the sampled data. The exact definition of a critical value related to a given significance level becomes more of an estimate as opposed to a fixed value, which is detrimental to the test if the sample test statistic is close to the critical statistic. Therefore, the CDF that produces that lowest RMSE with respect to the ECDF is selected as the distribution model.

5.4.1 Porosity Distributions per HSU

This section presents the matrix porosity ECDFs and CDFs for each HSU in graphical and tabular format. As reported, each distribution is representative of a composite HSU and does not include a significant component of vertical spatial variability (depth dependent trends). Further, the score assigned to each matrix porosity datum is meant to effectively remove the relative influence of the measurement method such that the variability described by the (E)CDF reflects that of the actual (HSU). However, outliers are expected to exist in each dataset that may have resulted from a large number of sources related to measurement uncertainty (e.g., borehole skin, borehole collapse along an interval, or temporary mechanical tool failure). For this reason, the total range of matrix porosities for each HSU are defined by the 2.5 and 97.5 CDF percentiles. Additionally, consideration is given to the relative closeness between the core- and geophysical log-derived porosity measurements (that comprise the probability distributions) and the matrix porosity values that should be applied in further related numerical modeling activities. Porosities measured from laboratory core analyses can be considered equivalent to matrix porosities if the sample captures a representative elementary volume and if the volume of isolated pore space is (assumed) negligibly small. Porosities measured using geophysical methods, with the exception of the electrical resistivity logging method, indirectly measure total porosity. In porous media, total porosity is a good estimator of matrix porosity. In fractured media, the same relationship can be assumed if the fracture porosity is small (less than 1 percent).

The (E)CDFs and their corresponding parameters are presented in [Figure 5-4](#) through [Figure 5-6](#), and [Table 5-4](#), respectively. [Table 5-4](#) lists each HSU and its associated distribution, describes the relationship between matrix porosity and the effective porosity for each HSU, and includes comments that relate quantitative properties of the porosity distribution to qualitative properties of the HSU lithology. [Table 5-4](#) is meant to serve as a brief yet comprehensive source of Frenchman Flat HSU matrix porosities for use in further related analyses.

The distribution parameters as presented in [Table 5-4](#) are meant for use in populating the model hydrogeologic flow domain with matrix porosity values. Methods of populating the domain, ranging from deterministic to stochastic to completely random, are beyond the scope of this section. However, consideration is given to resolving the difference in spatial scale between the matrix/total porosity measurements and that at which they will be applied in numerical models.

Figure 5-4
Clockwise from Upper Left: AA, PCU, BLFA, and OAA Matrix Porosity ECDFs and Model CDFs

Figure 5-5
Clockwise from Upper Left: TMWTA, LVTA, U/LTCU, and TSA Matrix Porosity ECDFs and Model CDFs

Figure 5-6
LCA Matrix Porosity ECDFs and Model CDFs

Table 5-4
Matrix Porosity Distribution Summary and Reference Table per HSU

HSU:	AA		OAA		PCU		BLFA		TM-WTA		TM-LVTA		TSA		U/LTCU		LCA		U/LCCU
Geologic Medium Classification	Unconsolidated Porous		Unconsolidated Porous		Unconsolidated Porous		Consolidated Fracture		Consolidated Fracture		Consolidated Porous		Consolidated Fracture		Consolidated Porous		Consolidated Fracture		Consolidated Porous
Distribution:	Logistic		Inverse Gaussian		Inverse Gaussian		Inverse Gaussian		Triangular		Gaussian		Beta General		Logistic		Log Logistic		Uniform
	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic	Fit Statistic	Sample Statistic
Mean (%)	39.03	39.16	33.48	33.32	35.76	37.92	17.62	17.95	29.04	28.75	35.34	35.70	24.05	24.14	28.33	28.25	6.76	7.49	3.5
Variance (% ²)	53.75	50.87	85.92	91.61	73.33	26.98	120.57	142.22	106.51	89.32	45.92	36.90	160.46	159.73	38.82	28.55	52.44	N/A	2.08
Min (2.5 Percentile) (%)	23.60	24.76	6.65	15.52	2.10	32.36	2.00	4.55	2.50	8.75	15.60	23.79	1.20	5.15	1.10	17.56	0.60	0.90	1.00
Max (97.5 Percentile) (%)	49.50	53.57	49.90	53.09	66.50	51.77	75.00	49.37	65.70	43.34	49.80	47.60	50.40	47.66	86.80	39.16	61.10	31.20	6.00
N (# of samples)	4,064		2,441		3,494		1,606		7,924		1,318		925		26,666		3,633		7
Fit RMSE ⁺ (-)	1.24 x 10 ⁻⁴		1.48 x 10 ⁻⁴		2.10 x 10 ⁻³		1.32 x 10 ⁻⁴		3.95 x 10 ⁻⁴		5.36 x 10 ⁻⁴		6.58 x 10 ⁻⁴		5.81 x 10 ⁻⁴		1.24 x 10 ⁻⁴		N/A
CAU Data Source	FF		FF		FF		PM*		FF		FF		FF		FF		FF		YF PM*
Comments	See Section 5.3.2				See comment on Figure 5-4 (top right)		Large variance indicates measurement of fracture and matrix porosity (see Figure D.5-2)		Large small-scale variability (see Figure D.5-3) indicates bedding of different units at small (hundreds-of-feet) scale		Source of depth trend (see Figure D.5-4) is unknown; does not appear to be compaction with depth		A highly variable degree of welding between strata probably produces the large variance Large matrix porosities above 45% would be unrealistic in the saturated zone		-		Unique distribution given the low mean and long right-tail; the right-tail is a result of intermittent fracturing or channel features that bias matrix porosity high		Data too few for probability model

* Shaw (2003a)
+ RMSE = Root Mean Squared Error of fit CDF to sample ECDF

The upscaling of the HSU matrix porosity distribution parameters is discussed in [Section 5.5](#).

5.5 Scaling Considerations

The matrix porosity data are small-scale (sub-meter) measurements that, in most cases, do not correspond with the larger (tens-of-meters to kilometer) scale at which flow and transport modeling are completed. As noted by McKenna and Rautman (1996), porosity can be effectively upscaled by the volume variance method, which is also presented in several textbooks including Journel and Huijbregts (1978) and Vanmarcke (1983). The method preserves the sample mean, and the upscaled variance reduction (due to sample averaging) is a function of the ratio of the correlation length of the point process to the averaging interval. The point process correlation length is unknown and cannot be sufficiently estimated (with respect to the sample number) in any orientation but the vertical; therefore, the method is impractical for application with this dataset.

In general, the spatial sampling of matrix porosity (and related hydrogeologic rock properties) is sparse in the horizontal plane, primarily because the majority of data are collected from vertical boreholes. Limited lateral porosity data have been collected at Yucca Mountain from surface outcrops (e.g., Flint et al. [1996]) and from tunnels (e.g., Freifeld [2001]); however, these data are from the unsaturated zone and do not represent the full suite of HSUs at Frenchman Flat. In order to circumvent the problem of limited data for estimation of a spatial statistic (e.g., the correlation length) in the horizontal plane, it is common to assume a ratio of anisotropy in the principle directions and to then scale the statistic relative to the orientation for which it is known. Lateral spatial statistics may also be inferred if the relationship is known between matrix porosity and a secondary variable for which directional spatial statistics are known. For example, in the alluvium, porosity is strongly correlated with the sample grain size distribution, which itself is dependent on depositional features. In other words, laterally varying deposits could be used to define the scale at which matrix porosity varies.

Additional complications to spatial averaging are related to heterogeneity that result from different lithologies within a single HSU. Consider, for example, a stratum of welded tuffs situated between non-welded tuffs in a single (composite) HSU. Because the welded tuff is likely to transmit most of the flow, the upscaled matrix porosity should reflect the welded unit (through weighting) rather than corresponding to the arithmetic mean of all lithologies in the unit. This adds uncertainty to the scaling process that cautions against a simple volume-averaging approach, at least at larger CAU scales.

In summary, the variance reduction for each HSU cannot be calculated at this time, although the HSU sample means ([Table 5-4](#)) can be as they are unaffected by the scaling process. Prior to application of the data at the larger CAU-scale, it may be important to resolve the quantity of variance reduction per HSU. For example, nonconservatively high porosities will result in either unrealistically slow groundwater flow rates, large amounts of matrix diffusion, or both. Alternatively,

the quantity of variance reduction may be addressed via a parameter sensitivity analysis during the numerical simulation of transport.

6.0 Effective Porosity

This section details the procedures and methods used to develop effective porosity estimates for the Frenchman Flat CAU groundwater flow and transport model. Effective porosity is defined as the void fraction of a geologic material through which water is transmitted. It is important in modeling contaminant transport because it affects the rate of groundwater movement and, therefore, the transport rate of contaminants of concern.

To determine how effective porosity values should be estimated for the groundwater flow and transport model, it is first necessary to examine the variability of effective porosity in the geologic units of FF. As will be discussed further, flow can be diffuse or channelized depending on the properties of the rock. Next, it is necessary to break the modeling area up into representative volumes to which effective porosity estimates can be assigned. The most obvious divisions are the HSU and HGU classifications. Both classification systems have desirable strengths and both will be used to assign effective porosity. Finally, sources of data must be evaluated and their appropriateness must be ranked. The SNJV (2004g) outlines a standard weighting method to determine the applicability of data for a CAU ([Appendix B](#)). An alternate means of analysis is put forth within this section for cases with multiple analysis methods that do not conform the method provided in SNJV (2004g). It should also be noted that all porosities within this section are listed as fractions rather than percentages.

6.1 The Role of Effective Porosity in Contaminant Transport

The nature of fluid flux through a porous system was first outlined by French engineer Henri Darcy in 1856. Darcy's law states that the volumetric discharge of a porous flow system is equal to the hydraulic conductivity of the media multiplied by the hydraulic gradient and the cross-sectional flow area. The law is described by the equation (Domenico and Schwartz, 1997):

$$Q = KiA \quad (6-1)$$

Where:

- Q = Volumetric discharge [L^3/T]
- K = Hydraulic conductivity of the medium/fluid system [L/T]
- i = Hydraulic gradient [dimensionless]
- A = Cross sectional area perpendicular to flow [L^2]

To evaluate contaminant transport in groundwater, groundwater velocity must be determined. Equation 6-1 can be manipulated by dividing both sides by the cross sectional area to yield units of [L/T]. This is called the specific discharge. This is not a true fluid velocity, however, because water cannot flow through the entire volume of the medium. Water cannot, for example, flow through the solid grains. The effective porosity is defined as the fraction of the media through which flow occurs, hence an “effective cross sectional area” is obtained by multiplying the total cross sectional area by the effective porosity. Equation 6-2 shows the relationship of fluid velocity to specific discharge.

$$v = \frac{q}{\phi_e} = \frac{Q}{\phi_e A} = \frac{K}{\phi_e} i \quad (6-2)$$

Where:

- v = Average fluid velocity [L/T]
- q = Specific discharge [L/T]
- ϕ_e = Effective porosity [dimensionless]

Because velocity is inversely related to effective porosity, as effective porosity increases a given discharge is able to flow through a larger fraction of the media and average velocity decreases.

This conceptual model is a useful for understanding how effective porosity will be used in the Frenchman Flat area. It is important to note that effective porosity of a geologic material is dependent on the flow geometry of a fluid flowing through the material. For analysis of the HGUs, geologic materials can be placed into two broad categories. Porous media tend to have more uniform, diffuse flow throughout the system. Fractured media (discrete flow systems) contain fractures that concentrates flow. The effective porosity of porous media can be adequately determined through large numbers of small-scale measurements, whereas the effective porosity for fractured systems must be measured at the scale of fracturing.

6.2 Data Evaluation Procedures

6.2.1 Division of the Modeling Area for Parameter Assignment

The geologic model for Frenchman Flat uses two classification systems, HGUs and HSUs. The HGUs categorize the ability of units to transmit groundwater. The HSUs divide the modeling area into stratigraphic blocks with similar hydraulic properties. In the Frenchman Flat model, HSUs are composed either entirely of one HGU or predominantly of one HGU with a minor amount of a secondary HGU. Detailed descriptions of the HGUs and HSUs in FF are presented in [Section 2.2](#).

To evaluate the effective porosity for Frenchmen Flat, the HSUs are grouped according to their primary HGU. The geologic characteristics of the HGU are

then evaluated to determine whether it behaves as fractured or porous media. After the flow type is determined, the sources of data for the HGU are examined to determine if sufficient data from within the FF modeling area are available to separate HSUs with the same primary HGU. If so, effective porosities are assigned by HSU. If not, effective porosity is evaluated for the HGU.

6.2.2 Data Transfer and Weighting Procedure

To assign an effective porosity to a unit in the geologic model, the quality and suitability of data sources for the unit need to be evaluated. Where multiple data sources exist for a given unit, they must be compared and condensed to define an estimate and account for uncertainty. To do this, two methods are used for the effective porosity analysis. For units with large numbers of independent measurements, the weight and multiplier system outlined in SNJV (2004g) is used (for further details see [Appendix B](#) and [Section 5.3](#)). For units with few independently measured data, the strengths and weaknesses of each measurement method and analysis method are discussed and an estimate is recommended based on these strengths and weaknesses.

6.3 Alluvial Aquifer HGU

The AA HGU consists of unconsolidated to partially consolidated gravelly sand, aeolian sand, and colluvium. The unit is loosely consolidated and, therefore, unfractured (see [Section 2.0](#) for further details). There are two HSUs in Frenchman Flat that correspond to the AA HGU, the AA and the OAA. The OAA is older, denser, zeolitized alluvium that is recognized only in northern Frenchman Flat (SNJV, 2004b). Flow through this HGU is diffuse and the effective porosity should be approximately the same or no greater than the matrix porosity. Geophysical- and core-derived matrix porosities were used as effective porosity to model radionuclide migration from the RNM project at the CAMBRIC site with good results (Burbey and Wheatcraft, 1986). The matrix porosities and uncertainty distribution for both the AA and the OAA HSUs have been evaluated in [Section 5.4](#); these porosities should be used as the effective porosities.

6.4 Playa Confining Unit HGU

The PCU HGU consists of clayey silt and silty sand playa lake deposits. There is no evidence of fracturing in the PCU. Therefore, matrix porosity and effective porosity should be equivalent for the FF flow and transport model.

There are two HSUs (PCU1 and PCU2) in Frenchman Flat that correspond to the PCU HGU. The two HSUs are geologically similar, so the matrix porosity in [Section 5.4](#) is assigned to the HGU as a whole. Therefore, effective porosities are assigned by HGU rather than HSU.

6.5 Vitric Tuff Aquifer HGU

The VTA HGU is composed of non-welded, non-zeolitized, bedded tuffs and generally does not extend far below the water table. The matrix porosity of the unit (HSU = TM-LVTA) ranges from 0.16 to 0.50 (expressed as percent in [Table 5-4](#)). The unit is less competent than the welded tuff units and is more easily altered into clays that can fill fractures.

While fracture surveys from Frenchman Flat VTA are unavailable, surveys conducted in the Pahute Mesa VTA show a lack of significant fracturing within the unit. A fracture survey of eight ER wells in Pahute Mesa located only one fracture in the VTA, although it is unknown exactly how many borehole meters of the VTA were examined by the survey (IT, 2001c).

A similar study of well cores from Pahute Mesa examined 215 to 235 m of VTA core from four wells for fractures. Open fractures were only found in core from one anomalous well (UE-18t) (Drellack et al., 1997). Well UE-18t is located in the Timber Mountain caldera moat (Warren, 1994) and within the outer collapse zone of the Rainier Mesa caldera (Warren 1994, Byers and Hawkins, 1981). No caldera features are known to exist in Frenchman Flat.

The significant matrix porosity and lack of open fractures indicate flow through the unit is diffuse. Therefore, the total porosity is an acceptable estimate of the effective porosity.

The TM-LVTA and LVTA are the only HSUs composed entirely of the VTA HGU ([Table 2-3](#)). The stratigraphic units composing the LVTA are included in the TM-LVTA where they are not separated by another HSU. The matrix porosity determined in [Table 5-4](#) for the VTA HGU will be assigned to the TM-LVTA and LVTA HSUs.

6.6 Lava Flow Aquifer HGU

The LFA HGU from the NTS Regional Model is composed of fractured Tertiary rhyolite lava flows (SNJV, 2004b). The abundant fracturing dominates flow and transport. The BLFA HSU is the only HSU in Frenchman Flat that is composed of the LFA; however, the BLFA is basaltic lava rather than rhyolitic lava.

There are no sources of effective porosity data available for the LFA in Frenchman Flat; however, there are several sources available from the LFA HGU in Pahute Mesa. There are also a few sources of effective porosity for basalt lava flows available from areas off of the NTS. These sources will be used to determine the effective porosity for the Frenchman Flat area.

6.6.1 Analysis of Tracer Responses in the BULLION Forced Gradient Experiment at Pahute Mesa (Reimus and Haga, 1999)

Overview. The BULLION Forced Gradient Experiment (FGE) tracer test was conducted in the ER-20-6 Well Cluster adjacent to the site of the BULLION test. The experiment utilized one primary pumping well and two injection wells completed in the LFA HGU in Pahute Mesa. The purpose of the experiment was to provide information about the transport of radionuclides in groundwater.

The tracer test was conducted using three wells (ER-20-6#1, ER-20-6#2, and ER 20-6-#3). The wells are positioned slightly to the sides of a straight line that extends from the center of the BULLION test cavity in the direction of the predicted natural flow path. Well #1 is 165.8 m, Well #2 is 207.3 m, and Well #3 is 296.0 m from the center of the test cavity.

Well #3 is the furthest down gradient of the test wells and was the primary pumping well for the experiment. Well #3 produced at approximately 630 cubic meters per day (m³/d) (116 gpm) during the experiment. Wells #1 and #2 were used both as injection wells and observation wells. These two wells started to pump at about 27 m³/d (5 gpm) within three days after tracer injection to allow the analysis of tracer flow from Well #1 to Well #2.

The BULLION FGE utilized several different tracers to allow differentiation between the two injection wells. Pentafluorobenzoic acid (PFBA) and 0.33 micrometers (μm) diameter carboxylate-modified latex (CML) polystyrene microspheres were mixed and injected into Well #2. Iodide (as sodium iodide), 2,6 difluorobenzoic acid (DFBA) and 0.33 μm CML polystyrene microspheres were injected into Well #1. The CML microspheres injected into each well were tagged with different florescent dyes to allow them to be distinguished.

Analysis. Reimus and Haga (1999) use a semi-analytical method to analyze the results of the BULLION FGE. Flow porosities were calculated using the equation:

$$\phi_e = \frac{(Q\tau)}{(\pi(R_o^2 - R_i^2)a)} \quad (6-3)$$

Where:

ϕ_e = Effective porosity [dimensionless]

Q = Pumping Rate [L³/T]

τ = mean tracer residence time [T]

a = Formation thickness [L]

R_o^2 = Distance from tracer injection well to pumping well [L]

R_i^2 = Distance from tracer monitoring well to production well [L]

The mean tracer residence times are determined by the use of the REactive transport LAPlace transform inversion code (RELAP) (Reimus and Haga, 1999) to analyze the breakthrough curves. The mean tracer residence time, the mass fraction, the longitudinal dispersivity (Section 7.0), and the diffusion coefficient

(Section 8.0) parameters were systematically adjusted in RELAP to achieve a least squared fit of modeled curves to the observed breakthrough curves. Table 6-1 presents a range of results from the analysis. The different estimates comes from three factors: use of linear versus radial flow patterns, whether discharge from Well #2 or Well #3 is responsible for tracer movement between Wells #1 and #2, and the uncertainty caused by having multiple adjustable parameters in the RELAP simulations.

**Table 6-1
Transport Parameters from Cross-Hole Tracer Responses in the BULLION FGE**

	Well 1-3	Well 1-2 ^a	Well 1-2 ^b	Well 2-3 ^c	Well 2-3 ^d
Linear τ , hrs	1,950	300	300	2,325	1,825
Radial τ , hrs	1,600	210	210	1,675	1,275
Q (gpm)	116	5	116	116	116
Linear Flow Porosity	0.008	0.0005	0.0023	0.021	0.016
Radial Flow Porosity	0.0066	0.00036	0.0016	0.015	0.011

Source: Reimus and Haga, 1999, Table 3

^aAssumes tracer movement due to pumping in Well #2

^bAssumes tracer movement due to pumping in Well #3

^cResidence time calculated using dispersivity between Wells #1 and #3

^dResidence time calculated using dispersivity between Wells #1 and #2

RELAP can fit the breakthrough curves used to determine mean residence time based on the assumptions of linear flow or radial flow. Good fits can be obtained for either assumption by adjusting the parameters. One set of effective porosities is presented to account for each assumption

Well #3 was the primary pumping well for the experiment and was pumped at 630 m³/day (116 gpm). Wells #1 and #2 began pumping at about 27 m³/day (5 gpm) within 3 days of injection to allow the analysis of tracer flow from Well #1 to Well #2. Two sets of porosity values were calculated for the flow field from Well #1 to Well #2. One set assumes the movement of tracers from Well #1 to Well #2 is due to pumping in Well #3, and the second assumes that the movement is due to the pumping of Well #2.

Most of the uncertainty caused by having multiple adjustable parameters in the RELAP analysis is offset by using multiple tracers with different diffusion coefficients. However, no unique solution for dispersivity between Well #2 and Well #3 exists. Therefore, two sets of mean residence time and effective porosity values are calculated assuming the smallest and largest diffusion coefficients for 2,6-DFBA determined from the Well #1 tracers.

The results of this analysis yield an effective porosity estimate of between 0.021 and 0.0005. The high end of these estimates is much higher than what is expected from the LFA as further sources will show. The most important shortcoming of

this method is its assumption that fracture distribution is homogeneous. If the injection wells have poor hydraulic connectivity to the pumping wells, effective porosities could be much lower than the estimates provided.

6.6.2 Report and Analysis of the BULLION FGE (IT, 1998a)

IT Corporation (1998a) presents another analysis of the results of the BULLION FGE tracer test described in [Section 6.6.1](#). In this analysis, effective porosities were calculated from the calibration of a flow and transport model built using MODFLOWT (Duffield et al., 1996) with a Dual Porosity/Permeability Package.

The MODFLOWT transport formulation used for this analysis assumes that there are two parallel continua in the transport equation, one for the fracture system and one for the matrix system. The matrix contributes to storage of the tracers through diffusion but does not contribute to advective transport. The fracture system is responsible for advective-dispersive solute transport.

The parameters derived from this calibration are listed in [Table 6-2](#) and [Table 6-3](#). [Table 6-2](#) shows the parameters used to obtain the best fit. [Table 6-3](#) shows alternate calibrations for one well pair that produced acceptable fits. The alternate calibrations result from the use of varied matrix diffusion coefficients, dispersivity, and fraction of tracer mass absorbed from the well into the LFA HGU.

Like the first analysis presented in [Section 6.6.1](#), this calibration-based method assumes homogeneous fracture distribution. The effective porosities predicted using this method are larger than those predicted by the semi-analytical method and are larger than the range of estimates obtained using other methods of analysis.

**Table 6-2
Transport Parameter Values Determined from MODFLOWT Calibration
of the BULLION FGE Model**

	DFBA Transport from Well #1 to Well #3	Iodide Transport from Well #1 to Well #2	PFBA Transport from Well #2 to Well #3
Fracture Spacing (m)	0.25	0.25	0.25
Matrix Porosity	0.35	0.35	0.35
Effective Porosity	0.018	0.018	0.023

Source: IT (1998a, Table 7-1)

**Table 6-3
Transport Parameters of the Alternative Calibrations for Transport from Well #1 and Well #3
in the BULLION FGE**

	Final Calibration	Alternative Calibration 1	Alternative Calibration 2	Alternative Calibration 3	Alternative Calibration 4	Alternative Calibration 5	Alternative Calibration 6
Fracture Spacing (m)	0.25	0.25	0.25	0.25	0.25	0.15	0.25
Matrix Porosity	0.35	0.35	0.35	0.35	0.35	0.1	0.35
Effective Porosity	0.018	0.018	0.018	0.036	0.036	0.018	0.009

Source: IT (1998a, Table 7-2)

6.6.3 Discrete Network and Continuum Approach for Modeling the BULLION FGE (IT, 2002a)

To address the larger-than-expected porosity determined from the MODFLOWT analysis (IT, 1998a), a series of 3-D Discrete Fracture Network (DFN) flow models based on the MAFIC code (Dershowitz et al., 1998) were generated and then calibrated from the results of the BULLION FGE to determine the effects of fracture heterogeneity.

Fifty fracture network models were randomly generated using fracture characteristics derived from borehole wall imaging and core information from Wells ER-20-6#1, ER-20-6#2, and ER-20-6#3. The remaining hydraulic properties for the model were estimated using information available from the wells.

The models simulate the pumping and tracer injections from the BULLION FGE and calculate well drawdown and tracer mean arrival times. The three models that best match the drawdown and the tracer mean arrival times of the BULLION FGE are averaged and reported.

An effective porosity of 2.4×10^{-5} is the average of the three best matching DFN models. This DFN model accounts for fracture heterogeneity that the previous analyses fail to address. The best matching DFNs are non-unique; however, the three are not sufficient to adequately characterize uncertainty.

6.6.4 Discrete Network and Continuum Approach for Modeling the BULLION FGE (IT, 2002a)

Appendix C of IT (2002a) was prepared by Reimus. This appendix is another examination of the BULLION FGE that takes into account variability in the spatial distribution, orientation, size, and conductivity of fractures.

To understand how fracture geometry variability can affect pumping tests, a 2-D fracture flow model was created containing an injection well and a pumping well.

Evenly spaced 208 x 208 node matrix conductivity fields were randomly generated for the model by the FAST algorithm (Shaw, 2003a) using a constant-mean, constant-log variance, and constant-correlation length.

A fracture field, with two sets of fractures, was then created by a similar random process. Each set was built around a mean length, orientation and conductivity. The difference between the mean orientations of the two sets was set to be 70 degrees. The mean length of the primary fracture set was set to be five times the mean length of the secondary fracture set. The mean of the conductivity of the primary set was set to be 10 times that of the second set. Two groups of fracture sets were created for the model: a high-conductivity contrast group in which the mean conductivity for the primary fracture set was 100,000 times greater than the mean matrix conductivity, and a moderate-conductivity contrast group in which the mean conductivity for the primary fracture set was 1,000 times the mean matrix conductivity.

Each fracture conductivity set was then superimposed on a matrix conductivity set to create a grid to be used for simulation. The orientations of the two fracture sets were rotated with respect to the orientation of the pumping and tracer wells in 22.5 degree increments over 90 degrees to allow the effect of fracture orientation to be determined.

A total of 25,000 particles were tracked through each of 250 realizations of the conductivity fields. A true effective flow porosity was determined by the mean or median arrival time of particles, multiplied by the flow rate through the domain, divided by the total domain volume. The differences resulting from the use of mean or median arrival times were later compared.

A set of simulated tracer test effective porosities to represent the erroneous assumption of homogeneous fracture distribution was determined by inserting the mean or median of tracer arrival times into the equation:

$$n = \frac{Qt}{\pi L^2 T} \quad (6-4)$$

Where:

n = Tracer test effective porosity [Dimensionless]

Q = Production rate [L^3/T]

t = Tracer arrival time [T]

L = Distance between the injection well and the production well [L]

T = Aquifer thickness [L]

The ratio of the modeled “true” effective porosity to the simulated tracer test effective porosity for each conductivity field was calculated and a CDF was created from the results of all the realizations to determine a correction factor with a distribution of error values.

The best estimate of true effective porosity for the BULLION FGE flow experiment is 0.0002. This results from the effective porosity estimate of 0.008 (Reimus and Haga, 1999) divided by a correction factor of 44.1. The estimate has

a standard deviation of 1.03 log units. The distribution results from 25 conductivity realizations each simulated at five different angles to the tracer wells and each with a high conductivity contrast between the fractures and the matrix.

Like all the BULLION FGE analysis methods here, this method has its strengths and weaknesses. The large number of independent results determined provides a good statistical basis to analyze the possible variations in effective porosity. The analysis also accounts for fracture heterogeneity which is necessary to get a reasonable effective porosity estimate. On the other hand, the fracture and other physical parameters used for the model to determine the correction factor are not firmly based on the properties observed in Pahute Mesa. Further, the fact that the fractures are only modeled in two dimensions may have a significant impact on the results.

6.6.5 TYBO/BENHAM: Model Analysis of Groundwater Flow and Radionuclide Migration from Underground Nuclear Tests in Southwestern Pahute Mesa, Nevada (Wolfsberg et al., 2002)

Wolfsberg et al. (2002) estimates fracture porosity using fracture spacing and fracture aperture data from surveys of Pahute Mesa (Drellack et al., 1997). The fracture porosity was estimated using a range of fracture spacing, and fracture aperture. The parallel plate model was used to calculate a 1-D fracture porosity with the highest spacing and smallest aperture to determine a lower limit on fracture porosity. The lowest spacing and largest aperture were used in the parallel plate model with a correction (DOE/ORD, 2000) to account for the assumption of three orthogonal fracture sets to determine an upper fracture porosity limit. The results of these simple calculations are shown in [Table 6-4](#).

**Table 6-4
LFA Fracture Porosities from
Pahute Mesa Well Cores**

	Fracture Porosity
Base	2.09E-03
Low	2.19E-04
High	2.00E-02

Source: Wolfsberg et al. (2002, Table F-20).

This fracture porosity estimate serves as an upper bound to the estimate of effective porosity. In the LFA, significant flow should occur only in the fractures, so the effective porosity cannot be larger than the fracture porosity.

6.6.6 Contaminant Transport Parameters for the Groundwater Flow and Contaminant Transport Model of Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nye County, Nevada (Shaw, 2003a)

Section 6.3 in Shaw (2003a) contains estimates of fracture porosity based on hydraulic conductivities derived from pump tests and fracture spacings determined from borehole logs and core surveys. The fracture porosity is calculated by combining the cubic law (Equation 6-5), Darcy's law (Equation 6-6), and the definition of fracture porosity (Equation 6-7) to yield Equation 6-8.

The following equation (Domenico and Schwartz, 1997) is used to calculate the discharge of a fracture given its aperture:

$$Q = \frac{\rho_w g b^2}{12\mu} b_w \frac{\delta h}{\delta L} \quad (6-5)$$

Where:

Q = Volumetric flow rate [L³/T]
 ρ_w = Density of water [M/L³]
 g = Gravitational acceleration [L/T²]
 b = Fracture aperture [L]
 μ = Viscosity of water [M/LT]
 b_w = Fracture width perpendicular to flow direction [L]
 $\frac{\delta h}{\delta L}$ = Hydraulic gradient [L/L]

Darcy's law is used to calculate the discharge through a porous medium as follows:

$$Q = KA \frac{\delta h}{\delta L} \quad (6-6)$$

Where:

K = Hydraulic conductivity [L/T]
 A = Discharge area perpendicular to flow direction [L²]

Fracture porosity is defined as:

$$\phi_e = \phi_f = \frac{v_f}{v_t} \quad (6-7)$$

Where:

ϕ_e = Effective porosity [dimensionless]
 ϕ_f = Fracture porosity [dimensionless]
 v_f = Fracture volume [L³]
 v_t = Total volume [L³]

Combination of equations 6-5, 6-6, and 6-7 yields:

$$\varphi_e = \left(\frac{K(12\mu)}{\rho_w g} \right)^{1/3} e^{-2/3} \quad (6-8)$$

Where:

φ_e = Effective porosity [dimensionless]

ρ_w = Density of water [M/L³]

g = Gravitational acceleration [L/T²]

μ = Viscosity of water [M/LT]

K = Hydraulic conductivity [L/T]

e = Fracture spacing [L]

In addition to the equations above, the derivation of equation (6-8) is dependent on the assumptions of the equivalent porous media model, which is necessary to assign an estimation of K to an interval containing fractures within a geologic media. With some algebraic manipulation, the equivalent porous media model shows that ew in a fractured system can be substituted for A in equation (6-6), and that b can be substituted for v_f and e can be substituted for v_t in equation (6-7). After these substitutions are made, equations (6-5) and (6-6) are solved for Q and set equal to solve for b . The result is substituted for b in equation (6-7) which yields equation (6-8). Stated in more simple terms, this cubic law based method uses fracture spacing and conductivity to calculate an estimate of fracture aperture, and then uses the estimated aperture with fracture spacing to estimate an effective porosity.

The two independent variables in equation (6-8) are fracture spacing and hydraulic conductivity. Of these two variables, fracture spacing is the most uncertain and has the largest effect on the effective porosity as $\varphi_e \propto e^{-2/3}$ and $\varphi_e \propto K^{1/3}$. The estimate of fracture spacings used for these analyses is probably too low because the surveys count fractures that are open at the borehole, and do not denote which fractures are clogged away from the hole or were opened up in the vicinity of the hole by drilling activities.

When hydraulic conductivity is estimated by a pumping test analysis, only hydraulically connected fractures will contribute to the discharge and conductivity. Pumping tests are also representative of a larger scale than borehole logs, although the scale varies based on the size of the test. Using fracture apertures calculated from hydraulic conductivity will overestimate effective porosity less than using the apertures measured in borehole logs. However, a fracture with an aperture of 2 millimeters (mm) has a higher conductivity than 2 fractures with apertures of 1 mm because $K \propto b^2$, as determined by setting equation (6-5) equal to equation (6-6) and assuming $bw = A$. Therefore, there will still be a systematic overestimation of effective porosity when using this method because a smaller number of larger fractures will have a lower effective porosity than a larger number of smaller fractures for a given K . Table 6-5 contains the effective porosity estimates from Shaw (2003a).

Table 6-5
LFA Porosity Estimates from Hydraulic Conductivity and Fracture Spacing

Well	Interval name	Top of Interval (m)	Bottom of Interval (m)	Hydraulic Conductivity Minimum (m/s)	Hydraulic Conductivity Maximum (m/s)	Fracture Spacing (m)	Aperture Minimum (m)	Aperture Maximum (m)	Fracture Porosity Minimum	Fracture Porosity Maximum	HGU
ER-20-6#1 ^a		701	898	2.40E-05		0.62	2.63E-04		0.0004260		LFA
ER-20-6#2 ^a		777	887	1.49E-05		3.37	3.95E-04		0.0001170		LFA
ER-EC-1	Screen Joint 1	691.9	715.7	1.26E-04	5.41E-04	1.68	6.39E-04	1.04E-03	0.0003800	0.0006170	LFA
ER-EC-1	Screen Joint 2	715.7	737.3	2.27E-05	1.23E-04	1.68	3.60E-04	6.34E-04	0.0002140	0.0003770	LFA
ER-EC-1	Screen Joint 3	737.3	758.6	8.26E-05	2.71E-04	1.68	5.55E-04	8.24E-04	0.0003300	0.0004900	LFA
ER-EC-1	Screen Joint 4	758.6	780	3.50E-06	3.70E-05	1.68	1.93E-04	4.24E-04	0.0001150	0.0002520	LFA
ER-EC-4	Screen 1	293.2	326.9	1.95E-04	4.76E-04	8.67	1.28E-03	1.72E-03	0.0001470	0.0001980	LFA
ER-EC-4	Screen 2	326.9	348.5	1.66E-04	7.38E-04	8.67	1.21E-03	1.99E-03	0.0001400	0.0002290	LFA
ER-EC-4	Screen 3-1	348.5	357	1.27E-04	6.90E-03	8.67	1.11E-03	4.19E-03	0.0001280	0.0004830	LFA
ER-EC-6	Screen 1	489.5	511.7	8.09E-06	2.60E-05	7.02	4.12E-04	6.08E-04	0.0000586	0.0000866	LFA
ER-EC-6	Screen 2	511.7	533.2	6.91E-07	2.78E-06	7.02	1.81E-04	2.88E-04	0.0000258	0.0000411	LFA
ER-EC-7	Screen 1	278	312.1	3.90E-06	2.60E-05	3.21	2.49E-04	4.68E-04	0.0000775	0.0001460	LFA
ER-EC-7	Screen 2	360.9	399.3	5.84E-05	1.22E-04	2.38	5.55E-04	7.09E-04	0.0002330	0.0002980	LFA
UE-18-r ^a		1,083.30	1,184.50	3.24E-06		1.64	1.87E-04		0.0001140		LFA

Source: Shaw (2003a) Table 6-6

^aOnly single values of K were available for these wells; Only single values of aperture and porosity were calculated

6.6.7 A Critical Review of Data on Field-Scale Dispersion in Aquifers (Gelhar et al., 1992)

Gelhar et al. (1992) contains the summaries of two estimates of effective porosity in a basalt lava flow aquifer at the National Rector Testing Station in Idaho, now known as the Idaho National Laboratory. The estimates were made by modeling the movement of a chloride plume in an aquifer approximately 76 m thick over a distance of about 20 km under ambient flow conditions. The effective porosity estimates in the studies are both 0.10. The tracer input curves are not well defined, and both estimates are given a reliability estimate of III, the lowest of three classes, in Gelhar et al. (1992).

The similarity of this basalt aquifer to the Frenchman Flat BLFA HGU is unknown. This estimate of effective porosity is much higher than the other tracer test estimates for LFAs at the NTS, which would result is slower transport times.

6.6.8 BLFA Summary

Table 6-6, 6-7, and Figure 6-1 shows the large range and variability in effective porosities estimated for the LFA HGU. The estimates cover almost five orders of magnitude from 0.000024 for the IT (2002a) DFN estimate to 0.10 for the estimation from chloride plume migration published in Gelhar et al. (1992).

**Table 6-6
Statistical Estimates of Effective Porosity for the LFA HGU**

	Shaw (2003a)	IT (2002a)	Wolfsberg et al. (2002)
Mean	0.00018	0.0002	0.0021
2.5% Percentile	0.000036	0.0000019	0.00037
97.5% Percentile	0.00085	0.021	0.012
Distribution	Log Normal ^{a, b}	Log Normal ^{a, c}	Log Triangular ^{a, d}

^aLog {distribution} is the distribution fitted to the log transforms of the porosity values.

^bDistribution fitted to sample in BestFit

^cDistribution recommended in IT (2002a)

^dDistribution assumed from a best estimate, minimum and maximum value.

**Table 6-7
Non-Statistical Estimates of Effective Porosity for the LFA HGU**

	IT (2002a)	IT (1998a)	Reimus and Haga (1999)	Gelhar et al. (1992)
Middle	0.000024	0.023	0.011	0.10
Minimum	--	0.01	0.00036	--
Maximum	--	0.04	0.021	--

1. Range of values presented as a uniform distribution.
2. Log triangular distribution assumed from a best estimate and minimum and maximum values.
3. Single number provided with no range of uncertainty. From 3-D discrete fracture network.

Figure 6-1
Estimates of Effective Porosity for the Pahute Mesa LFA HGU

The wide range of effective porosity estimates and the lack of individual measurements make the weight and multiplier system outlined in SNJV (2004g) impractical. The purpose of weighting is to remove error and uncertainty from a dataset compiled from large sets of separate measurements. Only the Shaw (2003a) dataset is composed of independent measurements. The rest of the datasets are given as recommended ranges or distributions rather than sets of individual measurements, and four of the effective porosity estimates are different interpretations of the same experiment. Most of the variation in the effective porosity estimates is due to variation in interpretation rather than variation in experimentally measured values. In this case, weighting will only cause further complications and introduce a new component of uncertainty.

The effective porosity estimate published in Gelhar et al. (1992) is the highest of the estimates and is the only estimate for a basalt lava flow aquifer. It is uncertain whether the BLFA HSU in Frenchman Flat is closer to the NTS rhyolite lavas flows, or to other basalt lava flows. This estimate, therefore, cannot be dismissed and will be treated as the upper bound of effective porosity.

Among the better constrained rhyolite LFAs, the fracture porosity estimates from Wolfsberg et al., (2002) should be the absolute maximum for effective porosity. The estimates of effective porosity made using MODFLOWT (IT, 1998a) and the semi-analytical method (Reimus and Haga, 1999) both are higher than the fracture porosity from the fracture survey. These two methods assume a homogeneous fracture distribution and are most likely too high for the effective porosity of a rhyolitic lava flow.

The analysis of fracture porosity based on hydraulic conductivity and fracture spacing (Shaw, 2003a) partially eliminates the inclusion of non-flowing fracture porosity into effective porosity. Although, there is likely to be a slight systematic overestimation because of the inclusion of non-flowing fractures in fracture spacing measurement, this method is an inherently more accurate method of determining effective porosity than the fracture survey in Wolfsberg et al, (2002).

The 3-D DFN model comparison to analyze the BULLION FGE (IT, 2002a) is the most detailed analysis of effective porosity for the LFA. The model used for comparison in the analysis explores the effects of fracture heterogeneity and uses parameters derived from the best estimates of the properties in the LFA. Unfortunately, the report provides the results of the analysis without an adequate characterization of uncertainty, and the geologic similarity of the BULLION FGE area to the LFA in Frenchmen Flat is uncertain. Thus, the report provides an effective porosity estimate that must be considered realistic, but is not representative of the full range of realistic values.

The 2-D model correction factor analysis of the BULLION FGE (IT, 2002a) provides the broadest range of estimates for the effective porosity of the LFA. This estimate has the greatest number of data points, and has the best statistical determination of uncertainty because of the number of model permutations and the methods used to randomize the correction factor models. However, the fracture properties used in the correction factor models are not based on the known fracture

properties in the LFA and it is uncertain how well the 2-D geometry used for the models represents the 3-D aquifer.

The full range of effective porosity estimates for the LFAs summarized above should be used in sensitivity analysis for the effective porosity of the Frenchman Flat LFA HGU. The range of estimates from Pahute Mesa LFA demonstrates the large range of uncertainty that can exist among reasonable estimates of effective porosity in an LFA that has been characterized by a number of different means. The larger effective porosity for a BLFA off of the NTS indicates that the value could be higher for a BLFA on the NTS, but the estimates from the rhyolite LFA are better constrained and also are lower, and therefore are more conservative.

6.7 Welded Tuff Aquifer HGU

The WTA HGU is present through much of the NTS and is composed of ash flow tuffs with various degrees of welding. The matrix and fracture porosity depend on the degree of welding, but in general, flow in the WTA is controlled by fracturing (SNJV, 2004b).

Effective porosity data from wells in Frenchman Flat are not available, so data used for the WTA HGU are transferred from Pahute Mesa.

The TM-WTA HSU and TSA HSU in the Frenchman Flat modeling area are composed primarily of welded tuff and correspond to the WTA HGU. The data are transferred at the HGU level because there is no direct correspondence between HSUs in the two modeling areas.

6.7.1 Contaminant Transport Parameters for the Groundwater Flow and Contaminant Transport Model of Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nye County, Nevada (Shaw, 2003a)

Estimates of effective porosity for the WTA are determined using fracture spacing from borehole surveys and hydraulic conductivities from pumping tests. The effective porosities are calculated in the same manner as those for the LFA in [Section 6.6.6](#), and the details of the calculation are not repeated here. [Table 6-8](#) contains a listing of the effective porosity estimations and [Figure 6-2](#) is a CDF plot of the estimates.

As is discussed in [Section 6.6.6](#), the cubic-law based method of estimating fracture effective porosities may slightly overestimate effective fracture porosity because non-flowing fractures may be included in the fracture spacing for the borehole. The estimate is more representative of effective fracture porosity than estimates using only fracture apertures and fracture spacing measured from borehole logs and core analysis.

Table 6-8
Shaw (2003a) WTA Porosity Estimates from Hydraulic Conductivity and Fracture Spacing

Well	Interval name	Top of Interval (m)	Bottom of Interval (m)	Hydraulic Conductivity Minimum (m/s)	Hydraulic Conductivity Maximum (m/s)	Fracture Spacing (m)	Aperture Minimum (m)	Aperture Maximum (m)	Fracture Porosity Minimum	Fracture Porosity Maximum	HGU
ER-18-2		411.9	758	7.31E-09	1.53E-08	2.65	2.88E-05	3.68E-05	1.09E-05	1.39E-05	WTA
ER-EC-5	Screen Joint 1	361.8	389.5	4.61E-06	5.13E-05	2.37	2.38E-04	5.31E-04	1.00E-04	2.24E-04	WTA
ER-EC-5	Screen Joint 2	389.5	410.9	7.83E-06	1.06E-04	2.37	2.84E-04	6.76E-04	1.20E-04	2.85E-04	WTA
ER-EC-5	Screen Joint 3	410.9	439.8	7.95E-08	8.59E-06	2.37	6.14E-05	2.92E-04	2.59E-05	1.23E-04	WTA
ER-EC-5	Screen Joint 4	565.4	601.4	5.58E-05	1.85E-04	2.37	5.45E-04	8.13E-04	2.30E-04	3.43E-04	WTA
ER-EC-5	Screen Joint 5	601.4	623	7.92E-05	6.52E-04	2.37	6.13E-04	1.24E-03	2.59E-04	5.22E-04	WTA
ER-EC-5	Screen Joint 6	623	654.1	3.89E-07	2.44E-04	2.37	1.04E-04	8.92E-04	4.40E-05	3.76E-04	WTA
ER-EC-5	Screen Joint 7	677.6	699.8	1.09E-05	1.92E-04	2.37	3.17E-04	8.23E-04	1.34E-04	3.47E-04	WTA
ER-EC-5	Screen Joint 8	699.8	721.5	1.11E-05	1.57E-04	2.37	3.19E-04	7.71E-04	1.34E-04	3.25E-04	WTA
ER-EC-5	Screen Joint 9	721.5	755.9	6.29E-06	1.71E-04	2.37	2.64E-04	7.92E-04	1.11E-04	3.34E-04	WTA
ER-EC-8	Screen Joint 9	544.6	566.2	9.14E-07	1.14E-05	2.5	1.41E-04	3.27E-04	5.64E-05	1.31E-04	WTA
ER-EC-8	Screen Joint 10	566.20	606.60	2.63E-07	9.15E-06	2.5	9.31E-05	3.04E-04	3.72E-05	1.22E-04	WTA
UE-18-r ^a		485.00	897.60	3.24E-06		0.72	1.42E-04		1.97E-04		WTA
UE-18-r ^a		1,027.2	1,083.3	3.24E-06		1.19	1.68E-04		1.41E-04		WTA
UE-18-r ^a		1,367	1,504	3.24E-06		0.62	1.35E-04		2.17E-04		WTA

Source: Shaw (2003a, Table 6-6)

^aOnly Single values of K were available for these wells; Only single values of aperture and porosity were calculated

Figure 6-2
WTA Effective Porosity Estimates From Shaw (2003a)

6.7.2 TYBO/BENHAM: Model Analysis of Groundwater Flow and Radionuclide Migration from Underground Nuclear Tests in Southwestern Pahute Mesa, Nevada (Wolfsberg et al., 2002)

These porosity estimates are determined by using fracture apertures and fracture spacings from borehole logs and core analysis. The details of the calculation method are outlined in [Section 6.6.5](#). As is explained in [Section 6.6.8](#), the porosity determined by this method is the fracture porosity and best used as maximum bound on effective porosity for fractured flow systems. The range of porosities recommended in Wolfsberg et al. (2002) is shown in [Table 6-9](#).

Table 6-9
WTA Fracture Porosities from
Pahute Mesa Well Cores

	Fracture Porosity
Base	4.98E-04
Low	7.00E-05
High	3.54E-03

Source: Wolfsberg et al. (2002, Table F-20).

6.7.3 WTA HGU Summary

Figure 6-3 and Table 6-10 summarize the effective porosity estimates for the WTA. This dataset does not lend itself to the weighted analysis method outlined in SNJV (2004g) because the Wolfsberg et al. (2002) estimate is provided as a recommended range rather than a set of measured values.

The fracture spacing and fracture aperture data analyzed in Wolfsberg et al. (2002) come from a fracture survey of Pahute Mesa wells by Drellack et al. (1997). The Shaw (2003a) estimate uses Drellack et al. (1997) and an IT (2001c) Pahute Mesa fracture survey as sources of data. Because the Shaw (2003a) estimate takes into account the dataset used for the Wolfsberg et al. (2002) estimate, it is a more complete dataset. As discussed in the LFA section, the Shaw (2003a) estimate is also a better estimate of effective porosity because it eliminates most of the error caused by including non-flowing fracture porosity. Therefore, the 2.5th and 97.5th percentiles of the distribution fitted to the Shaw (2003a) effective porosity estimate should be used as the range for the Frenchman Flat groundwater flow and transport model.

6.8 Tuff Confining Unit HGU

The TCU HGU is composed of non-welded, bedded airfall tuffs with lesser amounts of non-welded to incipiently welded ash-flow tuffs. The TCU's distinguishing characteristic is the extensive zeolitization that substantially decreases the permeability of the unit. Zeolitization diagenesis also tends to decrease the overall porosity of tuffs (Moncure et al., 1981).

While there are some fractures in the unit, they tend to be clogged with clay or zeolites and poorly hydraulically connected. Pumping tests in the unit indicate that fractured zones initially yield more water than the surrounding matrix, but the yield of these zones generally decreases rapidly as fractures are dewatered. Flow through the unit is probably controlled by interstitial permeability rather than fracture transmissibility (Winograd and Thordarson, 1975).

The UTCU, LTCU, WCU, and VCU are four HSUs in Frenchman Flat that are composed mostly of TCU. The matrix porosity in Section 5.4 is assigned to the TCU HGU as a whole, so these four HSUs will be assigned the matrix porosity from the TCU HGU as the effective porosity.

6.9 Carbonate Aquifer HGU

The CA HGU contains units Cambrian through Devonian in age and is mostly composed of limestone and dolomite. The unit is regional in extent and is an important source of water. The matrix porosity of the unit is low and fractures dominate flow through the unit (Winograd and Thordarson, 1975).

There are four sources of porosity that are available to determine effective porosity information for the LCA in the Frenchman Flat area.

1. Log triangular distribution assumed from a best estimate and minimum and maximum values.

Figure 6-3
Estimates of Effective Porosity for the Pahute Mesa WTA HGU

**Table 6-10
Estimates of Effective Porosity for the Pahute Mesa WTA HGU**

	Shaw (2003a)	Wolfsberg et al. (2002)
Mean	0.00018	0.00050
2.5% Percentile	0.000014	0.00011
97.5% Percentile	0.00052	0.0023
Distribution	Weibull ^a	Log Triangular ^{b, c}

^aDistribution fitted to sample in BestFit

^bLog {distribution} is the distribution fitted to the log transforms of the porosity values

^cDistribution assumed from a best estimate, minimum and maximum value

6.9.1 Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site (Winograd and Thordarson, 1975)

Winograd and Thordarson (1975) discuss the porosity of the LCA. The various porosities are summarized in [Table 6-11](#).

The first porosity listed is a bulk, or total porosity, determined by the difference in grain density and bulk density. The next porosity listed is called an effective porosity by Winograd and Thordarson (1975), but this is what is more commonly called matrix porosity in that it represents the accessible pore space of the unfractured LCA. The values were taken from mercury injection or water saturation measurements on core samples. A range of 0.000 to 0.090 was reported for this measurement with a median of 0.011 and a mean of 0.023 for 25 samples.

**Table 6-11
LCA Porosity Estimates from Winograd and Thordarson (1975)**

Porosity	Number of Samples	Range		Median	Mean
		Low	High		
Total Porosity	16	0.004	0.124	0.055	0.054
“Effective Porosity” / Matrix Porosity	25	0.00	0.09	0.011	0.023
Porosity of Partially Filled Fractures		0.00	0.01		0.001
Fracture porosity from 1963 (Geophysical Values)		0.01	0.12		
“Effective Fracture Porosity” mentioned at the end of the pumping test section of the document		a fraction of 1 percent			

A discussion on the fracturing of the rock in the area includes information on the porosity of partially filled fractures determined from core intervals. Winograd and Thordarson (1975) report, “The total porosity of the partly filled fractures is estimated to average [0.001] and to range from [0.00 to 0.01].”

The pumping test section of Winograd and Thordarson (1975) echoes the above estimate of effective fracture porosity “core examination suggests that the effective porosity of the lower carbonate aquifer is probably a fraction of 1 percent.”

It should also be noted that Winograd and Thordarson (1975) include the assertion that some wells drilled with air often had sudden increases in water production in short drill intervals. This assertion is further proof of fracture dominated flow within the LCA.

These estimates provide a general range for the effective porosity, but they are very broad and need to be supplemented with additional data from other studies.

6.9.2 Preliminary Tracer Experiment to Demonstrate Hydraulic Connectivity Between Water Wells C and C1, Yucca Flat, Nevada Test Site (Winograd and West, 1962) As Modified (Shaw, 2003a)

Winograd and West (1962) presents preliminary results of a tracer test conducted between Water Wells C and C-1 in the LCA under Yucca Flat. The report provides the transport time between the two wells, thicknesses of the LCA penetrated by the wells, pumping rates, and the distance between the two wells.

The results of the test were analyzed in the Frenchman Flat Groundwater Data Documentation Package (IT, 1999c) and then reprinted in the Pahute Mesa contaminant transport parameters report (Shaw, 2003a). The following is from the Shaw (2003a) report:

“The unconfined aquifer tapped by these wells is fractured limestone of Paleozoic age which, as shown by cores from Water Well C, transmits water primarily through fractures. The total depth of Water Well C is 518.5 m with 32.9 m of screen at the depth of 478.2 m to 511.1 m. The submersible pump delivered 1,200 m³/d, creating less than 0.15 m of drawdown. Water Well C-1 was drilled to a depth of 520.3 m. The opening (uncased hole) begins at the depth of 281.6 m to the bottom of the well. The actual distance between the two wells is 29.3 m at the water table.

Fluorescein, used as a tracer, was injected into Water Well C-1. The tracer was clearly seen in a sample collected 252 minutes after discharge began. Samples of water were collected periodically for 17 hours after the first appearance of the dye. The concentration of the tracer gradually increased to a maximum in another 3 to 4 hours (432 to 492 minutes after discharge began) and then slowly decreased until, in another 4 to 5 hours

(672 to 792 minutes after discharge began), it was no longer visually detectable. To estimate the effective porosity, the radial flow tracer experiment case of Welty and Gelhar (1989) was used to relate the time to the peak concentration to the pumping rate and porosity-thickness product through the relation:

$$t_m = \frac{R^2 \pi n b}{Q} \quad (6-9)$$

Where:

t_m = Time to the peak concentration (assuming a Gaussian breakthrough) [T]

R = Distance between wells [L]

Q = Discharge rate [L^3/T]

n = Effective porosity [Dimensionless]

b = Tested interval thickness [L]

This equation is similar to [equations \(6-3\) and \(6-4\)](#). Rearranging the equation and using $Q = 0.83$ cubic meters per minute (m^3/min), $R = 29.3$ m, and $t_m = 496$ min, the nb product is found to be 0.15 m. Using the thickness of 32.9 m from Water Well C, the effective porosity is 0.005. If the greater thickness from Water Well C-1 of 239 m is used, then the effective porosity is 0.00064.

The simplistic radial flow solution was used because the scarce experimental data did not allow the use of a more sophisticated solution. In the radial flow solution, the transport of the tracer is assumed to be caused by advection only. Other transport processes such as matrix diffusion are not accounted for in this method. The derived values of effective porosity may, therefore, be larger than the actual values.”

6.9.3 Lithologic Properties of Carbonate-Rock Aquifers at Five Test Wells in the Coyote Spring Valley Area, Southern Nevada, as Determined From Geophysical Logs (Berger, 1992)

Berger (1992) is an analysis of geophysical data from wells in the Coyote Springs Valley about 100 km due east of the Frenchman Flat area. The wells penetrate Paleozoic carbonate rocks that correlate to the CA HGU at the test site. Neutron-density, gamma-gamma density, acoustic transit-time, caliper, and natural-gamma logs from test well CE-DT-4 were analyzed to determine several different properties including fracture porosity. The calculated values for fracture porosity range from 0.006 to 0.096. Geophysical estimations of fracture porosity can be inaccurate. In this case, the fracture porosity estimate relies on geophysically estimated matrix density.

6.9.4 Influence of Pore Pressure on Apparent Dispersivity of a Fissured Dolomitic Aquifer (Leap and Belmonte, 1992); (Claassen and Cordes, 1975; Grove and Beetem, 1971; and Johnson, 1968)

The Amargosa Tracer Calibration Site is a USGS facility 45 km southwest of the Frenchman Flat area that has been set up to determine the properties of the carbonate aquifer beneath the NTS. The site is described in detail in Johnson (1968). Grove and Beetem (1971) contains an analysis of some early tracer tests, but the values listed for flow porosities are only approximated to allow calculation other parameters of interest to the authors.

Claassen and Cordes (1975) contains an estimate of a thickness (b) porosity (n) product for the aquifer (an nb product). The nb value determined was 0.88 m. Leap and Belmonte (1992) report the Claassen and Cordes (1975) nb product of 0.88 m, but the thickness porosity product that matched their test results was 0.84 m.

Leap and Belmonte (1992) describes the aquifer as a solution modified, low-angle reverse fault zone within the Cambrian Bonanza King dolomite from 3.1 m to 13.7 m thick. This is more or less consistent with the suggested range of 1.5 to 15 m listed as an effective thickness in Claassen and Cordes (1975). Combining a simple average of 3.1 m and 13.7 m (8.4 m) with a thickness porosity estimate of 0.84 m yields an effective porosity of exactly 0.10, which is the value reported in Leap and Belmonte (1992). This effective porosity is an overestimate for the carbonate unit as a whole because the thickness range is that of the fractured interval of the unit determined to be responsible for flow rather than the entire unit.

Johnson (1968) contains the lithologic logs, well completion details, and the results of a tracer injection survey to isolate permeable zones. The tracer test wells all fully penetrate and are either uncased or have perforated casing within the entire section of Cambrian Bonanza King dolomite. The thickness of the formation varies from 51.8 m to 20.7 m at the site. The Bonanza King dolomite is in fault contact with the underlying Cambrian Carrara Formation. Tracer Well 1 was originally open to 100.3 m of the Carrara Formation; however, the lower 58.7 m of the well was filled with a cement plug after the tracer injection survey did not find any significantly permeable areas within that section. [Table 6-12](#) lists estimated effective porosities for the LCA based on the nb product from Leap and Belmonte (1992) and various aquifer thicknesses from Johnson (1968).

6.9.5 Carbonate Aquifer HGU Summary

The range of porosity values for the LCA is listed in [Table 6-13](#). The fracture porosities are useful as a confirmation of maximum effective porosity; however, geophysical estimates tend to have a large margin of error. Tracer tests are the best way to determine effective porosity and will receive the most weight. The upper estimate of effective porosity from the tracer tests, 0.016, agrees well with the lower range of fracture porosity estimates. The highest of the fracture porosities,

Table 6-12
Effective Porosity of a Fractured Section of the LCA from
the USGS Amargosa Calibration Site

	Tracer Hole 2			Tracer Hole 3			Tracer Hole 1		
	ft	m	Effective Porosity ^a	ft	m	Effective Porosity ^a	ft	m	Effective Porosity ^a
Uncased Interval in Bonanza King Formation Dolomite ^b	148.0	45.1	0.019	170.0	51.8	0.016	68.0	20.7	0.041
Total Uncased Interval (within Carbonate Rock) ^b	169.0	51.5	0.016	187.0	57.0	0.015	205.0	62.5	0.013
Maximum Thickness of Carbonate Thickness Penetrated ^b							397.5	121.2	0.007

^aBased on a thickness porosity product of 0.84 m. Thickness (m) * Porosity = 0.84 m (Leap and Belmonte, 1992)

^bThicknesses from Johnston (1968)

Table 6-13
Summary of Effective Porosity Estimates for LCA

	Winograd and Thordarson (1975)	Berger (1992)	Winograd and West (1962) Shaw (2003a)	Amargosa Valley
	Core Fracture	Geophysical Fracture	Tracer	Tracer
High	0.01	0.096	0.005	0.016
Low	0	0.006	0.00064	0.007
Mean	0.001	--	--	--

0.096 from the Coyote Valley geophysical investigations, seems unrealistically high. For the Frenchman Flat area, a log uniform distribution between 0.00064 and 0.016 would best describe the uncertainty in CA effective porosity.

6.10 Clastic Confining Unit HGU

The Clastic Confining Unit (CCU) HGU contains the clastic sedimentary rocks in the model. There are two HSUs that correspond to the CCU. The UCCU HSU is composed of Late Devonian to Mississippian siliciclastic rocks. The LCCU encompasses the Precambrian to Devonian siliciclastic rocks that form the basement of the hydrologic model.

Winograd and Thordarson (1975) conclude that the elastic confining units lack integrated fracture transmissibility. Fractures are generally tightly sealed by either selvage minerals or by quartz or calcite veinlets. They list an effective porosity range of 0.006 to 0.050 with a mean and median of 0.019 as determined from mercury-injection and water saturation measurements on 20 core samples. This range is consistent with the matrix porosity values determined in [Section 5.0](#) and will be used for effective porosity of the CCU.

7.0 Dispersivity

This section includes descriptions of the role of dispersion in contaminant transport in groundwater, the available dispersivity data, and the data analysis and associated results. For additional information, the reader is referred to the technical basis document titled: *The Role of Dispersion in Radionuclide Transport - Data and Modeling Requirements* (SNJV, 2004f).

7.1 Role of Dispersion in Contaminant Transport

The hydrodynamic dispersion of solutes in groundwater describes the spreading phenomenon at a macroscopic level by the combined action of mechanical dispersion and molecular diffusion. At typical scales of observation, dispersion is a mixing process, the result of which causes dilution of the solute (Freeze and Cherry, 1979). The effect of dispersion is commonly quantified and measured in terms of longitudinal and transverse dispersivities. Assessment of aquifer dispersivity is essential for predicting contaminant concentrations in groundwater. The dispersivities, both longitudinal and transverse, are key input parameters to the governing transport equation used to estimate the concentration distribution of a solute in groundwater over time and space.

Dispersivity values are derived from data collected during tracer experiments or observation of plume migration. Based on the existing data, dispersivity appears to be scale-dependent (Grisak and Pickens, 1981; Gelhar et al., 1992; Neuman, 1990). Field-scale dispersion of plumes is generally accepted to be the result of the heterogeneous velocity field at scales smaller than the scale of the plume. Heterogeneity at scales larger than the plume cause changes in the mean position of the plume, but do not contribute to dispersion. The nature of heterogeneity likely differs from site to site; therefore, dispersivity values may differ from site to site, sometimes by orders of magnitude.

Field-scale tracer tests are limited in scale to a few hundred meters, so that experimentally derived dispersivity values are available only for short distances of transport. Dispersivity data for larger scales have been determined at some sites through calibration of transport models to observations of the distribution of contaminant plumes. With a site as large and as varied as the Frenchman Flat CAU, it is not practical to conduct tracer tests in enough locations to accurately measure dispersivity, particularly at a physical scale representative of transport for the 1,000-year period of interest. Tracer tests conducted at scales of a few hundred meters may not yield dispersivity values appropriate at the CAU scale because of the apparent trends in dispersivity with scale. Time and budget constraints make it nearly impossible to perform a tracer test at the CAU scale. Thus, the appropriate

dispersivity to use for the CAU-scale modeling will depend on the size of the plume and expected distance of travel. The treatment of dispersion in the CAU model will be documented as part of the model report. This contaminant transport parameter documentation report is intended to document the available data and provide a set of initial values for the transport model with suggested approaches for doing uncertainty analyses using two data distribution models.

7.2 Data Compilation

The dispersivity data types, the sources of data, and the data quality evaluation process are described in this section.

7.2.1 Data Types

As stated above, dispersivity values are derived from information collected during tracer tests or studies of contaminant plume migration. Data types needed to document dispersivity data include the location of the site, the primary lithology of the rocks, the concentration and identity of the tracer or contaminant that migrated, the scale of the analysis, and the data analysis method and results.

7.2.2 Data Sources

One contaminant migration experiment and several tracer tests have been conducted at or near the NTS. Five of these experiments were conducted at the following sites:

- CAMBRIC Site, Frenchman Flat, Nevada
- BULLION Test, Pahute Mesa, Nevada
- C-Well Complex, Yucca Mountain, Nevada
- Amargosa Tracer Calibration Site, Amargosa Desert, Nevada
- C-Well Site, Yucca Flat, Nevada

An experiment conducted at the CHESHIRE site was terminated prior to completion and dispersivity values were not determined. A seventh tracer study was conducted during 2004 in the LCA in southern Yucca Flat. The interpretation results from this tracer test these data are not available at the time this document was prepared. Additional data available from non-NTS sites were obtained from peer-reviewed scientific literature. The most current summaries of non-NTS dispersivity data are papers published by Gelhar et al. (1992) and Neuman (1990). Data from peer-reviewed literature will be used to supplement the tracer test data for the NTS and vicinity to derive a range of dispersivity values for use in the Frenchman Flat CAU model.

7.2.3 Data Documentation Evaluation

The DDE_Fs were assigned to information from a given tracer test based on the level of documentation available ([Section 4.0](#)). The BULLION FGE is the only tracer test conducted under the ERP and was assigned a DDE_F of 1 as adequate documentation is available. Documentation of the experiments conducted at the CAMBRIC and C-well complex of Yucca Mountain were assigned a level of 3 as these two tests were conducted outside of the ERP but are well documented. Documentation on the tracer tests conducted in Yucca Flat and Amargosa Desert was assigned a level 4. All other data were assigned a DDE_F of 5 as sufficient documentation on the procedures and their application during field data collection and analysis are not readily available.

7.3 Data Evaluation

The data evaluation approach is to summarize the existing NTS tracer experiments including the range of values obtained by different investigators. Data from dispersivity studies available in the scientific literature will then be incorporated to determine a range of values appropriate for the FF CAU transport modeling effort. Descriptions of the available data are presented, followed by the results of the data analysis.

7.3.1 Dataset Description

The dispersivity data derived from the available subsurface transport tests were compiled into a comprehensive dataset described in [Appendix F](#). The dataset includes 148 records containing NTS and non-NTS data. Summary descriptions of the available NTS-related and non-NTS dispersivity data are provided in this section. Dispersivity values derived from modeling are also presented and discussed. However, they were not included in the dataset because modeling studies rarely document numerical dispersion which can lead to overestimation of dispersivity because only a portion of the spreading is due to mechanical dispersion (SNJV, 2004f).

7.3.1.1 NTS Data

This section describes the contaminant migration experiment and tracer tests conducted to date at the NTS and vicinity. Results derived from the migration and tracer test data using different technical approaches are included in the descriptions. The data for five tests are summarized in [Table 7-1](#) and are described with regard to the aquifer type and geology, test method, tracer type, analytical method, and the derived longitudinal dispersivities.

**Table 7-1
Dispersivity Information Summary from the Nevada Test Site and Vicinity**

Site Location	Test Site Geology	Scale of Test (meters)	Test Method	Tracers	Analysis Method	Longitudinal Dispersivity (meters)	References
CAMBRIC Test, Frenchman Flat, Nevada	Tuffaceous Alluvium	91.0	Radial converging with monitoring the elutions of tritium and chlorine-36 at pumping Well RNM-2S	Nuclear test radionuclides: tritium	Welty and Gelhar, (1994)	9.6	Thompson, 1991 (calculation not included)
				Nuclear test radionuclides: tritium	Sauty's Method	2.0	Burbey and Wheatcraft, 1986
				Nuclear test radionuclides: tritium	Sauty's Method	9.1	Travis et al., 1983
				Nuclear test radionuclides: Cl-36, tritium	Sauty's Method	15.1	Thompson, 1988; Ogard et al., 1988
BULLION Test, Pahute Mesa, Nevada	Fractured Lava-Flow Aquifer, Calico Hills Formation	42.3 to 131.5	Radial converging with monitoring at an intermediate well and the pumped well	PFBA, DFBA, NaI, CML, polystyrene microspheres	Calibration of numerical 3-D transport model and 2-D analytic	10 (horiz. trans. 3) (vert. trans. 2)	IT, 1998a; Reimus and Haga, 1999
C-Well Complex, Yucca Mountain, Nevada	Bull Frog and Tram Tufts	90	Radial conversion with two injection wells	Iodide; DFBA; pyridone; PFBA; lithium bromide; polystyrene microspheres	1-D and 2-D analytical models	3.3 to 59	Winterle and La Femina, 1999
Amargosa Tracer Calibration Site, Amargosa Desert, Nevada	Cambrian Bonanza King Dolomite (fractured)	122.8	Doublet recirculation (tritium, sulfur-35, bromide)	Tritium (pulse)	1-D quasi-uniform Fitting of Grove's curves	15 to 30.5	Leap and Belmonte, 1992
C-Well Site, Yucca Flat, Nevada	Fractured Limestone	29.3	Radial converging (fluorescein) test at Well C and C-1	Fluorescein dye	2-D analytical Welty and Gelhar (1994)	0.6 to 1.4	Winograd and West, 1962 (calculation not included)

7.3.1.1.1 CAMBRIC Site

The CAMBRIC nuclear test was conducted in the subsurface at the NTS in May 1965. Beginning in 1974, the site was studied under the Hydrology Radionuclide Migration Project (HRMP) (also called the Radionuclide Migration [RNM] Project). The nuclear test took place at a depth of 294 m below land surface and below the water table in the tuffaceous alluvium of Frenchman Flat. There is very slow ambient groundwater movement at the location, and the radionuclides resulting from the test remained in the cavity region (Hoffman, 1979). The RNM-1 hole was drilled into the cavity in 1974. An auxiliary well, RNM-2S, was drilled 91 m away to a depth of 350 m. It was pumped continuously at an average rate of about 1.0 m³/min from October 1975 until October 1977, and then at an average rate of 2.3 m³/min until August 1991.

The concentrations of radionuclides were monitored. Analyses of water samples showed that the migration velocities of tritium, Cl-36, Kr-85, Tc-99, Ru-106, and I-129 were nearly the same, from the explosion site to the pumped well (Bryant, 1992). The concentration of Pu-239 at the pumping well was below the detection limit of 10^6 atoms per milliliter in water collected at the time of peak tritium concentration. As of 1990, the last samples collected from the cavity, levels of activity of both tritium and Kr-85 had fallen almost below the limits of detection capability (Thompson, 1991). Other radionuclides such as Sr-90 and Cs-137 decreased considerably in concentration in the cavity region during the period of pumping at Well RNM-2S. Less than 0.5 percent of the total Sr-90 and 0.0003 percent of the total Cs-137 accompanied the tritium to the pumped well, although both isotopes appear to have migrated away from the source zone to some extent. Additional monitoring results from the CAMBRIC experiment are presented and discussed in [Section 2.5](#).

In 1977, two years after initiation of groundwater pumping from Well RNM-2S, tritium began to appear in the water collected from Well RNM-2S. The tritium concentration peaked late 1980 and has been declining since. Although almost 91 percent of the CAMBRIC tritium source term had been pumped out of Well RNM-2S by September 1990, continued pumping allowed the definition of the tail of the elution curve (Thompson, 1991). The concentrations of tritium and Kr-85 (in $\mu\text{Ci/mL}$) versus the cumulative volume of water pumped (i.e., the elution curves) are shown in [Figure 7-1](#) and [Figure 7-2](#), respectively.

Figure 7-1
Tritium Concentration in Water Pumped from
Well RNM-2S versus Volume Pumped
(Thompson, 1991; activity concentrations corrected to
CAMBRIC zero time)

Figure 7-2
The ⁸⁵Kr Concentration in Water Pumped from Well RNM-2S
versus Volume Pumped
(Thompson, 1991; activity concentrations corrected
to CAMBRIC zero time)

With the above information, the longitudinal dispersivity (α) of the porous aquifer can be estimated by two different approaches. The estimates are presented below.

Welty and Gelhar Method

Welty and Gelhar (1989) developed an equation to estimate the longitudinal dispersivity as follows;

$$\Delta t = t_2 - t_1 = t_m \left[\frac{16\alpha}{3R} \right]^{1/2} \left[\left[1 - \left(1 - \frac{t_2}{t_m} \right) \left| 1 - \frac{t_2}{t_m} \right|^{1/2} \right]^{1/2} + \left[1 - \left(1 - \frac{t_1}{t_m} \right) \left| 1 - \frac{t_1}{t_m} \right|^{1/2} \right]^{1/2} \right] \quad (7-1)$$

Where:

- t_1 and t_2 = The times corresponding to the breakthrough concentration at the $C_m e^{-1}$ level, respectively, on both sides of the curve (T)(Figure 7-3)
- t_m = The time when peak concentration occurs (T)
- α = The longitudinal dispersivity (L)
- R = The distance between the injection well and the pumping well (L)

Using the tritium concentration data shown in Figure 7-1:

- Peak concentration $C_m = 7.0 \times 10^6$ pCi/L

Figure 7-3
Illustration of the Breakthrough-Curve, Pulse-Width Method of Analysis
(Welty and Gelhar, 1989)

- Cumulative volume of water pumped corresponding to the time at peak concentration, $V_m = 5 \times 10^6 \text{ m}^3$

The time variables t_1 and t_2 in [Equation 7-1](#) can be calculated from the following information:

- The value for C_m/e is $7.0 \times 10^6 / 2.7183 = 2.6 \times 10^6 \text{ pCi/L}$.
- The cumulative volume corresponds to C_m/e is $2.95 \times 10^6 \text{ m}^3$ (V_1) on the rising limb and $12.5 \times 10^6 \text{ m}^3$ (V_2) on the falling limb (illustrated as t_1 and t_2 , respectively, in [Figure 7-3](#)).
- Assuming continuous pumping at Well RNM-2S with a rate of $2.3 \text{ m}^3/\text{min}$ (Q), the time at V_1 , V_2 , and V_m is calculated by $t = V/Q$:
 - $t_1 = 891 \text{ days}$
 - $t_2 = 3,774 \text{ days}$
 - $t_m = 1,510 \text{ days}$

Using [Equation 7-1](#) with $R = 91 \text{ m}$, $t_1 = 891 \text{ days}$, $t_2 = 3,774 \text{ days}$; and $t_m = 1,510 \text{ days}$, the longitudinal dispersivity (α) calculated for the CAMBRIC experiment is 9.6 m .

Sauty Model

The transport of tritiated water from the source to the satellite well was compared with Sauty's (1980) 2-D calculation for instantaneous tracer injection in a radial, converging flow field that is similar to the RNM well tracer tests (Daniels, 1981; Daniels et al., 1983; Daniels and Thompson, 1984). Sauty provided a series of calculated "type curves" with dimensionless time T_r and dimensionless

concentration C_r for different Peclet numbers (Figure 7-4). The shape of the elution curve depends on the Peclet number, which is inversely proportional to the dispersivity. The smaller the Peclet number, the larger the dispersivity; hence, the broader and more skewed the elution peak. A Peclet number is defined as (Zheng, 1990):

$$P_e = \frac{|v|L}{D} \quad (7-2)$$

Where:

- v = The seepage velocity
- L = A characteristic length, commonly taken as the distance from the source to the point of observation
- D = The dispersion coefficient

Because D is equal to αv when ignoring the molecular diffusivity, Equation 7-2 can be reduced to:

$$P_e \approx \frac{L}{\alpha} \quad (7-3)$$

Figure 7-4
Type Curves for Instantaneous Tracer Injection in Radial Converging
Flow Field: Comparison with Derivative of Imposed Step Function
(Sauty, 1980)

To compare the experimental data with the calibrated type curves, the time of experiment has to be converted to a dimensionless T_r and, similarly, the observed concentration has to be converted to a dimensionless C_r . A dimensionless time $T_r = 1$ corresponds to the time required to pump the volume of water contained in a cylinder whose radius is the distance from the satellite well to the source. The dimensionless concentration, C_r , is calculated relative to the maximum concentration.

The Sauty model has been applied to the CAMBRIC site data several times. Three applications were performed by the following authors:

Burbey and Wheatcraft (1986)

In the case of the CAMBRIC site, the time to pump water from the 91-m radius cylinder from Well RNM-2S was estimated to be 2,100 days. From this point, the initial tracer breakthrough and the time to peak can be related to T_r . Sauty's type curve fitting those two points corresponds to a Peclet number of 45. The corresponding dispersivity (α) is estimated at about 2 m ($L = 91$ m, $P_e = 45$) from [Equation 7-3](#).

Burbey and Wheatcraft (1986) used this longitudinal dispersivity as an input parameter to a 3-D, transient, finite difference, transport model called the "Deep Well Disposal Model." In the model, the longitudinal dispersivity was not calibrated (i.e., fixed at 2 m), only the transverse dispersivity was calibrated. They used $\alpha_L/\alpha_T = 1.3, 0.67$, and 10.0 to produce the tritium concentration breakthrough curve. They concluded that the transverse dispersivity, $\alpha_T = 1.5$ m would produce the most accurate peak concentration in relation to the field data.

Travis et al. (1983)

Travis et al. (1983) employed a 3-D numerical code "TRACR3D" to the overall transport problem at the CAMBRIC site. They also used Sauty's type curves to fit the field elution data for tritium. A good fit was found for data from Well RNM-2S using a Peclet number of 10 ([Figure 7-5](#)), but the tritium source had to be adjusted downward to 70 percent of the original estimated value. With $P_e = 10$, the longitudinal dispersivity was estimated to be 9.1 m. The need to use a reduced initial concentration makes this result less reliable than the others.

Thompson (1988) and Ogard et al. (1988)

In the migration study of tritium and Cl-36, it was found previously that the Cl-36 elution at Well RNM-2S preceded the tritium elution by a significant volume (Thompson, 1988) ([Figure 7-6](#)). Researchers at LANL attributed this phenomenon to the "anion exclusion" effect, that is, anions such as chloride were eluted before cations or neutral species such as tritiated water. Anions, being of the same charge as the clays and zeolites in the soil, are repelled and effectively prevented from entering into the intragranular porosity of the soil particles. Also, the anion exclusion effect will tend to keep the anions in the center of the pore channels, where groundwater velocities are higher. Although a Sauty-type curve with $P_e = 10$ fits the tritium data through the maximum, a better fit to the tailing portion of the data up to 12×10^6 m³ of the water pumped can be made using a type curve with a Peclet number of 6 ([Figure 7-7](#)). A Peclet number of 6 corresponds to a dispersivity of 15.1 m. A similar fit to the Cl-36 data is shown on [Figure 7-8](#). The difference in slope between data and the Sauty curve at a longer pumping time is evident (especially for Cl-36), which indicates that a curve with a still lower Peclet number; hence, a higher dispersivity ([Equation 7-3](#)) may be expected to fit the subsequent data. The alluvium of Frenchman Flat is heterogeneous with interbedded fine- and coarse-grained material. If the observed dispersion includes a dead-end pore or mobile/immobile effects, then the observed dispersivities may be an over-estimate of the mechanical dispersion. On the other hand, the excellent

Figure 7-5
Tritium Concentration Data (X) for Well RNM-2S Water and Calculated Elution of Tracer after Instantaneous Tracer Injection in a Radial Converging Flow Field for Peclet Number 10 (Daniels and Thompson, 1984)

Figure 7-6
Elution of Tritium and Cl-36 from Well RNM-2S (Thompson, 1988)

Figure 7-7
Elution of Tritium Compared with Sauty Model (Thompson, 1988)

Figure 7-8
Elution of Cl-36 Compared with Sauty Model (Thompson, 1988)

fit between observed and theoretical breakthrough curves suggests that using the derived dispersivities will be adequate for simulation of transport in Frenchman Flat alluvium with a single porosity model.

7.3.1.1.2 BULLION Site

The field portion of the BULLION FGE was performed from June to August 1997 at the BULLION underground nuclear test site on Pahute Mesa, Area 20, of the NTS (see [Section 6.6](#)). Three characterization wells (ER-20-6 #1, #2, and #3) were completed in a fractured lava-flow aquifer, approximately downgradient of the BULLION cavity, aligned with the dominant fracture system. The most downgradient well (#3) was pumped to induce groundwater movement from the BULLION cavity and from Wells #1 and #2 to Well #3. The distance between wells (i.e., straight line length) ranged from 42 to 132 m (IT, 1998a). The shortest distance is between Wells #1 and #2 and the largest distance is between Wells #1 and #3. Pentafluorobenzoic acid and yellow polystyrene microsphere tracers were injected into Well #2. Sodium iodide, difluorobenzoic acid, and red polystyrene microspheres were injected into Well #1. Tracer concentrations were monitored to produce decline and/or breakthrough curves for each well. Hydraulic data were also collected during the FGE. Groundwater flow and tracer transport were evaluated by analytical (Reimus and Haga, 1999) and numerical modeling (IT, 1998a). Further details and discussion of BULLION FGE are presented in [Section 6.5](#) regarding the determination of effective porosity. Based on calibration of the BULLION numerical transport model, the following dispersivities were determined ([Table 7-1](#)):

- Longitudinal: 5, 10, or 25 m (alternative calibrations)
- Horizontal transverse: 1, 3, or 7.5 m (alternative calibrations)
- Vertical transverse: 1, 2, or 5 m (alternative calibrations) (IT, 1998a).

The semi-analytical solutions of Reimus and Haga (1999) yielded the following dispersivity values:

- Longitudinal: 9 to 30 (alternative calibrations)
- Horizontal transverse: not applicable
- Vertical transverse: not applicable

The longitudinal and horizontal transverse dispersivities are in the range of measured values summarized by Gelhar et al. (1992) for tests at scales of about 100 m. Both the numerical and semi-analytic models simulated matrix diffusion as a separate process. Therefore, the longitudinal dispersivities are representative of mechanical dispersion and are not biased upward by lumping matrix diffusion effects. There is not much confidence in the horizontal transverse dispersivity because the radial flow configuration of the FGE is not sensitive to transverse dispersion due to averaging at the pumped well. The vertical dispersivity is also unreliable because the tracer was vertically mixed within the model layer. Therefore, the vertical dispersivity in the model was irrelevant.

The longitudinal dispersivity for the shorter flow path (42 m from Well #1 to #2), may be too large, based on a sensitivity analysis of dispersivity where it appeared that a relatively large dispersive flux was causing tracer migration upgradient against the direction of groundwater flow. This situation is physically unrealistic (IT, 1998a). Another explanation for the large spreading predicted by the model, including upgradient, may be numerical dispersion. If this is a numerical dispersion effect, then part of the dispersive flux is generated by the numerical dispersion and the calibrated longitudinal dispersivity may be too small. The similarity between the numerical and semi-analytical (which does not suffer from numerical dispersion) derived longitudinal dispersivity suggests that the impact of numerical dispersion is not too large.

7.3.1.1.3 C-Well Complex Site

The C-well complex is located at Yucca Mountain, Nevada, less than 16 km south of the Pahute Mesa-Oasis Valley area. The flow and transport experiments were conducted to determine the properties of the Bullfrog volcanic tuff beneath Yucca Mountain in the saturated zone.

Shaw (2003a) reports that the estimated transmissivity of the aquifer, determined from pump tests, varies from 640 to 3,500 square meters per day (m^2/d), with much of the variance due to a significantly higher transmissivity for Well C#2, which may not be indicative of the large-scale aquifer properties. Composite analysis of the aquifer tests using the Theis method yielded 2,200 m^2/day , and considering horizontal anisotropy, the Papadopoulos method gave 1,300 m^2/day (Shaw, 2003a). The horizontal anisotropy analysis indicates a directional transmissivity of 2,900 m^2/day oriented N 33° E, and a minimum of 580 m^2/day at N 123° E (Shaw, 2003a). Shaw (2003a) reported that the fracture network is primarily responsible for the anisotropy.

The tracer tests consisted of two pilot tests using PFBA and iodide, and a long-term multiple-tracer test using PFBA and lithium bromide. Colloidal transport was also performed using 360-nanometer (nm) microspheres. The method used to estimate the aquifer parameters is described in Appendix A of Reimus et al. (1999b). The method applies to 1-D, steady-state, advective-dispersive flow through parallel-plate fractures in a homogenous, dual-porosity aquifer. The longitudinal dispersivity from the single successful pilot test is reported to be 1.1 m. The longitudinal dispersivity from the long-term test yielded a range from 3.3 to 59 m (Winterle and La Femina, 1999). The test provided important information about the relative role of matrix diffusion as a result of normalized peak concentrations between bromide and the PFBA. Although the matrix diffusion was not specifically determined, it was apparent that it played an important role as an effective attenuation mechanism for dissolved species in the volcanic aquifer.

7.3.1.1.4 Amargosa Tracer Calibration Site

Tracer tests were conducted at the Amargosa Tracer Calibration Site (see [Section 6.9](#)) located in the Amargosa Desert in southern Nevada, approximately 24 kilometers southwest of Mercury, Nevada (Leap and Belmonte, 1992). The objectives of the tracer tests were to:

- Determine the apparent longitudinal dispersivity of a fissured and fractured aquifer within the Cambrian Bonanza King dolomite draining the NTS.
- Determine the effective porosity of the carbonate aquifer.
- Study the usefulness of tritium, sulfur-35, and bromide as tracers in this aquifer.

The tests were performed under different recirculating rates and pore pressures. Two fully penetrating wells, aligned parallel with the direction of regional flow (northeast to southwest), were used for tracer recirculating tests. The injection well was located 122.8 m upgradient of the pumping well, and they were connected together by a polyvinyl chloride (PVC) pipe. Measurements of the transmissivity of the aquifer ranged from 4,800 to 10,900 m²/day. The storage coefficient was approximately 5×10^{-4} and the regional hydraulic gradient was between 10^{-4} and 10^{-5} . Two other fully penetrating wells in the vicinity were used to collect water samples.

Breakthrough curves were constructed from analysis of effluent samples collected from the pumping well. These curves were matched and compared to synthetic curves constructed from various combinations of porosity and longitudinal dispersivity using the Grove method (Grove and Beteem, 1971), which provides a solution to the Fickian dispersion model. Apparent dispersivities of the aquifer were then taken to be those of the best-fit synthetic curves, within an accuracy of ± 3.0 m.

The results of these tests are as follows:

- Test 1 (tritium as tracer) yielded a best-fit apparent dispersivity of 15 m and a porosity of 10 percent.
- Test 2 (sulfur-35 in the form of sodium sulfate as tracer) yielded a best-fit dispersivity of 22.9 m and a porosity of 10 percent.
- Test 3 (tritium and bromide as tracers), the tritium curve fit yielded an apparent dispersivity of 27.4 m and a porosity of 10 percent; the bromide curve fit yielded an apparent dispersivity of 30.5 m and a porosity of 10 percent. The tests were run at a recirculation rate of 31 percent less than that of Test 1.

The relatively large difference in apparent dispersivity between the sulfur-35 and tritium tests is likely caused by greater adsorption and/or retardation of the more

active sulfate ion than that of either the bromide or tritiated water. The 10 percent difference in computed apparent dispersivity between the two tracers (tritium and bromide) for the same recirculation rate (Test 3) was attributed to the adsorption or retardation difference between tritium and bromide. The difference between Tests 1 and 3 is more difficult to explain. Leap and Belmonte (1992) postulated that the differences were due to changes in fracture openings caused by the increased pressure for the higher flow test. The variation between Tests 1 and 3 emphasizes the typical range in dispersivity values at a single site. These tests were interpreted using a single-porosity transport conceptualization, ignoring transport in fractures and fracture-matrix interaction. The impact of this interpretation approach on the dispersivities and porosities determined is unknown.

7.3.1.1.5 C-Well Site, Yucca Flat

The tracer test was conducted at the southern end of Yucca Flat in Area 6 of the NTS to determine the rate of movement of groundwater between two wells (Water Wells C and C-1) 30.5 m apart (Winograd and West, 1962) (see [Section 6.9](#)). The objective of the test was to understand whether the drilling mud used at Water Well C-1 might be carried by groundwater to the production Well C.

The unconfined aquifer tapped by these wells is fractured limestone of Paleozoic age which, as shown by cores from Water Well C, transmits water primarily through fractures. The total depth of Water Well C is 518.5 m with 32.9 m of screen at the depth of 478.2 to 511.1 m. The submersible pump delivered 1,200 m³/d creating less than 0.15 m of drawdown. Well C-1 was drilled to a depth of 520.3 m. The opening (uncased hole) begins at the depth of 281.6 m to the bottom of the well. The actual distance between the two wells is 29.3 m at the water table.

Fluorescein, used as a tracer, was injected in Water Well C-1. The tracer was clearly seen in a sample collected 252 minutes (t_0) after discharge began. Samples of water were collected periodically for 17 hours after the first appearance of the dye. The concentration of the tracer gradually increased to a maximum in 3 to 4 hours (432 to 492 minutes) after discharge began, and then slowly decreased until, in another 4 to 5 hours ($t_e = 672$ to 792 minutes) after discharge began, it was no longer detectable with the naked eye.

The velocity of the first arrival was estimated to be 0.12 meters per minute. However, the peak concentration was not included in the report.

The Welty and Gelhar (1989) approach, was used to estimate the longitudinal dispersivity, but since the peak concentration (C_m) is not available, t_1 and t_2 were estimated assuming that the breakthrough curve is a triangular distribution ([Figure 7-9](#)), meaning that the following proportionality holds:

$$\frac{t_1 - t_0}{t_m - t_0} = \frac{\frac{C_m}{e}}{C_m} = \frac{1}{e} \quad (7-4)$$

Figure 7-9
Conceptualized Breakthrough Curve

Where t_m is the average of the time interval (432 to 492 minutes) during which the peak concentration was reported. This implies that t_1 is not a function of C_m . In other words, t_1 and t_2 can be estimated regardless of C_m . Using Equation 7-4, t_1 was calculated to be 329 minutes. Likewise, t_2 was estimated to be 632 minutes. Therefore, using Equation 7-1, $\alpha = 0.6$ m. An alternative interpretation would be to use t_0 for t_1 (252 minutes) and t_e for t_2 (732 minutes), thus providing a longitudinal dispersivity of $\alpha = 1.4$ m.

7.3.2 Non-NTS Dispersion Studies

Dispersivity data available for locations outside the NTS were obtained from the review paper prepared by Gelhar et al. (1992). Thirty seven additional data records were also collected from peer-reviewed publications reported after Gelhar et al. (1992).

Gelhar et al. (1992) reviewed dispersivity observations from 59 different field sites, domestic and abroad. The review included tabulation of information on site location, description of aquifer material, average aquifer saturated thickness, hydraulic properties, effective porosity, mean pore velocity, flow configuration, dimensionality of monitoring network, tracer type, method of data interpretation, overall scale of observation, and longitudinal and transverse dispersivities from original sources (Gelhar et al., 1992).

Gelhar et al. (1992) classified the dispersivity data into three reliability classes corresponding to the data quality evaluation flags described in Section 7.4.1. The analysis indicated a trend of systematic increase of the longitudinal dispersivity with observation scale, but the trend is much less clear when the reliability of the data is considered. The longitudinal dispersivities reported by Gelhar et al. (1992) ranged from 10^{-2} to 10^4 m for travel distances ranging from 10^{-1} to 10^5 m; however, the largest distance with high-reliability data was only 250 m, and the longitudinal dispersivity was only 4 m. Gelhar et al. (1992) also concluded from the data that, overall, dispersivity values did not appear to vary with lithology (porous versus fractured media).

Gelhar et al. (1992) reported that, based on two high-reliability data points, horizontal transverse dispersivity is one order of magnitude less than longitudinal dispersivity. Gelhar et al. (1992) found that in all cases where both horizontal and vertical transverse dispersivities were measured, the values of vertical transverse dispersivity were one to two orders of magnitude less than those of the horizontal transverse dispersivity.

7.3.3 Dispersivity Estimation Through Modeling

Borg et al. (1976) and Neuman (1990) reported longitudinal dispersivity obtained from the calibration of numerical solute transport models against hydraulic and concentration data. More recently, Hu (1998) derived dispersivity values from contaminant transport simulations in heterogeneous porous material in Frenchman Flat using a random field approach.

The longitudinal dispersivities reported by Borg et al. (1976) ranged from 11.6 to 91 m for a wide variety of lithologies, ranging from glacial outwash sand and gravel, basalt lava, to dolomite and limestone. The value was 21.3 m for a sand or gravel deposit, which is a lithology that most closely resembles the tuffaceous alluvium at the CAMBRIC site (Daniels and Thompson, 1984). The dispersivity for the Bonanza King Formation near the NTS was estimated to be 15 m (Borg et al., 1976).

Neuman (1990) provided a universal scaling model that described the increase in longitudinal dispersivity as a function of scale for laboratory and field transport studies. When the universal scaling model was applied to calibrated, numerical model results for plumes with transport scales greater than 100 m the model fit was poor; therefore, inconsistent with theoretical results. However, the dispersivities obtained from the calibrated, numerical models were found to vary more slowly with the scale of the study than did dispersivities determined by other from field and laboratory measurements. This appears to be because calibration often provides information about the spatial variation of hydraulic conductivities on scales exceeding the dimensions of model subregions (called “zones”) within which they are kept constant or allowed to vary at a relatively slow rate. The calibrated dispersivities are associated with a reduced length scale L_r that depends on the dimensions of the zones rather than on the mean travel distance L_s of the plume. A regression analysis showed that L_r increased with the mean travel distance at an average rate proportional to $L_s^{0.5}$. This, in turn, explains that groundwater modelers tended to design the zones of their computational grids in a manner roughly proportional to $L_s^{0.5}$. Neuman (1990) concluded that the scale parameter not only controls dispersivities in a given transport model, but that the scale parameter diminished as the density of information about hydraulic heterogeneity increases.

The DRI performed 50 transport simulations of a hypothetical nonreactive contaminant in heterogeneous Frenchman Flat HSUs (Hu, 1998) using a random field approach. Effective dispersivities were derived from each of the simulations. Based on the locations of underground nuclear tests, two separate areas of Frenchman Flat were selected for modeling: a northern test area (tests conducted

near the border of Areas 5 and 11) and a central test area (tests conducted near the center of Frenchman Flat). Input data for the simulations included randomly generated hydraulic conductivity fields from Shirley et al. (1996) and hydraulic head data from the regional model (DOE/NV, 1997) at the simulation boundaries. Table 7-2 presents the mean dispersivities derived from the transport simulations. For the northern test area, the mean groundwater flow was mainly downward, and for the central test area primarily horizontal (Hu, 1998).

**Table 7-2
Dispersivity from Hypothetical Transport Simulations for
Frenchman Flat Underground Test Areas**

Test Area	Transport Distance (meters)	Flow and Transport Direction	Mean Longitudinal Dispersivity (meters)	Mean Horizontal Transverse Dispersivity (meters)	Mean Vertical Transverse Dispersivity (meters)
Northern	1,280	Downward	$9^c < 74 < 394^d$	ND ^a	ND
Northern	400	Downward	$7 < 45 < 286$	$0.5 < 2.1 < 14$	$0.7 < 6.0 < 88^b$
Southern	3,000	Horizontal	$72 < 320 < 1,421$	$6 < 21 < 24$	$2 < 6.3 < 42$
Southern	1,200	Horizontal	$42 < 176 < 882$	$4 < 10 < 38$	$1 < 4.2 < 19$

^aNo data

^bNot a vertical dispersivity; both transverse dispersivities are horizontal, because flow direction is downward

^cThe smallest dispersivity of the simulations

^dThe largest dispersivity of the simulations

Table 7-2 also contains the smallest and largest dispersivity determined from any of the realizations. The reader will notice that the ranges are quite large, typically spanning between 1 and 2 orders of magnitude. Additionally, for flow perpendicular to the layering (northern test area), the range of values is typically larger than for flow parallel to layering (central test area). The longitudinal dispersivity values fall in the range of values as presented by Gelhar et al. (1992). The same is true for the horizontal transverse dispersivity (for the northern test model of 400 m, both transverse dispersivities are horizontal). The vertical dispersivities from the modeling of Hu (1998) tend to be much larger than observed data. The comparison is tenuous, however, because of the lack of vertical dispersivity measurements at scales in the literature greater than 300 m.

The values determined from the work of Hu (1998) are generated from hypothetical conductivity fields and cannot be treated as data. However, it illustrates one method to estimate large-scale dispersivity values. If the characteristics of the heterogeneity can be quantified and represented by a covariance function, then multiple realizations of the random field can be created. These random fields are generated on a model grid that is much smaller than the scale of interest (i.e., plume scale or maximum distance of travel). Simulating flow in the random field explicitly models the small-scale velocity variations that lead to dispersion. The simulated contaminant distributions are summarized by spatial moments or averaged over a breakthrough plane to yield apparent dispersion. These apparent dispersivities are applicable to the larger scale

transport simulations using the advection-dispersion-equation (ADE) approach. The limitation and uncertainty in this method is the scarcity of data with which to define the heterogeneity.

7.4 Data Evaluation

Data assessment includes an evaluation of data quality and an evaluation of the variability of dispersivity values and the factors influencing them.

7.4.1 Data Quality Evaluation

Data Quality Evaluation Flags were used to rank the level of quality of the data. The quality levels defined correspond to the levels of reliability defined by Gelhar et al. (1992). They are as follows:

- Level 1: Corresponds to “High Reliability” Level I data of Gelhar et al. (1992). The tracer study meets the following criteria: (1) tracer test was either ambient flow, radial diverging flow, or two-well instantaneous pulse test without recirculation, (2) tracer input was well defined, (3) tracer was conservative, (4) spatial dimensionality of the tracer concentration measurements was appropriate, and (5) analysis of the tracer concentration data was appropriate and consistent with the measurements.
- Level 2: Corresponds to “Intermediate Reliability,” Level II, of Gelhar et al. (1992). Tracer study does not meet the criteria for high or low reliability.
- Level 3: Corresponds to Gelhar et al.’s (1992) “Low Reliability,” Level III. Tracer study meets the following criteria: (1) two-well recirculating test with step input was used, (2) single-well, injection-withdrawal test with tracer monitoring at the single well was used, (3) tracer input was not clearly defined, (4) tracer breakthrough curve was assumed to be the superposition of breakthrough curves in separate layers, (5) measurement of tracer concentration in space was inadequate, and (6) equation used to obtain dispersivity was not appropriate for the data collected.

7.4.2 Evaluation of Scale Dependency

A preliminary examination of the dispersivity dataset ([Appendix F](#)) which has been updated to include newer data confirms Gelhar et al.’s (1992) conclusion that dispersivity values do not appear to be differentiated with respect to lithology (porous versus fractured media). The evaluation was, therefore, limited to examining the scale dependency. Log-log plots were prepared using the dataset ([Appendix F](#)) to analyze the variations in longitudinal, transverse horizontal, and

transverse vertical dispersivity with the scale of the tracer test or contaminant plume (Figure 7-10, Figure 7-11, and Figure 7-12, respectively). In each figure, if multiple interpretations of a test or plume were reported, the mean of value was used for the evaluation.

The analysis indicated a trend of systematic increase of the mean longitudinal dispersivity with observation scale (mean as calculated by the minimum and maximum for a particular data interpretation), as shown in Figure 7-10. These findings are consistent with those of Gelhar et al. (1992) and Neuman (1990) and indicate that, in general, larger dispersivity values are associated with larger scale problems. The longitudinal dispersivities ranged from 5×10^{-3} to 2.28×10^4 m for travel distances up to 10^5 m. However, the trend is much less clear when the quality of the data is considered: the largest distance with high-reliability data (DQE_F=1) was only 280 m with a longitudinal dispersivity of 7.5 m. The high-reliability data tends to be somewhat smaller in magnitude than other data at any particular scale. At large scales only lower quality data is available which leads to greater uncertainty in dispersivity for large plumes or longer transport distances.

Figure 7-10
Mean Longitudinal Dispersivity Versus Transport Scale

The scale dependency is, however, still somewhat debated. The data presented in this document should not be interpreted to suggest that dispersivity simply increases with distance for any particular plume. At two sites, Borden and Otis Air Force Base, the dispersivity was observed to increase for a limited distance

Figure 7-11
Transverse Horizontal Dispersivity Versus Transport Scale

and then reach an asymptote. In Neuman's model (1990), universal scaling is operative over large distances and dispersivity may increase significantly as plumes migrate downgradient. However, many examples exist of long plumes that retain relatively modest dispersion, such as the Cape Cod sewage lagoon plume of LeBlanc (1982). An additional interpretation is for the plume-scale dispersivity to reach an asymptote, while the plume remains within a geologic unit with a stationary covariance function describing variability. As the plume crosses into other geologic units (with presumably different correlation structure), the plume may again begin to exhibit increased spreading. The dispersivity for this case may, in fact, be represented by a series of increasing plateaus.

The data available for horizontal transverse dispersivity, or the spreading of the tracer at right angles to the direction of groundwater flow horizontally, is shown in Figure 7-11. Transverse horizontal dispersivities up to 1,370 m have been observed. Although not as numerous as in the longitudinal case, the low quality data exhibit the same pattern as longitudinal dispersivity of increasing value with distance. However, the appropriate value at large scale is not at all clear. Although low-reliability data show an increasing trend, the intermediate- and high-reliability data show a trend of constant horizontal dispersivity values with scale. The horizontal transverse dispersivity is, in general, about one order of magnitude less than the longitudinal dispersivity, but is much smaller if only high-reliability data are included.

Figure 7-12
Transverse Vertical Dispersivity Versus Transport Scale

Figure 7-12 depicts the sparse data for transverse vertical dispersivity or the vertical spreading of the tracer. Transverse vertical dispersivities up to 2 m have been observed. A possible trend of increasing values is indicated by the low- and intermediate-reliability data, but no trend appears with the high-reliability data. The only significant observation is that the transverse vertical dispersivity is much less than either longitudinal or horizontal transverse dispersivity. This reduction in spreading may be controlled mainly by the layering of the geologic materials themselves, where less permeable layers will significantly reduce the ability of the tracer to disperse upward or downward.

The measured longitudinal dispersivity values for the NTS region and worldwide are shown in Figure 7-13. These are the same data as the data plotted in Figure 7-10, but Figure 7-13 highlights all of the data collected at the NTS. It can be clearly seen in Figure 7-13 that the values of dispersivity from tracer tests conducted at the NTS and vicinity are consistent with those derived from tracer tests conducted elsewhere.

Figure 7-13
NTS Data as Compared to Non-NTS Data for Longitudinal Dispersivity

SNJV (2004f) summarized several important conclusions related to the selection of dispersivity for solute transport modeling for the NTS based on the available information. They are as follows:

- The longitudinal dispersivity apparently increases with scale (distance from the contaminant source or the spacing between the injection well and the monitoring well). However, it is not clear how increases occur for an individual plume. Some data suggest that if dispersivity increases, it is not a smooth monotonic function of travel distance.
- The ratio longitudinal dispersivity/transverse dispersivity is in the range of 3 to 50, and the ratio of longitudinal dispersivity/vertical dispersivity is in the range of 10 to 700. The vertical dispersivity is also about 10 to 100 times smaller than the horizontal transverse dispersivity.
- As the density of information about hydraulic conductivity increases, the effect of the scale parameter may be reduced. Dispersivity accounts for unmeasured variability. As more of the variability is modeled explicitly, the dispersivity does not need to increase.
- The lithology, porous or fractured media, has no significant effect on the dispersivity. In other words, dispersivities used for porous media can also

be used in fractured media. This conclusion is considered valid at the scale of the Frenchman Flat CAU model.

- The longitudinal dispersivity data from the NTS fall within the range of values published in peer-reviewed scientific literature.

7.5 Scaling Considerations

As presented in [Section 7.4.2](#), the dispersivity values tend to be scale dependent. As a result, it is helpful to know the expected distances of contaminant transport *a priori* to best assess the range of dispersion values that would be most appropriate for modeling efforts. For Frenchman Flat, Phase I modeling activities provide insight into the expected transport distances from each of the nuclear test locations. As a means to constrain the initial dispersion values for use in the CAU-scale transport model, the expected transport distances from Phase I were used to develop a range of anticipated contaminant transport distances. [Table 7-3](#) contains the calculated transport distances from the uncertainty analysis conducted for the Phase I model. The geometric mean of the travel distances is between 163 and 588 m for all tests other than the WISHBONE Test, where little transport (less than or equal to 3 m) was simulated. Based on the longitudinal dispersivities for high quality data presented in [Figure 7-10](#) for scales identical to the simulated transport, it appears that dispersivity values measured at Frenchman Flat will be appropriate for transport modeling. If, however, transport occurs over a greater distance, scaling for dispersivity is uncertain; therefore, a range of longitudinal dispersivities will be defined to account for this uncertainty, see [Section 7.6](#). The sensitivity of the assigned ranges will be tested in the modeling via sensitivity and uncertainty analyses.

The transverse and vertical dispersivity are also scale-dependent parameters, but the trends with increasing scale are more uncertain than was the case with longitudinal dispersivity. High-reliability data suggest that the transverse and vertical dispersivities will always be small, regardless of scale. However, there is no consensus among researchers defining the large-scale behavior of the transverse dispersivities. We must, therefore, leave open the possibility that larger transverse and vertical dispersivity values are possible at large scales.

7.6 Dispersivity Parameter Distributions and Uncertainty Models

The dispersion dataset, described above, was sorted by the scale of the transport to isolate data within the range of geometric means observed during Frenchman Flat Phase I transport modeling. Records that contained minimum and maximum dispersivity values or distance of transport were averaged to provide a mean value for use in the analysis. Data quality evaluation scores described in [Section 7.4.1](#) were used as weights during construction of CDFs. A weight of 100 was assigned to data quality evaluation 1, weights for the other data quality evaluation scores decreased by an order of magnitude for each subsequent data quality evaluation rank.

**Phase II Contaminant Transport Parameters for the Groundwater Flow and
Contaminant Transport Model of CAU 98: Frenchman Flat, Nye County, Nevada**

Table 7-3
Transport Distance (m) after 1,000 Years from each Test Location Calculated from
Frenchman Flat Phase I Transport Modeling Uncertainty Runs (IT, 1999c)
(Page 1 of 2)

Realization	Wishbone	Diluted Waters	Cambric	Derringer	Milk Shake	Pin Stripe	New Point	Diana Moon	Minute Steak	Diagonal Line
basekh	2	258	529	143	254	111	174	153	84	91
1	1	195	406	121	216	71	144	122	82	76
2	1	211	441	131	240	37	156	136	101	84
3	1	149	313	105	191	42	130	106	70	65
4	1	200	420	103	199	38	127	101	51	63
5	1	213	437	105	198	52	129	104	59	64
6	1	254	522	141	255	140	163	140	87	89
7	1	173	361	114	206	62	136	112	72	70
8	2	536	984	260	500	107	297	287	222	170
9	2	355	711	250	454	248	282	273	261	213
10	1	177	371	144	250	92	169	153	137	94
11	2	348	713	272	498	217	316	311	314	222
12	1	144	303	117	204	53	142	124	108	74
13	1	445	873	256	471	294	282	265	183	215
14	0	141	293	74	142	30	105	75	58	41
15	1	156	330	116	214	50	137	111	66	67
16	1	175	367	112	205	88	134	108	59	68
17	2	319	663	264	473	283	299	290	296	227
18	2	744	1311	394	717	448	465	463	408	435
19	2	367	773	298	540	208	329	317	273	216
20	2	502	997	398	749	272	486	486	503	311
21	1	361	728	216	384	185	235	216	153	144
22	2	330	692	243	430	341	262	245	183	208
23	2	587	1104	310	569	198	352	339	236	221
24	1	240	502	142	267	50	164	142	89	87
25	2	409	828	301	551	400	337	327	299	320
26	1	405	816	272	504	400	305	295	254	302
27	1	241	499	137	247	400	159	136	84	86
28	1	353	705	240	435	250	266	255	227	193
29	1	328	689	219	396	243	240	220	142	153
30	2	485	942	355	674	425	430	431	464	404

Table 7-3
Transport Distance (m) after 1,000 Years from each Test Location Calculated from
Frenchman Flat Phase I Transport Modeling Uncertainty Runs (IT, 1999c)
 (Page 2 of 2)

Realization	Wishbone	Diluted Waters	Cambric	Derringer	Milk Shake	Pin Stripe	New Point	Diana Moon	Minute Steak	Diagonal Line
31	1	64	156	84	162	35	122	95	81	56
32	1	431	847	208	378	195	229	207	112	133
33	1	169	358	160	277	250	184	168	152	104
34	1	195	419	150	278	129	174	155	117	94
35	2	823	1419	458	818	623	626	599	476	631
36	2	310	645	236	414	356	259	248	226	228
37	1	311	619	168	315	192	192	172	121	107
38	2	454	921	366	704	497	449	456	477	499
39	2	363	771	304	545	966	333	320	275	539
40	2	845	1418	422	765	270	496	499	434	322
41	2	500	1029	435	818	325	545	574	561	375
42	1	88	205	76	153	33	104	69	49	42
43	2	560	1074	380	720	346	459	460	448	364
44	3	507	1064	450	818	536	591	673	608	512
45	1	280	615	296	551	340	354	355	375	321
46	2	366	776	266	480	648	290	273	190	287
47	1	99	217	91	172	53	120	93	63	56
48	1	118	258	154	253	74	183	171	175	107
49	2	162	364	236	403	904	254	241	224	246
50	2	401	893	437	802	830	645	755	759	643
51	1	430	853	294	554	847	342	339	328	573

Cumulative distribution functions for longitudinal, transverse horizontal, and transverse vertical dispersivity with transport distances between 150 and 600 m are shown in Figure 7-14. The central value [$F(x) = 0.5$] of these CDFs is a reasonable, first guess, for dispersion in the CAU model. Refinement to the CAU groundwater flow and transport model and sensitivity analyses will require more detailed information than the generalized distribution developed from the Phase I modeling efforts.

In an effort to better constrain the Frenchman Flat CAU transport model and the uncertainty in longitudinal dispersivity values, two approaches were implemented:

1. Develop many discrete bins to describe different scales of longitudinal dispersivity data and fit CDFs to each bin. The appropriate bin can then be sampled to obtain the range of values needed for a sensitivity analysis based on the scale (travel distance) of the specific simulation.
2. Develop a single linear model of longitudinal dispersion as a function of scale that can be sampled for the observed residuals to complete an uncertainty analysis for the CAU model. The idea is to fit a linear regression line that can predict longitudinal dispersivity based on scale. Then, for sensitivity analyses, add a quantity based on the distribution of the regression residuals to the linearly predicted value.

Figure 7-14
Cumulative Distribution Functions of Dispersivity (m) for 150 to 600 m Transport Distances

Both of these approaches were evaluated using not only the typical goodness of fit measures, but also Monte Carlo simulations that were designed to demonstrate the effectiveness of the final models as well how these models reproduce the original datasets.

The first step that was required for both approaches was to carefully evaluate the available data and ensure that none of the individual data was causing an undue influence on the predicted CDFs or correlation model. This was accomplished in an iterative manner where linear regression was used to fit the dispersivity values to scale (both log transformed). The log transformation is consistent with not only our observation using the compiled dispersivity datasets but also with previous studies including Lallemand-Barres and Peaudecerf (1978), Gelhar (1986), and Gelhar et al. (1992), among others. It could also be seen from the significant correlation coefficient between the log-transformed dispersivity and scale values (about 0.67).

A number of regression diagnostics have been developed and widely used to evaluate the influence of specific data points on the fitted regression line (e.g., Belsley et al., 1980). For example, the deleted residual is calculated as the residual (difference between observed dispersivity value and that predicted using the regression line at the same scale) value calculated after that data row is deleted. Procedurally, this could be viewed as dropping a specific data point from the dataset, re-fitting the regression line, and calculating the residual at the deleted data point. This deleted residual value is then compared with the original residual value (calculated from the original regression line). When the difference between the residual and the deleted residual is large, this indicates that the data point has an undue influence on the fitted regression line. Whenever that was detected, the data point was not automatically removed. Instead, the data point was evaluated in relation to the rest of the dataset and similar studies, especially at similar scale values. Only one data point (the one with the largest difference between residual and deleted residual) was allowed to be dropped out of the dataset each time. This process resulted in the elimination of five data points. All eliminated data points had the lowest data quality evaluation (Level 3). [Table 7-4](#) provides a summary of the eliminated data points along with the rationale for elimination.

7.6.1 First Approach: Probabilistic Models

Seven data bins were established based on transport scale. These bins were designed to maximize the number of bins while maintaining enough data points in each bin to provide a reasonable dataset for probability distribution function fitting. An additional consideration was to establish bins that would have the transport scale at the edges of the distribution in the next highest or lowest distribution to allow for more flexibility when performing the sensitivity analysis. [Table 7-5](#) shows the range of scale and longitudinal dispersivity values for the seven data bins. For any transport scale encountered in a model, the appropriate bin may be selected and used to generate the range of possible dispersivity values appropriate to the scale of interest.

**Table 7-4
Data Points Eliminated from Dispersivity Dataset due to Deleted Residual Analysis**

Source ^a	Scale (km)	Longitudinal Dispersivity (m)	Reason for Elimination
Wood (1981)	10	5,600	The study used a 1-D uniform flow solution. This dispersivity is unlikely for 10 km in any natural formation.
Robertson (1974) and Robertson and Barraclough (1973)	20	910	The same study concluded that transverse dispersivity was 1,370 m; a value larger than the longitudinal dispersivity. This against a body of literature that have clearly demonstrated that longitudinal dispersivity is 3 to 50 times larger than transverse dispersivity (SNJV, 2004f).
Bierschenk (1959) and Cole (1972)	3.5 4	6 460	The study used a 1-D uniform flow solution. This is unlikely for about 3.5 to 4 km travel distance in any natural formation, especially with the highly heterogeneous glaciofluvial sands and gravels reported in the study.
Goode and Konikow (1990)	3	2,700	The estimated longitudinal dispersivity value is much larger than any other value in our dataset. For example, between scale values of 1 and 20 km, the rest of the studies found dispersivity values between 5.5 and 910 m. Further, the study used a chloride contaminant plume. In general, contaminant plumes are less understood and have lower quality data than tracer tests. Further, chloride occurs naturally and may be difficult to discern chloride contamination from naturally occurring chloride in the subsurface.

^aSource information and data as reported by Gelhar et al. (1992)

**Table 7-5
Longitudinal Dispersivity Data Bins for Probabilistic Modeling Approach**

Bin (number of data points)	Transport Scale (m)		Longitudinal Dispersivity (m)	
	Minimum	Maximum	Minimum	Maximum
1 (33)	0.75	10.7	0.01	15.2
2 (60)	5	29.3	0.005	77
3 (63)	14	80	0.0915	131
4 (41)	35	200	0.1	234
5 (35)	79.2	600	0.345	234
6 (22)	250	5,000	0.345	182
7 (18)	800	50,000	5.5	170

For the first four bins, that maximum longitudinal dispersivity is greater than the maximum scale of transport. This reflects two issues. The most significant is that the vast majority of the occurrences in the data where the longitudinal dispersivity is larger than the transport scale is for data where the data quality rank is 3 (poor). The second issue is that the transport distance is a measure of the location of the center of mass, so systems that have high molecular diffusion at the leading edge of the plume or significant mechanical dispersion adjacent to the injection point (because of density effects or induced velocities) related to the tracer test may have greater longitudinal dispersion than mean transport scale.

Log-logistic distribution functions ([Appendix C](#)) provided the best, most consistent fits, to these bins. Both graphical and quantitative evaluations were used to judge the goodness of fit for each probability distribution function in each bin. [Figure 7-15](#) shows the graphical CDF fit to each data bin. [Table F.3-1](#) has the log-logistic parameters that characterize each bin.

Figure 7-15
Cumulative Distribution Functions of Dispersivity (m)
for Binned Transport Distances

7.6.2 Second Approach: Linear Regression Model

Linear regression using both a weighted least squares method and standard linear regression analysis was completed. The weighted regression line provided a worse fit for the data for the large-scale values since the data quality evaluation level 1 data have scale values below 280 m and only one medium quality (Level 2) value has a scale above 300 m. Therefore, non-weighted least squares fit was deemed most appropriate for a description of longitudinal dispersivity increasing with scale of transport ([Figure 7-16](#)). Because the majority of the longitudinal dispersivity values are representative of a transport scale of 10 to 400 m, the best fit line is most representative to this scale of transport. Caution should be used by the analyst if this linear regression model is used outside this range of transport scale.

Figure 7-16
Linear Regression Analysis of Longitudinal Dispersivity (m)
as a Function of Transport Distances

The residual values from the non-weighted regression line were evaluated using a probability distribution for sensitivity analysis purposes. A log-logistic CDF provided the best fit to the residual values ($\gamma = -0.83$, $\beta = 2.25$, $\alpha = 2.38$; see [Appendix C](#) for equations). This provides a model that has two components: a deterministic component that depends only on scale (using the linear regression line to predict one value of longitudinal dispersivity) and a stochastic component that can be independent of scale and will be generated from a probability distribution that is determined by fitting the distribution to the regression residuals.

7.6.3 Evaluation of the Longitudinal Dispersivity Models: Monte Carlo Analysis

Monte Carlo simulations were used to evaluate the developed models and demonstrate that they are capable of reproducing the observed variability in longitudinal dispersivity values with scale. For the probabilistic model, a procedure was developed that assumed the entire ensemble of longitudinal dispersivity values followed a mixture distribution consisting of seven log-logistic CDFs with mixture ratios taken to be proportional to the sample size that was used for each distribution. For example, the first bin included 33 data points out of a total of 272 data points. This gives a ratio of 0.1213 for the first log-logistic distribution. Obviously, the sum of the ratios across the seven bins is one. A

sample of 1,000 from this mixture distribution was generated and the empirical CDF for this sample was compared to the empirical CDF for the longitudinal dispersivity dataset (Figure 7-17). Figure 7-17 demonstrates that the mixture distribution provides a very good representation of the entire range of longitudinal dispersivity values included in the analysis, thus indicating that this model is valid for use during the transport model sensitivity analysis.

Figure 7-17
Comparison of Empirical CDFs of Longitudinal Dispersivity (m)
as a Function of Transport Distances Generated from the
Binned Dispersivity Model and Published Dispersivity Data

A similar Monte Carlo simulation was used to evaluate if the linear-regression model is capable of reproducing the variability displayed by the observed longitudinal dispersivity values (Figure 7-18). For this analysis, realizations were generated by adding a random quantity to the value predicted from the fitted regression line at each observed scale value. However, since the log-logistic distribution used to generate the residual values has no upper or lower bound and since the residual values are generated in the log space, it was found that few (less than 2 percent) of the generated longitudinal dispersivity values can have extremely large values. Therefore, a procedure was implemented where any residual value generated from the log-logistic distribution is only used if it does not exceed 5 times the largest observed residual (difference between observed dispersivity and that predicted using the linear regression line). Only qualitative (graphical) evaluation was performed. This evaluation concluded that the linear regression plus log-logistic residual procedure is only valid for larger travel distances (above 5 m). Below 5 m, the linear relationship tends to overestimate

Figure 7-18
Comparison of Longitudinal Dispersion (m) as a
Function of Transport Distances Generated from the
Linear Regression Model and Published Dispersion Data

dispersivities. This may provide an unconservative value at Peclet numbers above 3 because larger dispersivity values will result in more dilution in the transport model. For very-large-scale transport, the linear regression model tends to underestimate the total longitudinal dispersivity when compared to the poor quality data above approximately 1,200 m of transport. This suggests that the linear model should be used with caution at the extremes of the data, but is reasonable in the region with the greatest data control (between 10 and 1,200 m).

7.6.4 Sensitivity Analysis for Transverse Horizontal and Transverse Vertical Dispersivities

Sensitivity analysis for transverse horizontal and transverse vertical dispersivity will use ratios of transverse dispersivity to longitudinal dispersivity. As indicated by the high-reliability data, transverse horizontal dispersivity would be much smaller than the longitudinal dispersivity value. An additional constraint will be placed on the ratio of longitudinal to transverse dispersivity. That ratio will be maintained between 3 and 50 for all realizations. The vertical transverse dispersivity is more difficult to define. Few values are available for scales greater than 500 m. The most reliable values are very small; therefore, the distribution

will be biased toward smaller values. Constraints of the ratio of longitudinal/vertical (10 to 700) and transverse to vertical (10 to 100) will be imposed. It is expected that longitudinal and horizontal transverse horizontal dispersion will be the most important, with transverse vertical dispersivity relatively unimportant. These assumptions will be tested as part of the modeling activities.

7.7 Data Limitations

Dispersivity is not an intrinsic property of the medium in the way that porosity and hydraulic conductivity are thought to be. Dispersivity is dependent on the scale of the measurement, and on the type of test and method of analysis. The data available from the NTS region come from only six tracer experiments, five of which yielded quantitative values of longitudinal dispersivity. None of the NTS tracers tests produced good estimates of transverse dispersivities. The trends in dispersivity with travel distance come from a compilation of data from around the world. As a result, the appropriate longitudinal dispersivity to apply at large scales for the Frenchman Flat CAU model has uncertainty associated with the range and distribution of data. Two well constrained models have been developed to provide a means of quantifying the uncertainty associated with this dispersivity dataset in the Frenchman Flat CAU transport model.

8.0 Matrix Diffusion Parameters

This section includes descriptions of the role of matrix diffusion in contaminant transport in groundwater, the data available for matrix diffusion parameters, and the data analysis and associated results. The objective of this analysis is to develop a matrix diffusion coefficient range (lower bound, mean, upper bound) and distribution for each HSU in Frenchman Flat.

8.1 Role of Matrix Diffusion in Contaminant Transport

Solute transport in high-permeability zones is typically dominated by advective-dispersive processes while low permeability zones are dominated by diffusion. In fractured media, matrix diffusion between the fractures and the adjacent matrix has the effect of attenuating both the concentration and travel time of aqueous phase contaminants moving through fractures. This process involves the diffusion of contaminants from groundwater flowing in rock fractures into and out of the relatively stagnant water in the pores of the surrounding rock matrix.

In radionuclide transport modeling in fractured media, the matrix diffusion mass transfer coefficient (MTC) is the lumped parameter that governs the rate at which the contaminant diffuses out of fractures and into the matrix. The MTC may be expressed as follows:

$$MTC = n \frac{\sqrt{D_m}}{b} \quad (8-1)$$

where:

D_m = the matrix diffusion coefficient [L^2 / T]

n = matrix porosity [dimensionless], and

b = the fracture half-aperture [L].

The MTC can be estimated directly in tracer tests conducted in the field or by directly measuring the individual parameters that make up the MTC during laboratory tests. This section deals only with development of one component of the MTC, the matrix-diffusion coefficient for Frenchman Flat HSUs. Development of other components of the mass transfer coefficient, such as matrix porosity and fracture spacing and aperture thicknesses, are discussed in other sections in this document.

As discussed in SNJV (2004g), mass transfer can also occur in unfractured media, including alluvium, by diffusion between the more permeable zones and low permeability zones. The low permeability zones may consist of layers of

fine-grained sediments (e.g, clay, interstitial pore spaces filled with very fine-grained materials, or within the grains or cobbles of the alluvium) if these grains have some porosity and permeability, but act as dead-end pores. Diffusion, however, would be expected to be of less importance for alluvium compared to fractured media because the ratio of stagnant to flowing water volume in unconsolidated media is usually much smaller than in fractured media. Secondly, the contrast in permeability between the stagnant and flowing zones is typically much less for alluvium than for fractured rocks. For these reasons, matrix diffusion is not expected to be a significant source of reduction in transport distances for alluvium when compared to fractured media.

Two field tracer tests provide further insight into the potentially important HSUs for diffusive transport within the Frenchman Flat system: (1) tracer tests conducted through a fractured, welded-tuff formation showed “significant effects of matrix diffusion (Salve et al., 2004),” while (2) a test conducted through alluvium observed little diffusive mass transfer (Reimus et al., 2003). Reimus et al. (2003) determined diffusion coefficients from tracer experiments conducted at Well EWDP-19D1, 18 km south of Yucca Mountain. In the alluvium at this well, the diffusive mass transfer was found to be inconsequential. The field test involved several sets of two tracers with different molecular diffusion coefficients that were simultaneously injected (pairs of halides and fluorinated benzoates). Each tracer in the pair had essentially an identical response, “consistent with little diffusive mass transfer between flowing and stagnant water in the aquifer over the time scales of the test.” The nearly identical responses of the tracers with different diffusion coefficients in all three tests provide strong evidence that diffusion did not play an important role in solute transport in the alluvial aquifer (Reimus et al., 2003).

Additionally, the BULLION Test (IT, 1998a) was conducted within the LFA HGU at Pahute Mesa, composed of fractured Tertiary thryolite lava flows (SNJV, 2004b). Three tracers (PFBA, DFBA, and iodide) and microspheres were injected into two wells, and concentrations were measured in one pumping well. The experiment was extended from the planned duration of 30 days to 87 days, at which point the peaks of all tracer breakthrough curves had been captured, though one injector’s tracers (ER-20 6 #3) had not yet exhibited the “cross-over” in produced concentrations expected of paired tracers with different matrix diffusion coefficients. A wide range of alternative calibrations with different combinations of parameters (matrix diffusion, porosity, fracture spacing) were developed that adequately matched these tracer breakthrough curves. These calibrations suggest that, the uncertainty in the porosity is around a factor of two and a factor of five for dispersivity; while the uncertainty in the matrix diffusion coefficient is “at least one order of magnitude” (IT, 1998a). In the simulation of the BULLION Test, the tracer diffused only a few centimeters into the matrix. “The low effective porosity (2 percent), the clear evidence of matrix diffusion, and the physical evidence in the core all support the conclusion of fracture dominated transport The observed breakthrough curves cannot be explained without invoking matrix diffusion” (IT, 1998a).

While D_m , the matrix diffusion coefficient, is calculated for all Frenchman Flat HSUs including alluvium, the mass transfer process between more permeable and

less permeable zones is expected to be inconsequential for solute transport in Frenchman Flat alluvium.

The molecular diffusion model is based on Fick's second law of diffusion (Miller, 1989) which, for a one-dimensional system, may be expressed as:

$$\frac{\partial C}{\partial t} = D_m^* \frac{\partial^2 C}{\partial z^2} \quad (8-2)$$

where C is the relative species concentration at time, t , and vertical position, z . The parameter D_m^* is the effective matrix diffusion coefficient through the cross-section occupied by the pores. This form of Fick's Second Law is seen in many standard hydrology texts, including Bear (1972), Freeze and Cherry (1979), Walton (1985), and others. However, an alternate form is also common in sources (Lerman, 1979; Huyakorn and Pinder, 1983; and Currie, 1960), where porosity is included in the formulation.

The matrix diffusion coefficient in porous media, D_m , is directly related to the solute molecular diffusivity in free water, D_o , by the tortuosity of the porous media:

$$D_m = \omega D_o \quad (8-3)$$

where ω is the tortuosity (SNJV, 2004g). There are several alternate forms of this equation in the scientific literature (for example, $D_m = D_o/\tau$ [SNJV, 2004g], $D_m = D_o \kappa/\tau^2$ [SNJV, 2004g], or $D_m = D_o \phi/\theta^2$ [Drever, 1988]) and it is important to note which formulation was used for experimentally-derived or calculated parameters. In these alternative formulations, τ is the tortuosity factor, ϕ is the porosity, θ is the tortuosity, and κ is the constrictivity factor. ω , τ , and θ are different but related variables describing tortuosity Equation (8-6). In this chapter, unless otherwise noted, tortuosity is of the “ ω ” form.

Porosity and tortuosity affect the electrical conductivity of a water-saturated sediment in almost the same way as they affect the diffusion coefficient (Drever, 1988, p. 355; Bear, 1972, p. 112-116). For this reason, electrical conductivity can be a useful surrogate for the more difficult to measure tortuosity. Diffusion coefficients of dissolved species can be related to porosity ϕ and tortuosity θ of rock-core samples by means of the formation factor f . Where f is the ratio of the resistivities and $1/f$ is the ratio of C_s (the electrical conductivity of a brine-filled core sample) to C_w , the bulk electrical conductivity:

$$D_m = \frac{\phi}{\theta^2} D_o = \frac{C_s}{C_w} D_o = \frac{1}{f} D_o \quad (8-4)$$

or:

$$f = \frac{\theta^2}{\phi} \quad (8-5)$$

where:

$$f = \frac{1}{\omega} \text{ and } \omega = \frac{\phi}{\theta^2} \text{ and } \omega = \frac{1}{\tau} \quad (8-6)$$

Formation factors determined for 15 rock-core samples at the Waste Isolation Pilot Plant (WIPP) site varied from 13 to 407, with porosity varying from 0.07 to 0.26, and tortuosity θ varying from 0.029 to 0.331 (average = 0.141) (Jones et al., 1992). Since electrical conductivity and the solute molecular diffusion coefficient are relatively straightforward to measure, this provides a simple way to estimate matrix diffusion coefficients for a large number of core samples, and may be particularly useful for determining relative variation in matrix diffusion coefficients for different lithologies.

Relating the formation factor to tortuosity and porosity is not necessarily straightforward, and a number of relationships have been proposed (Lerman, 1979) in addition to [Equation \(8-5\)](#):

$$f = \frac{\theta^{5/3}}{\phi} \text{ almost identical to 8-5 above (Winsauer et al., 1952)} \quad (8-7)$$

$$f = \frac{\theta}{\phi^2} \text{ (Bear, 1972)} \quad (8-8)$$

$$f = \frac{1}{\phi^2} \text{ for sandstones (Archie, 1942)} \quad (8-9)$$

$$f = \frac{1}{\phi^{1.3}} \text{ for sands (Archie, 1942)} \quad (8-10)$$

$$f = \frac{1}{\phi^n} \text{ } n=2.5-5.4 \text{ for clays (Manheim and Waterman, 1974)} \quad (8-11)$$

$$f = \frac{1}{\theta\phi} \text{ (Jones et al., 1992, referencing Klinkenberg, 1951)} \quad (8-12)$$

The various relationships between f (and therefore D_o and D_m) and porosity ϕ suggest forms of equations that might be expected when developing correlations between experimentally determined D_m and porosity, discussed in more detail in [Section 8.4](#), and may be particularly useful for those Frenchman Flat HSUs with limited data.

8.2 Data Analysis

The matrix diffusion data analysis, sources of data, and the data quality evaluation process are described in the remaining sections of this chapter. The data analysis process consisted of the following primary steps:

1. Combine the matrix diffusion data from the previous Pahute Mesa matrix diffusion parameter analysis (Shaw, 2003a), consisting of a spreadsheet

and a Microsoft[™] Access database, plus one limited experimental study that determined matrix diffusion using Frenchman Flat rock samples (Papelis and Um, 2003a).

2. Eliminate duplicate and null data (23 measurements).
3. Confirm the reported matrix diffusion values and other information and gather additional information regarding the above measurements (tracer species, porosity, temperature, etc.) for the above measurements from the original study reports.
4. Determine the HSU for each D_m measurement, including Pahute Mesa and YMP rock samples.
5. Determine the equivalent FF HSU for each D_m experimentally determined for Pahute Mesa and YMP samples.
6. Group the D_m measurements into groups representing the FF HSUs.
7. Determine the data quality and data transferability of each matrix diffusion measurement using the data transfer protocol outlined in SNJV (2004g).
8. Adjust the matrix diffusion measurements, conducted using a wide variety of tracers, to a consistent basis; tritiated water was chosen for this analysis.
9. For FF HSUs with D_m experimentally-derived data (four of the FF HSUs), determine the most appropriate statistical model of the data using BestFit (see [Appendix C](#)), and calculate the D_m range (mean D_m with upper and lower confidence intervals or CIs) for each FF HSU.
10. For FF HSUs which do not have datasets of experimentally-derived matrix diffusion, determine the D_m range using a porosity- D_m correlation (Shaw, 2003a) plus the porosity range for that FF HSU. Also develop a D_m range using this correlation for the four FF HSUs with experimentally-derived datasets, to compare results: correlation versus experimentally-derived D_m range.
11. Adjust the D_m range for each HSU for the temperature of that HSU.
12. For each of the FF HSUs, develop a recommended statistical model for matrix diffusion values, to cover the range of matrix diffusion values expected for the range of radionuclides with the highest to the lowest molecular diffusion and, therefore also matrix diffusion, encountered at Frenchman Flat: tritiated water to americium.

These steps are discussed in more detail in the sections below.

8.2.1 Data Sources

Frenchman Flat matrix diffusion data is limited (only one study of a few samples); for this reason, data from Pahute Mesa and YMP were included in the analysis. Diffusion cell tests have been employed to derive matrix diffusion coefficients (D_m values) for various radionuclides and anions for a small number of samples in the Frenchman Flat area and for a large number of volcanic rocks from beneath Pahute Mesa and from the saturated zone near Yucca Mountain. The data sources for the matrix diffusion analyses are summarized in the [Table 8-1](#).

**Table 8-1
Sources of Matrix Diffusion Coefficient Data Applicable
to the Frenchman Flat CAU**

Data Source	Description
Reimus et al., 2002a	Derived matrix diffusion coefficients by diffusion cell experiments for a wide range of saturated volcanic rock samples from Pahute Mesa, including zeolitic, basalt flow, and welded ash flow, many with mineral-coated fractures. Used three different tracers: tritiated water, $\text{NaH}^{14}\text{CO}_3$, and $\text{Na}^{99}\text{TcO}_4$. Experimental replicates were included in the study and extensively documented, to gain insights into experimental errors, reproducibility, and variability. Very clear documentation, from experimental methodology to the discussion of results, including possible causes for anomalous results and suggestions for improving future measurements. A total of 85 measurements in the dataset from this source included Frenchman Flat HSU equivalents.
Walter, 1982	Derived matrix diffusion coefficients by diffusion cell experiments with fractured tuff samples from Yucca Mountain. Also determined constrictivity and tortuosity from conductive experiments. Duplicate tracer samples were collected and the mean value was used. The concentration in the tracer cell was replaced every 24 hours to keep the concentration constant. One of the few experimental reports to include temperature and comments on quality of each measurement. This report included calibration information. The text and methodology of this report are clear and easy to follow. A total of 24 measurements in the dataset from this source included Frenchman Flat HSU equivalents.
Papelis and Um, 2003a	Studied adsorption and diffusion and also spectroscopic analysis of Frenchman Flat rock samples using pulverized, sieved particles (welded ash flow and zeolitic volcanic tuffs). The diffusion experiments ("rate of uptake") were conducted with batch experiments, measuring the change in tracer concentration over time for a test tube containing spherical volcanic tuff particles in a tracer solution. Used three different tracers: Sr, Cs, and Pb. A total of 15 measurements were included in the dataset from this source. This was the only experiment using porous media samples from Frenchman Flat.
Reimus et al., 1999a	Derived matrix diffusion coefficients by diffusion cell experiments on zeolitic tuff samples from Pahute Mesa. The study used two different tracers: iodide and PFBA. All 57 samples for this reference were from a Pahute Mesa HSU – CHZCM - with no Frenchman Flat equivalent HSU.
Triay, 1996	Derived matrix diffusion coefficients by diffusion cell experiments with volcanic tuff samples from Yucca Mountain. Used two different tracers: tritiated water and $^{99}\text{TcO}_4$. A total of 11 measurements in the dataset from this source included with Frenchman Flat HSU equivalents.
IT Corporation, 1998a	All samples for this reference were from Yucca Mountain and Pahute Mesa HSUs with no Frenchman Flat equivalent HSUs. For this reason, this report was not researched further, and the multiplier factors are not important (for this analysis).

Figure 8-1 shows the experimentally-derived matrix diffusion for the entire dataset.

Experimentally-derived matrix diffusion coefficients from the above data sources are shown as a function of porosity, for the 226 samples where measured porosity is reported. For the 32 samples where porosity was not reported, the matrix diffusion is plotted on the left axis. Figure 8-1 shows D_m values as reported, not adjusted to a common tracer species using molecular diffusion (discussed in a later section); Figure 8-2 displays the adjusted values. The matrix diffusion coefficient generally varies over a two orders magnitude. Porosity ranges from 1 to 37 percent.

Using the relationship between matrix diffusion coefficient and solute molecular diffusivity Equation (8-3), tortuosity may be calculated for each rock sample where matrix diffusion was determined. By this equation, the matrix diffusion coefficient would be equal to the molecular diffusion coefficient when the tortuosity ω is equal to 1.0, equivalent to a porous media with a porosity of 1.0 (an open cavern or vug). Tortuosities greater than 1.0 or calculated matrix diffusion coefficients greater than molecular diffusion coefficients are physically impossible (like porosities greater than 1.0) and reflect uncertainties and error in the measurement process. For this reason, all tortuosities greater than 1.0 are excluded from the analysis. These few “non-physical” points in the data are indicated by the three points above the molecular diffusivity line graphed in Figure 8-2. The tortuosities (in the form of ω or κ/τ , also referred to as geometric factor) calculated for this database are shown in Figure 8-3. Tortuosities range from 0.002 to 0.93, with the 95-percent confidence interval from 0.01 to 0.26. The correlation between porosity and tortuosity appears to have considerable spread, consistent with the considerable spread in correlation between porosity and the matrix diffusion coefficient.

8.2.2 Pahute Mesa and YMP HSUs and FF Equivalent HSUs for Each Sample

For the purpose of this analysis, Frenchman Flat HSUs were grouped into 10 primary HSUs, corresponding to those used in the porosity analysis for Frenchman Flat:

AA	Alluvial Aquifer
BLFA	Basalt Lava Flow Aquifer
OAA	Older Alluvial Aquifer
PCU1U	Playa Confining Unit, Upper
TM-WTA	Timber Mountain Welded Tuff Aquifer
TM-LVTA	Timber Mountain Lower Vitric Tuff Aquifer
ULTCU	Tuff Confining Unit, Upper & Lower
TSA	Topopah Spring Aquifer
LCA	Lower Carbonate Aquifer, including thrust plate
ULCCU	Clastic Confining Unit, Upper & Lower

Note: Matrix diffusion coefficients are plotted on left axis when no porosity data reported.

Figure 8-1
Matrix Diffusion Coefficients as a Function of Porosity (No Correction for Tracer Species)

Figure 8-2
Matrix Diffusion Coefficients as a Function of Porosity (Corrected for Tracer Species)

Figure 8-3
Tortuosity as a Function of Porosity

The matrix diffusion measurements from PM and YMP samples were determined and correlated to an equivalent Frenchman Flat HSU with similar lithology, if possible. [Table 8-2](#) shows PM and YMP HSUs (and the equivalent Frenchman Flat HSU, if it exists) that are represented in the matrix diffusion dataset. This information was used to assign the data into the appropriate, equivalent FF HSU for later statistical analysis and uncertainty range development.

[Figure 8-4](#) shows the matrix diffusion data that is applicable to Frenchman Flat HSUs (i.e., samples from FF or samples with equivalent FF HSUs). There is a possible trend of increasing D_m with increasing porosity.

8.2.3 Data Quality/Transferability Protocol

A complete explanation of the data documentation and data transfer protocol used for this analysis is included in Appendix B and Attachment B of the document titled: *Transferability of Data Related to the Underground Test Area Project, Nevada Test Site, Nye County, Nevada* (SNJV, 2004g). The scoring protocol used to assign weights and multipliers to the data is reported in [Table 8-3](#), and discussed in the following text while [Appendix B](#) provides a general overview.

The scoring is calculated for each measurement in the matrix diffusion dataset. Additional scoring factors than those supplied in the guideline document (SNJV, 2004g) are noted with an asterisk in [Table 8-3](#). The overall *multiplier factor* is a product of the multiplier factors for the three criteria discussed below. The overall “score” of the data is the product of the *weight* and *multiplier factors*,

**Table 8-2
Equivalent^a Frenchman Flat HSUs for Pahute Mesa and
YMP Samples With Matrix Diffusion Measurements**

Location	Location HSU or Sample	Equivalent FF HSU	Comments
PM	BFCU	ULTCU	
PM	TSA	TSA	
PM	LPCU	ULTCU	
PM	VCU	ULTCU	
PM	PBRCM	ULTCU	
PM	CHZCM	NP ^b	
PM	TMCM	NP	Timber Mtn Composite Unit, part of the Caldera Complex, geology not transferable to Frenchman Flat.
YMP	UVA	TSA	Topopah Spring member of Paintbrush Tuff, densely welded devitrified ash-flow tuff
YMP	UVCU	NP	
YMP	U12G	TM-WTA	HSU not available; equivalent FF HSU determined by using the regional EarthVision HSU model and using Table 2-4 to transfer data from regional HSUs to Frenchman Flat HSUs.
YMP	USW-G1	ULTCU	HSU not available; equivalent FF HSU determined by using the regional EarthVision HSU model and using Table 2-4 to transfer data from regional HSUs to Frenchman Flat HSUs.
YMP	USW-G4	TM-LVTA	HSU not available; equivalent FF HSU determined by using the regional EarthVision HSU model and using Table 2-4 to transfer data from regional HSUs to Frenchman Flat HSUs.
YMP	GU3	TM-LVTA	HSU not available; equivalent FF HSU determined by using the regional EarthVision HSU model and using Table 2-4 to transfer data from regional HSUs to Frenchman Flat HSUs.
YMP	Topopah	TSA	HSU not available; equivalent FF HSU determined by using the regional EarthVision HSU model and using Table 2-4 to transfer data from regional HSUs to Frenchman Flat HSUs.

^aEquivalent HSUs for Frenchman Flat and Pahute Mesa determined using [Table 2-4](#)

^bNP = Not Present.

representing both the quality of the data and its appropriateness for the Frenchman Flat HSU under consideration. These scores are used as relative weights when developing the statistical models for matrix diffusion coefficients for each HSU.

The weight factors for the 258 measurements in the matrix diffusion dataset range from 0.4 to 1.0. The multiplier factors range from 0.03 to 2.0 ([Appendix E](#)). The total scores for the 258 measurements in the matrix diffusion dataset range from 0.03 to 2.0 ([Appendix E](#)).

In accordance with SNJV (2004g) “Weight factors for D_m values obtained from outside of NTS CAUs should be highly correlated with the *similarity* of matrix porosity and log matrix permeability at the two different locations.” Of these two factors, SNJV (2004g) suggests that log permeability should be given more emphasis than porosity. However, for Frenchman Flat the database of

Figure 8-4
Matrix Diffusion Coefficients vs. Porosity, for Samples With
an Equivalent Frenchman Flat HSU, Corrected for Tracer Species

permeability is limited, and a much more extensive porosity database is available, both for the matrix diffusion coefficient measurements and for Frenchman Flat HSUs. For this reason, the use of porosity rather than permeability was necessary in determining the weight factor for each derived D_m value in this analysis.

“The weight factors are adjusted based on differences in matrix porosity by the following: For matrix porosities that differ by less than 25 percent of the larger value, the initial weight factor determined from permeability differences is multiplied by 1. When porosities differ by 25 to 90 percent of the larger value, the initial weight factor is multiplied by 0.7. When porosities differ by more than an order of magnitude (greater than 90 percent of the larger value), the initial weight factor is multiplied by 0.4” (SNJV, 2004g).

SNJV (2004g) states that, “For D_m values, the geologic setting should not be used at all as a transferability factor, unless there are no matrix porosity and permeability data available (note that porosity data should be available because porosities are generally necessary to obtain diffusion coefficient estimates). If matrix porosity and permeability data are both not available, then there is no choice but to rely on similarity of geologic setting to determine a relevance weight factor. Similarities and differences in geologic setting (including rock type, deposition history, geochemical/hydrothermal alteration, structural setting, and mechanical alteration) should be evaluated and weights assigned using a sliding scale of 0 to 0.7, with 0.7 indicating a very similar setting. The scale does not go to 1.0 because similarity of geologic setting is a more arbitrary measure of

**Table 8-3
Summary of Data Transfer Protocol for Frenchman Flat Matrix Diffusion Coefficient Dataset**

Total score = W x M (for both data quality and transferability) - see each dataset entry for specific values		
<u>WEIGHT FACTORS</u>	W = W1 x W2	for geologic similarity of the data to the HSU of interest
W1. Determine Weight Factor for Permeability Similarity		
1	If Permeability of measured sample is less than one order of magnitude of FF HSU Permeability	
0.6	If Permeability of measured sample is within 1-2 orders of magnitude of FF HSU Permeability	
0.3	If Permeability of measured sample is within 2-3 orders of magnitude of FF HSU Permeability	
0	If Permeability of measured sample is greater than 3 orders of magnitude different from FF HSU Permeability	
0.5	*If Permeability of sample is not measured and reported	
1	*If Mean Permeability of FF HSU is not yet available	
W2. Adjust Weight Factor for Porosity Similarity by multiplying above by:		
1	If Porosity of measured sample is less than 25 percent different from FF HSU porosity	
0.7	If Porosity of larger value (between measured and FF HSU) is within 25 to 90 percent of small value	
0.4	If Porosity of larger value (between measured and FF HSU) is greater than 90 percent different than smaller value	
0.5	*If Porosity of D _m sample is not measured and reported	
<u>MULTIPLIER FACTORS</u>	M = M1 x M2 x M3	for measurement method and quality of the analysis and documentation
M1. Measurement Method: M1a x M1b x M1c		
1.0	Laboratory Diffusion Cell Experiments (DCE) (M1a)	
0.5	If D _m determined by a method other than diffusion cell experiment, such as x-ray or neutron imaging, electrical conductivity, batch experiments using pulverized particles, etc. (non DCE) (M1a)	
2	If sample includes natural fracture surface, which may have mineral coatings that affect diffusion (Frac) (M2b)	
0.6	If sample thickness is 80 percent smaller than average and, therefore, less representative of field-scale diffusive path lengths: < 0.27 cm (M1c)	
1.4	If sample thickness is 80 percent larger than average and, therefore, more representative of field-scale diffusive path lengths: > 2.5 cm (M1c) (1.4 cm, average sample thickness of all samples (arithmetic average of dataset sample thicknesses, "avg_sample_thickness")	
1.5	If both increasing and decreasing concentrations are measured (no such experiments were identified in study reports for this analysis)	
M2. Data Reduction and Analysis Method: = M2a x M2b		
1.0	Current	
0.5	Good method, but calibration information is suspect or not possible to verify (M2a)	
0.5	Based on older or less-widely accepted methods, but calibration information is good (M2a)	
0.2	Both method and calibration information are suspect (M2a)	
0.1 - 2.0	Variable, author's evaluation of measurement's quality, fit of the data to the experimental model, etc., noted in the "Multiplier_Comments" column of the dataset (M2b)	
M3. Quality of the Documentation		
1.0	Good (thorough, easy to follow, traceable)	
0.6	Appearing in a reputable or peer-reviewed report, but otherwise lacking in thoroughness	
0.3	Poor	

similarity for the purposes of transferring D_m values than comparing porosity and permeability data.”

8.2.4 Adjusting Matrix Diffusion Coefficients for Different Species, Ionic Strength, and Temperature

SNJV (2004g) provides general guidelines for adjusting diffusion coefficients for species size, charge, and temperature. “The Stokes-Einstein equation predicts that diffusion coefficients will be directly proportional to absolute temperature and inversely proportional to fluid viscosity (which decreases as temperature increases, but not linearly) (SNJV, 2004g, Attachment B, pages 30-31).”

Solute molecular diffusivities (D_o) of most species range from 10^{-10} to 10^{-9} m²/s (Drever, 1988). Solute molecular diffusivities are generally lower for larger molecules or ions with higher charges. Solute molecular diffusivities refer to “free water” diffusivities, also referred to as the solute diffusion coefficient in free water. Since matrix diffusion coefficients are a property both of the rock (through ω) and the tracer species (through D_o), it is important that both be known, particularly when analyzing large sets of measurements from disparate sources. Since D_o is directly related to D_m , experimentally derived D_m values conducted using different tracers with different D_o values may be compared directly by “ratioing” the D_o values, so that all values in a dataset are on a consistent basis. Equation (8-3) may be rearranged to:

$$\omega = \frac{D_m}{D_o} \quad (8-13)$$

where the left hand side contains a parameter that is a function of the rock properties alone and the right hand side contains parameters that are also a function of the tracer species. This relationship may be used to adjust matrix diffusion coefficient values reported for disparate tracer species to a consistent basis, in this example a matrix diffusion coefficient from an experiment using strontium to one for tritiated water:

$$\omega = \frac{D_{mHTO}}{D_{oHTO}} = \frac{D_{mSr}}{D_{oSr}} \Rightarrow D_{mHTO} = D_{mSr} \frac{D_{oHTO}}{D_{oSr}} \quad (8-14)$$

The matrix diffusion coefficient value for strontium was derived from a formulation that explicitly accounted for sorption effects. The formulation above assumes that the only factor affecting the matrix diffusion coefficient other than porous media properties is the tracer species’ molecular diffusivity; i.e., no other processes other than diffusion are affecting the “apparent” diffusion coefficient (e.g., cation exchange, unaccounted sorption, complexation, anion exclusion, lowering of effective porosity for large molecules excluded from small pores) and that all tracer solutions are dilute (less than 1 molar [M]). If cation sorption is significant, cation matrix diffusion coefficients may be determined from calculations using values for tortuosity, porosity, and molecular diffusion, as it can

be difficult to impossible to determine a unique solution to fitting both parameters, sorption and matrix diffusion, simultaneously. Multi-component diffusion effects have also been excluded in this analysis. Given these assumptions, D_m values derived from experiments using the same rock with different tracers should vary only by the difference in their molecular diffusivity D_o , and such duplicate measurements using the same rock are useful as experimental quality checks.

Reimus et al. (2002a), however, found that matrix diffusion coefficients conducted on the same rock with three different tracers (tritiated water, $\text{NaH}^{14}\text{CO}_3$, $\text{Na}^{99}\text{TcO}_4$) did not vary as expected, by the ratio of the solute molecular diffusivities of the three tracers. This result suggests that both the $\text{H}^{14}\text{CO}_3^-$ and $^{99}\text{TcO}_4^-$ anions had access to less porosity than the tritiated water molecule, possibly due to anion exclusion, or that these ions may have been retarded by sorption or ion exchange.

Unless otherwise noted, all D_m values reported in this section have been adjusted to a tritiated water basis. Tritium is the radionuclide with the highest molecular diffusivity, therefore, has the highest matrix diffusion coefficient (whether in the form of a tritium ion or as tritiated water; the matrix diffusion coefficient for tritiated water is used for this analysis). The radionuclide with the lowest molecular diffusivity is americium (highest retardation), and matrix diffusion coefficients are also reported for this species, to give the full range of values expected. [Table 8-4](#) reports molecular diffusion coefficients for tracer species used in experiments or in modeling.

The first column of [Table 8-4](#) contains tracer and radionuclide species for which solute molecular diffusivities are reported. The second and third columns contain solute molecular diffusivities reported at two different temperatures (Lerman, 1979). These values of molecular diffusivity are appropriate only for dilute solutions (< 1 M). The fourth column reports the ratio between the solute molecular diffusivities for the reported species relative to a tritiated water tracer species. For example, a strontium tracer has a molecular diffusivity lower than tritiated water by a factor of 3.02 times (larger molecules have lower diffusivities). Bromide, iodide, chloride, potassium, and cesium species all have very similar solute molecular diffusivities (with ratios varying between 1.18 and 1.22). If these were the only tracer species used in matrix diffusion experiments, no correction would be necessary for molecular diffusivity. However, there are a wide range of tracer species used in the diffusion experiments, including tracers with much lower solute molecular diffusivities, (e.g., PFBA and strontium, by factors of 3.53 and 3.02, respectively). For this reason it was necessary to adjust matrix diffusion coefficients for tracer species so the entire dataset of values are directly comparable, and the differences in reported matrix diffusion only reflect differences in rock properties, not differences in tracer as well.

Diffusion coefficients are a relatively weak function of ionic strength until ionic strengths become greater than about 1 M (Newman, 1973). As ionic strengths greater than 1 M are unlikely to occur at NTS (even in cavities) the effect of ionic strength on diffusion coefficients is considered to be relatively minor compared to the effect of rock properties and temperature (SNJV, 2004g). The concentration of the tracer species was not reported in all experiments discussed here; however, when reported the concentrations were much less than 1 M.

**Table 8-4
Summary of Molecular Diffusivities, for Matrix Diffusion Cell Experiments
and Frenchman Flat Radionuclides**

Reported in Lerman (1979) Geochemical Processes					Reported in Pahute Mesa, Yucca Mountain, and Frenchman Flat studies	
Tracer	18°C Molecular Diffusivity (m ² /s)	25°C Molecular Diffusivity (m ² /s)	Ratio with Tritiated Water	Percent Increase with 7°C Temp. Increase	°C Temp. Molecular Diffusivity (m ² /s)	Reference
Tritiated water			1.00		2.40E-09	Reimus et. al., 2002b, p. 2,18 referencing Skagius and Neretnieks 1986
Americium (Am ⁺)			7.84		3.06E-10	DOE/ORD, 2000
Tritium (³ H ⁺)			0.26		9.31E-09	SNJV, 2004g
Bromide (Br ⁻)	1.76E-09	2.01E-09	1.19	14%	2.08E-09	Shaw, 2003a, p. 8-13, referencing Newman, 1973. Reported as 1.62E-9 m ² /s by Papelis & Um, 2003b
Iodide (I ⁻)	1.72E-09	2.00E-09	1.20	16%	2.04E-09	Shaw, 2003a, P. 8-13, referencing Newman, 1973. Also 2.045E-9 m ² /s in "use of Yucca Mountain..."
Chloride (Cl ⁻)	1.71E-09	2.03E-09	1.18	19%		
Potassium (K ⁺)	1.67E-09	1.96E-09	1.22	17%		
Cesium, (Cs)	1.77E-09	2.07E-09	1.16	17	1.97E-09	Papelis & Um, 2003b, p. 43, calculated value using Nemst-Haskell eq (Reid et al., 1977)
Lead (Pb ²⁺)	7.95E-10	9.45E-10	2.54	19	1.41E-09	Papelis & Um, 2003a, p. 24
Strontium (Sr ²⁺)	6.70E-10	7.94E-10	3.02	19%	1.29E-09	Papelis & Um, 2003b, p. 39 calculated value using Nemst-Haskell eq (Reid et al., 1977)
Bicarbonate (HCO ₃ ⁻)		1.18E-09	2.03		1.10E-09	Reimus et. al., 2002a, p. 2-19, referencing Newman, 1973
Pertechnetate (⁹⁹ TcO ₄ ⁻)			1.26		1.90E-09	Reimus et al., 2002a, p. 2-18, referencing Sato et al., 1996
Perchlorate (ClO ₄ ⁻)			1.33		1.80E-09	Reimus et al., 2002a, p. 2-19, referencing Newman 1973
Difluorobenzoate (DFBA)			3.24		7.40E-10	IT, 2002a, p. 7-4
Pentafluorobenzoate (PFBA)			3.53		6.80E-10	Shaw, 2003a, p. 8-13, referencing Callahan et al., 2000
Mean	1.44E-9	1.62E-09	2.13	17%	2.08E-09	
Minimum	6.70E-10	7.94E-10	0.26	14%	3.06E-10	
Median	1.71E-9	1.98E-09	1.26	17%	1.80E-09	
Maximum	1.77E-9	2.07E-09	7.84	19%	9.31E-09	

Molecular diffusivity is directly related to temperature; therefore, temperature may be an important variable if there is a large ranges in temperature in the measurements or throughout the modeled porous media. If temperature is increased from 18 to 25 degrees Celsius ($^{\circ}\text{C}$), the diffusion coefficient (D_m or D_o) increases by 14 to 19 percent, as shown in [Table 8-4](#). If temperature is increased from 20 to 30 $^{\circ}\text{C}$, the diffusion coefficient (D_m or D_o) is increased by 30 percent (Shaw, 2003a). Temperatures are seldom reported for the matrix diffusion experiments reported here, but those that had reported values ranged from 25 to 30.5 $^{\circ}\text{C}$. Because experimental temperatures are seldom reported, and because when it is reported the range is small (typically laboratory ambient temperatures), matrix diffusion coefficient values were not corrected in this analysis for temperature. All laboratory measurements were assumed for the purposes of this analysis to be conducted at a temperature of 25 $^{\circ}\text{C}$; the error introduced by this assumption is likely to be small, as the range of ambient indoor laboratory temperatures is small, especially compared to the range in temperatures expected in the HSUs over the hundreds of feet of depth.

It is necessary, however, to correct the HSU diffusion coefficients for temperature effects, as temperatures in the HSUs of Frenchman Flat range from 23 $^{\circ}\text{C}$ to 49 $^{\circ}\text{C}$. The higher temperature ranges will result in a significant increase in diffusion.

[Figure 8-5](#) shows measured temperatures versus depth from three wells: ER-5-4#2, ER-5-3, and ER-5-3#2 (Shaw, 2003b; IT, 2002b). The least-squares linear regression best fit relationship between depth and temperature is also shown on this graph. The slope is 1/201 $^{\circ}\text{C}$ per foot, for an average geothermal temperature gradient of 0.005 $^{\circ}\text{C}$ per foot, or 0.009 degrees Fahrenheit ($^{\circ}\text{F}$) per foot of depth, generally consistent with the average gradient estimated for the Pahute Mesa area of 0.014 $^{\circ}\text{F}$ per foot of depth (Bright et al., 2001).

The relationship between temperature and matrix diffusion coefficients and the relative adjustment needed is presented in Shaw (2003a) and shown in [Table 8-5](#).

These data, developed from the Stokes-Einstein equation, were fit to the polynomial shown in [Figure 8-6](#), where the data in [Table 8-5](#) are plotted as open circles and the polynomial relationship is shown as the red curve.

The two relationships (depth versus temperature and temperature versus matrix diffusion adjustment) were combined to develop the depth versus matrix diffusion adjustment shown in [Figure 8-7](#). The exponential relationship shown in this figure was used to develop the correction needed to adjust the HSU matrix diffusion ranges from the experimental (indoor ambient) temperatures to the HSU temperatures ([Table 8-6](#) and [Section 8.6](#)).

Figure 8-5
Measured Temperatures as a Function of Depth,
Frenchman Flat Wells

Table 8-5
Factor by Which Diffusion Coefficients Change as a
Function of Temperature in Water (Shaw, 2003a)

Temperature °C	Relative Diffusion Coefficient
20	1.00
25	1.14
30	1.30
40	1.64
50	2.14
60	2.58

Figure 8-6
Matrix Diffusion Adjustment (Multiplier) for Increasing Temperature

Figure 8-7
Matrix Diffusion Adjustment (Multiplier) for Increasing Depth

**Table 8-6
Adjustment Needed to Correct Each Frenchman Flat HSU for Increasing Temperature**

HSU	Average or Typical Depth (feet bgs)	Temp. (°C)	Temp. (°F)	Temperature Correction to D _m	Source for Typical Depth
AA	1,000 to 2,000	24-29	74-83	None	ER-5-3, Depth to Top of AA HSU = 0 ft bgs
BLFA	1,000 to 2,000	24-29	74-83	None	ER-5-3, Depth to Top of BLFA HSU = 903 ft bgs
OAA	1,000 to 2,000	24-29	74-83	None	ER-5-3, Depth to Top of OAA HSU = 933 ft bgs
PCU1U	2,300	30	86	1.23	ER-5-4, Depth to Top of PCU HSU
TM-WTA	3,700	37	98	1.46	ER-5-4, Depth to Top of TM-WTA HSU
TM-LVTA	4,300	40	104	1.57	ER-5-4#2, Depth to Top of TM-LVTA HSU
ULTCU	4,500	41	106	1.61	ER-5-4#2, Depth to Top of LTCU HSU
TSA	2,900	33	91	1.32	ER-5-3#2, Depth to Top of TSA HSU
LCA	4,700	42	107	1.65	ER-5-3#2, Depth to Top of LCA HSU
ULCCU	7,000 to 13,000	53-83	128-182	2.14-3.58	From cross-sections (no LCCU depths recorded)

Table 8-6 shows the temperature correction for matrix diffusion for each Frenchman Flat HSU as well as the typical depth or average depth range at which that temperature correction was applied. The typical depths are feet below ground surface and were obtained from well measurements. For the first three HSUs the temperature correction is small, much less than the uncertainty in the depths, and no temperature correction is applied.

For the AA HSU in Frenchman Flat, the depths to the tops of the units are typically quite shallow, 0 ft bgs in Well ER-5-3. The thickness of the AA HSU varies substantially in Frenchman Flat, ranging from a few feet up to 4,000 ft in geologic cross-sections. For average saturated zone depths of 1,000 to 2,000 ft bgs, the temperature increase with depth is small (5 to 10 °C), the matrix diffusion correction is likewise small (5 to 19 percent increase), and no temperature correction is applied in this analysis for the top three HSUs: AA, BLFA, and OAA. For uncertainty analysis of transport in the deepest portion of the alluvial aquifer (3,000 to 4,000 ft bgs), the increase in matrix diffusion over the base value would be 36 to 55 percent.

The LCA unit is a very thick unit (around 9,000-11,000 ft); however, the majority of the transport would be expected to take place at or near the top of the unit. To calculate temperature corrections for the LCA, the unit top at Well ER-5-3#2 was used. This well was considered representative since the wellbore is centered under a cluster of 7 of the 10 nuclear tests at Frenchman Flat. For simulations that may examine transport deep into the LCA HSU, the temperature of the zone half-way through the LCA of FF (approximately 10,000 ft bgs) would be 68°C, and the matrix diffusion correction factor would increase from 165 to 284 percent. No radionuclides are expected to reach the deepest HSU, ULCCU, over the range of uncertainties, based on Phase I modeling results (IT, 1999c); however, for completeness a matrix diffusion temperature correction was also calculated for this HSU at an average depth in the FF HSU cross sections.

8.3 Development of Matrix Diffusion Ranges from the Experimentally-Derived Matrix Diffusion Dataset

For FF HSUs with D_m experimentally-derived data (4 of the 10 FF HSUs), the most appropriate statistical model of the data was determined using BestFit (Appendix C), and the D_m range (mean D_m with upper and lower confidence intervals [CI]) is reported for each FF HSU.

Four of the ten HSUs have FF experimentally-measured data from regional NTS or Pahute Mesa HSUs that correspond to those FF HSUs. Of the 258 measurements in the dataset, 139 measurements are for samples with a Frenchman Flat equivalent HSU and 119 measurements are for a regional NTS or Pahute Mesa HSUs not present at Frenchman Flat. Table 8-7 summarizes the dataset by equivalent Frenchman Flat HSU (mean values are arithmetic means, not weighted by data transfer scores).

**Table 8-7
Summary of Matrix Diffusion Coefficient Dataset,
by Equivalent Frenchman Flat HSUs**

HSU	# pts	D_m , in m^2/s , $\times 10^{10}$		
		Mean	Range	
			Min	Max
AA	0			
BLFA	0			
OAA	0			
PCU	0			
TM-WTA	6	0.524	0.001	1.296
TM-LVTA	9	1.407	0.378	3.500
ULTCU	72	11.765	0.003	411.
TSA	52	7.407	0.003	217.
LCA	0			
LCCU	0			
Total Equivalent FF:	139	8.979	0.001	411.
Not Present at FF:	119	3.725	0.048	40.6
Total pts:	258	6.556	0.001	411.

The data for each of the four HSUs were grouped and sorted by increasing matrix diffusion coefficient. The cumulative probability distribution was developed based on the total data transferability score-weighting for each data point. These cumulative probability distributions are shown in Figure 8-8. The distributions are generally very narrow, except for low-probability tails at either end, and are consistent with ranges developed for the YMP (DOE/ORD, 2001): “For cations, the average matrix diffusion coefficient is $1.6 \times 10^{-10} m^2/s$ with a standard

Figure 8-8
Score-Weighted Cumulative Probability Distributions for Frenchman Flat HSUs,
Entire Dataset, and Yucca Mountain

deviation of $0.5 \times 10^{-10} \text{ m}^2/\text{s}$, a minimum value of zero and a maximum value of $10^{-9} \text{ m}^2/\text{s}$ with a Beta distribution.”

The best statistical model for each of the four HSUs above was determined using the BestFit statistical analysis software. The results of this analysis are summarized in [Figure 8-9](#) and [Table 8-8](#). The gray vertical lines in these graphs represent the bounds of the 95-percent confidence interval for each HSU.

The data for the Frenchman Flat TM-WTA HSU was very limited, only six data points, from two experimental series, with half of these data points having very low data transferability scores (less than 5 percent cumulative probability). For these reasons, a uniform distribution model was chosen. This distribution fit the data quite well, as shown in the upper left hand graph of [Figure 8-9](#), with a root mean square (RMS) error of 0.0037.

The dataset for the TM-LVTA HSU has nine data points from two experimental series; however, all data points were more equally score-weighted. A triangular distribution was chosen, for reasons of minimizing RMS error while keeping with a relatively simple statistical model in line with the data quantity. This distribution fit the data fairly well, as shown in the upper right hand graph of [Figure 8-9](#), with an RMS error of 0.005.

The data for the Upper and Lower TCU HSU was more extensive, with 72 data points from three experimental series (note that on [Figure 8-9](#) the points are so close together that they overlap). An exponential distribution statistical model was chosen, for reasons of minimizing RMS error while keeping with a relatively simple statistical model in line with the data quantity. This distribution fit the data well, as shown in the lower left hand graph of [Figure 8-9](#), with an RMS error of 0.0022.

The data for the TSA HSU was also reasonably extensive, with 52 data points from four experimental series. A log-normal distribution statistical model was chosen, as this had the highest ranking (lowest RMS error). This distribution fit the data very well, as shown in the lower right hand graph of [Figure 8-9](#), with an RMS error of 0.0004.

The results of the four Frenchman Flat HSUs with D_m experimentally-derived data are shown in [Table 8-8](#), for tritiated water and for Am. Matrix diffusion coefficients for Am (the radionuclide with the highest molecular weight and, therefore, among the lowest expected diffusion coefficients), were calculated from the tritiated water ranges (by the relationship in [Equations 8-13](#) and [8-14](#)), using the molecular diffusion coefficient ratio ([Table 8-4](#)).

These results are compared in [Figure 8-10](#), for a tritiated water solute, with the Yucca Mountain values also shown.

The mean is represented as blue diamonds, with the 95-percent confidence interval (upper and lower) represented by the rectangle above and below the diamond. The minimum and maximum range of the data are represented by the lines above and below the rectangles.

Figure 8-9
Fit of CDFs to Score-Weighted ECDFs for Four Frenchman Flat HSUs

**Table 8-8
Summary Ranges of Experimentally-Derived Matrix Diffusion Data,
by Frenchman Flat HSU**

	TM-WTA	TM-LVTA	U/L TCU	TSA
Statistical Distribution Model	Uniform	Triangular	Exponential	Log-Normal
Tritiated Water Tracer				
-----all values reported as 10^{-10} m ² /s-----				
Mean	0.8	1.2	3.2	2.0
SD	0.4	0.9	3.6	1.9
Lower 95% Conf. Int.	0	0	0	0
Upper 95% Conf. Int.	1.4	3.1	11	7.1
Am⁺ Tracer				
-----all values reported as 10^{-10} m ² /s-----				
Mean	0.1	0.2	0.4	0.3
SD	0.05	0.1	0.5	0.2
Lower 95% Conf. Int.	0	0	0	0
Upper 95% Conf. Int.	0.2	0.4	1.4	0.9

**Figure 8-10
Matrix Diffusion Ranges for the Four Frenchman Flat HSUs and YMP Reported Values
using Experimentally-Derived Matrix Diffusion Data**

8.4 Development of Matrix Diffusion Ranges From Correlation

For FF HSUs which did not have datasets of experimentally-derived matrix diffusion either from the CAU itself or transferred from other data sources, the D_m range was determined using a porosity- D_m correlation (Shaw, 2003a) with the porosity range for that FF HSU. This correlation-based D_m range was also developed for the four FF HSUs with experimentally-derived data, to allow comparison of results using the two different techniques and assess potential bias or error in the correlation.

Shaw (2003a) developed three porosity- D_m correlations: (1) for fracture transport experimental data, (2) for diffusion cell data using non-fractured samples, and (3) a combined regression of all the data, from both fractured and non-fractured rock samples. Equation (8-15) below is the correlation developed using all the data:

$$\text{Log}D_m = 0.5538\text{Log}\phi - 5.3649 \quad (8-15)$$

This correlation is shown in Figure 8-11, plotted against the dataset of matrix diffusion coefficient values with equivalent Frenchman Flat HSUs.

Figure 8-11
Empirical Correlations Compared to Frenchman Flat Matrix Diffusion Dataset

Due to the wide variability of the data, the R-squared measure of correlation quality is poor for all three correlations, ranging from 0.26 to 0.42, and even the 0.42 value is based on having porosity in both the x- and y- values (the combined regression correlation is actually a nD_m to n correlation). These correlations were all developed based on an equal weighting to the data; before the geological or quality weighting scores were developed.

As an alternative, the combined regression correlation above is compared to a correlation based on a simple form of porosity to a power (the “formation factor” relationships of Equations 8-9 and 8-10 above):

$$D_m = \phi^2 D_o \text{ or } D_m = \phi^{1.3} D_o \quad (8-16)$$

Both of these simple relationships converge to the molecular diffusion value as porosity increases to one. As shown in Figure 8-12, the power relationship with an exponent of 1.3 is within an order of magnitude of the Shaw (2003a) regression correlation throughout the region with data (porosity = 0.05 to 0.40), while the 2.0 power relationship is significantly below this correlation throughout most of this region.

Figure 8-12
**Empirical Correlations and Formation Factor Type Correlation Compared
to Frenchman Flat Matrix Diffusion Dataset**

There is an extremely wide scatter in the matrix diffusion coefficient data and none of the correlations stand out as of clearly better quality. For the Frenchman Flat HSUs without experimentally-derived data, the Shaw (2003a) correlation was chosen as the basis for calculating diffusion data ranges for this analysis for a good fit with the general trends in the data and consistency with previous work. These ranges are shown in the Figure 8-13 and Table 8-9, with the YMP range included for comparison (the YMP range was not determined by the correlation).

In Figure 8-13, the mean matrix diffusion and 95-percent confidence interval is based upon the mean porosity and the 95-percent confidence interval for the porosity for each unit. Likewise, the error bars above and below the confidence

Figure 8-13
Matrix Diffusion Ranges Determined by Correlation

Table 8-9
**Matrix Diffusion Ranges Determined From Shaw et al. (2003a),
Correlation, by Frenchman Flat HSU ($\times 10^{-10}$ m²/s)**

HSU	Mean	95 % Confidence Interval
AA	2.4	1.8 to 3.0
BLFA	1.7	0.8 to 2.9
OAA	2.2	1.5 to 2.9
PCU1U	2.4	2.3 to 3.0
TM-WTA	2.2	1.1 to 2.7
TM-LVTA	2.4	1.9 to 2.9
ULTCU	2.1	1.6 to 2.6
TSA	2.0	0.8 to 2.9
LCA	1.0	0.3 to 2.3
LCCU	0.7	0.3 to 0.9
Yucca Mtn	1.6	0.6 to 2.6

Note: All D_m values above $\times 10^{-10}$ m²/s

intervals are determined from the minimum and maximum porosity measured for that Frenchman Flat HSU.

The matrix diffusion ranges calculated from the correlation (“corr”) are compared to those calculated from experimentally-derived data in the dataset (“ds”) in [Figure 8-14](#). The ranges calculated from experimentally-derived data rather than from correlations show a much wider scatter, an expected result given the wide

Figure 8-14
Comparison of Matrix Diffusion Ranges by Correlation
and by Statistical Fit to Experimentally-Derived Data

scatter of the matrix diffusion data. However, the mean values of the matrix diffusion range for each HSU are fairly similar for the two techniques, within $1 \times 10^{-10} \text{ m}^2/\text{s}$.

8.5 Matrix Diffusion Coefficient Range for Each Frenchman Flat HSU, Before Temperature Correction

For each of the 10 major FF HSUs, recommended ranges of matrix diffusion coefficient are shown in Figure 8-15 and reported in Table 8-10. The coefficients span the range of likely matrix diffusion values expected for FF CAU groundwater flow and transport model.

8.6 Recommended Matrix Diffusion Range for Each Frenchman Flat HSU

As discussed in Section 8.2.4, matrix diffusion increases with temperature, becoming significant for temperature increases of 10 to 15°C greater than average indoor (laboratory measurement) temperatures. For this reason, matrix diffusion ranges for each HSU were corrected for temperature effects. Table 8-6 lists the correction needed to adjust each HSU for that HSU's temperature, where the temperature correction is a multiplier, ranging from 1.0 to 2.84, applied to the matrix diffusion values in Table 8-10. Table 8-11 shows the calculated matrix diffusion coefficient for each HSU, after temperature correction.

For each of the 10 major FF HSUs, calculated ranges of matrix diffusion coefficient are presented (Figure 8-16), to cover the range of matrix diffusion expected for the range of radionuclides with the highest to the lowest molecular diffusion; therefore, also matrix diffusion encountered at Frenchman Flat: tritiated

Figure 8-15
Matrix Diffusion Ranges for Frenchman Flat HSUs (Before Temperature Correction)

Table 8-10
Calculated Matrix Diffusion Ranges for Frenchman Flat HSUs
(Before Temperature Correction) ($\times 10^{-10} \text{ m}^2/\text{s}$)

HSU	Method	Tritiated Water		Am ⁺	
		Mean	95% Confidence Interval	Mean	95% Confidence Interval
AA	Correlation	2.4	1.8 to 3.0	0.3	0.2 to 0.4
BLFA	Correlation	1.7	0.8 to 2.9	0.2	0.1 to 0.4
OAA	Correlation	2.2	1.5 to 2.9	0.3	0.2 to 0.4
PCU1U	Correlation	2.4	2.3 to 3.0	0.3	0.3 to 0.4
TM-WTA	Experimental Data	0.8	0.0 to 1.4	0.1	0.0 to 0.2
TM-LVTA	Experimental data	1.2	0.0 to 3.1	0.2	0.0 to 0.4
ULTCU	Experimental data	3.2	0.0 to 11	0.4	0.0 to 1.4
TSA	Experimental data	2.0	0.0 to 7.1	0.2	0.0 to 0.9
LCA	Correlation	1.0	0.3 to 2.3	0.1	0.0 to 0.3
LCCU	Correlation	0.7	0.3 to 0.9	0.1	0.0 to 0.1

Table 8-11
Recommended Matrix Diffusion Ranges for Frenchman Flat HSUs
(Corrected for Temperature) ($\times 10^{-10} \text{ m}^2/\text{s}$)

HSU	Method	Tritiated Water		Am ⁺	
		Mean	95% Confidence Interval	Mean	95% Confidence Interval
AA	Correlation	2.4	1.8 to 3.0	0.3	0.2 to 0.4
BLFA	Correlation	1.7	0.8 to 2.9	0.2	0.1 to 0.4
OAA	Correlation	2.2	1.5 to 2.9	0.3	0.2 to 0.4
PCU1U	Correlation	3.0	2.8 to 3.7	0.4	0.4 to 0.5
TM-WTA	Experimental data	1.1	0.0 to 2.0	0.1	0.0 to 0.3
TM-LVTA	Experimental data	1.9	0.0 to 4.8	0.2	0.0 to 0.6
ULTCU	Experimental data	5.1	0.0 to 17.7	0.7	0.0 to 2.3
TSA	Experimental data	2.6	0.0 to 9.4	0.3	0.0 to 1.2
LCA	Correlation	1.6	0.5 to 3.7	0.2	0.1 to 0.5
LCCU	Correlation	1.9	1.0 to 2.6	0.2	0.1 to 0.3

Note: All D_m values above are corrected for increased temperature with depth of the HSUs.

water to Am⁺. Matrix diffusion coefficients are a function of both the rock properties and the tracer species properties. If, for a specific rock, the matrix diffusion coefficient is known for one radionuclide species, then the matrix diffusion coefficient can be calculated for any other radionuclide species using the ratio of the molecular diffusion coefficients, as discussed in [Section 8.2.4](#). For example, to calculate the matrix diffusion coefficient for americium from that experimentally determined for tritium, the following formulation may be used:

$$D_{mAm} = D_{mHTO}(D_{oAm}/D_{oHTO}) \quad (8-17)$$

Where D_{mAm} is the matrix diffusion coefficient for americium, D_{mHTO} is the matrix diffusion coefficient for tritiated water, D_{oAm} is the molecular diffusion coefficients for americium, and D_{oHTO} is the molecular diffusion coefficients for tritiated water.

Therefore, to calculate the matrix diffusion coefficient for any other radionuclide of interest in transport modeling, only the molecular diffusion coefficient for that radionuclide is required. Many of these values are presented in [Table 8-4](#) and others may be found in the references presented in this table. Additionally, the relationship above assumes that the matrix diffusion measurements are carefully designed and conducted to measure the matrix diffusion in that porous media and to exclude all other processes other than diffusion (such as cation exchange, complexation, anion exclusion) and that sorption is either negligible or explicitly accounted for in the analysis of the experiment.

Figure 8-16
Matrix Diffusion Ranges for Frenchman Flat HSUs

For HSUs without equivalent measured matrix diffusion data, the matrix diffusion range was calculated using a porosity- D_m correlation (indicated by “corr” in Figures 8-14 and 8-15). This resulted in a narrower matrix diffusion range than that developed using a dataset of actual measured matrix diffusion data from an HSU equivalent to that Frenchman Flat HSU (indicated by “ds” in Figures 8-14 and 8-15). This is due to the typically narrower range of variation for measured porosity datasets (less than 1 order of magnitude) compared to the typically wider variation for measured matrix diffusion coefficient datasets (2-3 order of magnitude) with a reasonable quantity of data. To increase the variation of the correlation-derived matrix diffusion to a level consistent with that derived from measured D_m data, the variation of the entire Frenchman Flat equivalent D_m dataset could be considered when conducting sensitivity studies for the contaminant transport model. The cumulative probability distribution function for the Frenchman Flat equivalent D_m dataset is graphed in Figure 8-8, and this score-weighted dataset fits very well to a log normal distribution with a mean $\ln D_m$ value of -22.5 m^2/s (mean $D_m = 1.65 \times 10^{-10} \text{ m}^2/\text{s}$) and a standard deviation in $\ln D_m$ of 0.9 m^2/s . Ranges of values calculated from this log normal distribution of the Frenchman Flat equivalent matrix diffusion dataset are shown below:

	Confidence Interval	CDF range	D_m range, (x 10 ⁻¹⁰ m ² /s)	Range relative to mean D_m
1-sigma	68%	16% - 84%	0.7 - 4 (less than 1 order of magnitude)	$\frac{\bar{D}_m}{2.4} - 2.4 \times \bar{D}_m$
2-sigma	95.5%	2.3% - 97.8%	0.3 - 10 (over 1 order of magnitude)	$\frac{\bar{D}_m}{6.1} - 6.1 \times \bar{D}_m$
3-sigma	99.7%	0.15% - 99.85%	0.1 - 24 (over 2 orders of magnitude)	$\frac{\bar{D}_m}{14.5} - 14.5 \times \bar{D}_m$

8.7 Data Limitations and Recommendations for Further Analysis

This analysis assumes that all non-diffusive processes encountered during matrix diffusion experimental measurements can be neglected or are otherwise explicitly accounted for prior to reporting of diffusion values. Some of the non-diffusive processes include adsorption, cation exchange, complexation, anion exclusion, and lowering of effective porosity for large molecules excluded from small pores. This analysis also assumes that all experimental tracer solutions are dilute (less than 1M). Multi-component diffusion effects have not been included in this analysis.

The importance of the matrix diffusion coefficient is expected to be greater for transport in fractured media than in alluvial media; therefore, of much greater importance in transport model realizations where there is significant movement of contaminants in the volcanic aquifers or LCA. In determining whether additional matrix diffusion data acquisition or analysis is worthwhile, the effect of the uncertainty range of the matrix diffusion coefficient upon predicted contaminant transport should be compared to that for other parameters which may have greater uncertainty and a greater impact over their range of uncertainty, such as fracture frequency and width. The intensiveness and sophistication of the matrix diffusion analysis, and whether further measurements are of value, should be related to the relative impact of this parameter, over its range of uncertainty, in predicting contaminant transport.

9.0 Matrix Sorption Parameters

9.1 The Role of Matrix Sorption in Contaminant Transport Models

Matrix sorption is a physiochemical process at mineral-water interfaces that controls solute mobility and solute retardation within the pore spaces of the immobile rock matrix. Similar physiochemical processes may occur on minerals coating fractures. Fracture sorption is treated separately in [Section 10.0](#) because the conceptual and numerical models differentiate between the sorption process within the matrix pore space and along fracture walls. There are multiple methods for mathematically representing the matrix sorption process in parameterized groundwater transport models. These methods include, but are not limited to: (a) mechanistic pore-scale models that represent the sorption process on each immobile mineral grain with thermodynamic relationships for each type of reactive surface; (b) mechanistic complexation and exchange models representing average processes on integrated volumes represented with discretized continuum models; and (c) isotherms that seek to describe or abstract, on a laboratory scale, the integrated behavior of the smaller-scale mechanistic processes.

9.1.1 The K_d Parameter

A commonly used isotherm is the linear distribution coefficient, K_d . In fact, most isotherms at low solute concentrations, or over a narrow range of concentrations, simplify to a linear model. Modeling solute transport using K_d s is attractive due to the simplicity with which models are implemented and because the models represent an average behavior, thus decreasing the number of molecular-scale processes that need to be quantified and explicitly accounted for in transport models.

For the purposes of this document, it is assumed that the distribution coefficient will be used to parameterize radionuclide-rock interactions for use in the CAU transport model.

The distribution coefficient (K_d) value is defined as:

$$K_d = \frac{\text{Moles of solute per gram of solid phase}}{\text{Moles of solute per milliliter of solution}} \quad (9-1)$$

This approach assumes that the sorbent (radionuclide) has a uniform affinity for the rock surface, independent of the mass of sorbent already adsorbed. Put simply,

this means that there are many more places for sorption to occur than radionuclides sorbing. Another assumption inherent in the use of this parameter is instantaneous equilibrium between the aqueous and sorbed phase. Although laboratory measurements rarely guarantee that experiments have reached equilibrium conditions, measurement of sorption and desorption frequently confirm that little error has been introduced by assuming these measurements are in equilibrium. The use of distribution coefficients in the CAU-scale model requires the assumption of local equilibrium conditions because contact times between radionuclides and rocks may not be the same for laboratory experiments at the rate of groundwater flow through the reactive rocks in the CAU model.

The K_d parameter may be developed either by direct measurement on aquifer material samples or it can be computed by upscaling mechanistic processes. Both approaches are discussed in the next sections.

9.1.2 Significance of the K_d Parameter

Grid cells in the Frenchman Flat CAU transport model may be large relative to sub-block heterogeneities (non-uniform mineral distributions, fluctuations in aqueous chemistry) that effect water and solute flow and mineral-solute contact. Thus, averaging of the specific processes that occur at each mineral reaction site is necessary and appropriate for CAU-scale simulations. Although measured on a small sample, the K_d begins to provide such averaging. Additionally, modeling transport of sorbing solutes at the CAU scale presents a computational challenge when mechanistic-transport models are fully integrated. Distribution coefficients, however, are easy to include in large-scale transport models.

9.1.3 Limitations of the K_d Parameter

Use of the K_d parameter requires the assumption of local equilibrium. Reactions that are kinetic in nature must be assumed to occur fast enough relative to groundwater flow that the K_d captures the process either adequately or conservatively in field-scale simulations. Further, the K_d parameter does not allow for changing sorption behavior due to temporal changes in water chemistry or mineral surfaces. It can vary spatially but is not capable of representing dynamic system changes during the course of a simulation.

9.2 Contaminants of Potential Concern

The unclassified radiologic inventory for the Frenchman Flat CAU is reported by Bowen et al. (2001) and is summarized in [Section 2.5.1.2](#). A total of 43 source-term radionuclides were included in the list prepared by Bowen et al. (2001).

Tompson et al. (2004) evaluated the Bowen et al. (2001) radionuclide inventory to determine the list of radionuclides important for the Frenchman Flat radiologic

source term (RST). Each radionuclide in the Bowen et al. (2001) list was evaluated to determine whether the radionuclide was naturally occurring or whether the decay of a particular radionuclide would result in the production of other radionuclides. Accounting for the possibilities noted above, Thompson et al. (2004) provide an inventory of 44 candidate source-term radionuclides from the 10 underground nuclear tests at Frenchman Flat. These radionuclides were divided into 11 classes with unique partitioning and sorption characteristics (Thompson et al., 2004).

Many of the 44 candidate radionuclides are listed by Thompson et al. (2004) as tracers (i.e., non-reactive constituents) or represent multiple isotopes of the same element (Table 9-1), thus decreasing the number of radionuclides for which sorption data are required. Thompson et al. (2004) list as non-reactive tracers: isotopes of tritium, carbon (C), chlorine (Cl), argon (Ar), krypton (Kr), technetium (Tc), iodine (I), nickel (Ni), zirconium (Zr), niobium (Nb), tin (Sn), palladium (Pd), cadmium (Cd), and thorium (Th). Some of the radionuclides listed by Thompson et al. (2004) as non-reactive tracers are implicated as non-conservative species in other studies, and there is available data to characterize their transport behavior; therefore, they are considered here as well. Thus, the 13 reactive elements (and their isotopes) of interest for Frenchman Flat CAU transport modeling include calcium (Ca), strontium (Sr), cesium (Cs), samarium (Sm), europium (Eu), holmium (Ho), gadolinium (Gd), curium (Cm), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and Ni. Of these elements, K_d measurements or estimates appear to be unavailable only for Ho, Gd, and Cm. Thompson et al. (2004) group these elements with Eu, suggesting they have similar transport characteristics.

Laboratory sorption data on representative alluvium are available for Cs, Sr, Am, Eu, Sm, Np, U, Pu, Ni, Tc, and I. Laboratory sorption data for representative volcanic rocks are available for Cs, Sr, Am, Np, U, and Pu. The K_d values of the representative alluvium and volcanic rocks will be summarized for each HSU at the end of this chapter. K_d values for the remaining elements are estimated based on data collected for other materials, elemental properties of the radionuclides, or mechanistic simulation estimates.

9.3 K_d Data Types

A description of the available K_d data is provided in this section. Data types include K_d values derived from upscaled mechanistic sorption models, directly-measured K_d values (for alluvium and volcanic rocks), and a few field observations from the CAMBRIC RNM (Hoffman, 1979).

9.3.1 K_d Derived From Upscaled Mechanistic Sorption Models

Reactions of solutes with immobile minerals involve a host of processes. Triay et al. (1997) and Zavarin and Bruton (2004a and b) provide descriptions of the reactive processes and controls affecting solute sorption to immobile minerals

**Table 9-1
Eleven Radionuclide Classes as Reported by Thompson et al. (2004)**

RN Class	Component		RN Analogs
1	Tracer 1 ^a	Tritium, C-14, Cl-36, Ar-39, Kr-85, Tc-99, I-129 ^b	Al-26 ^b , Ni-59 ^b , Ni-63 ^b , Zr-93 ^b , Nb-93m ^b , Nb-94 ^b , Pd-107 ^b , Cd-113m ^b , Sn-121 ^b , Sn-126 ^b , Th-232 ^b
2	Tracer 2 ^a		
3	Ca-41		
4	Sr-90		
5	Cs-135,137		
6	Sm-151		
7a	Eu-150,154		Gd-150, Gd-152 ^{c,d} , Ho-166m ^c
7b	Eu-152		
7c			Cm-244 ^e
8	U-232,233,234,235,236,238		
9	Np-237		
10a	Pu-239,242		
10b	Pu-238		
10c	Pu-240		
10d	Pu-241		
11a	Am-243		
11b	Am-241		

^aThe behavior of non-sorbing radionuclides is described by defining two tracers of unit mole inventory in the melt glass and exchange volume, respectively. The behavior of each non-sorbing radionuclide can be determined by proportionally combining results for each tracer and then accounting for decay.

^bAl-26, Ni-59, Ni-63, Zr-93, Nb-93m, Nb-94, Pd-107, Cd-113m, Sn-121, Sn-126, and Th-232 are conservatively assumed to be non-reactive species because their reactive transport behavior has not been determined, even though many (e.g. Cd-113m and Th-232) are expected to be highly sorbing.

^cGd-150, Gd-152, Ho-166m, and Cm-244 sorption behavior is assumed to be equivalent to that of Eu.

^dThere is no initial abundance of Gd-152; it is only produced by ingrowth.

associated with the groundwater systems of the NTS. Mechanistic modeling approaches seek to represent the fundamental reactions between the solutes and the specific surfaces with which they come into contact. Using thermodynamic reaction-constant databases, mechanistic approaches represent processes including surface complexation, ion exchange, and precipitation. Additionally, the mechanistic modeling approach seeks to incorporate all aqueous-aqueous and aqueous-solid reactions. These include speciation reactions such as those involving carbonate complexes, oxidation/reduction reactions, and rock-water reactions that may control the concentration of surface sites with which radionuclides come into contact. K_d s can be developed from mechanistic models

by simulating the effective distribution of a solute between its aqueous phase and sorbed phase by considering all relevant reactions, listed above, for a sample of aquifer material and specified geochemical conditions.

A benefit of the mechanistic modeling approach is its ability to specifically represent the reactions that control and affect radionuclide mobility. Due to the complete representation of all expected reactions, the mechanistic modeling approach describes how groundwater chemistry changes (e.g., pH), affect sorption reactions, as well as how sorption reactions may affect groundwater chemistry.

A limitation of the mechanistic modeling approach is that, although a detailed set of reactions may be simulated, parameters for those reactions may not be available, particularly at the CAU scale. For example, a mechanistic transport model requires the concentration of available reactive surface sites (often represented as percent mass of various minerals for which total reactive surface sites are known) be specified. Characterization of surfaces that a solute may come in contact with is generally not known and must be inferred. Further, coatings of reactive mineral sites with other compounds may serve to modify the available reactive surface sites for a given mineral. Another limitation of mechanistic models is that they require large amounts of computer resources due to the complexity and nonlinearity of the processes that they attempt to capture when used in a fully coupled flow and transport model.

Although mechanistic models are faced with some limitations in their application for large-scale systems, they remain attractive due to their ability to capture heterogeneity. By doing so, they present both a capability to provide technical credibility to scaled or abstracted methods as well as providing a process with which to develop such scaled parameters.

Until recently, mechanistic sorption modeling has been primarily focused on small-scale systems where detailed characterization of mineral composition is available. Recognizing the need to extend such models to CAU-scale problems, Zavarin et al. (2004) developed a methodology that upscales mechanistic sorption models to prescribe K_d values. This approach formalizes concepts for Pahute Mesa presented by Pawloski et al. (2001) and Wolfsberg et al. (2002, Appendix B), as well as by Davis et al. (1998) and others too numerous to fully review for other hydrogeologic systems. Only a brief summary of the method, results, and limitations of the mechanistic scaling approach are presented here. Zavarin et al. (2004) provide detail on the methods and results.

Upscaled mechanistic sorption accounts for aqueous speciation, surface complexation, ion exchange, and precipitation reactions. Such processes for one radionuclide may be codependent upon the similar reactions associated with other radionuclides, thus leading to a large set of coupled reactions that must be considered simultaneously. The methods for solving such systems of equations are well documented. Zavarin et al. (2004) recognized that such methods are well suited for small or well-constrained problems, but that simplification is necessary for applicability at larger scales (e.g., CAU scale). Thus, following a set of assumptions, K_d s are developed based upon the mechanistic modeling approach. The assumptions include: (a) time-invariant solution groundwater chemistry;

(b) time-invariant sorbing mineral abundances; (c) far greater abundance of available sorption sites than sorbing radionuclides in solution; and (d) conditions in which precipitation of minerals with the radionuclides can be neglected. Wolfsberg et al. (2002) made similar assumptions to justify simplifications in mechanistic models of fracture sorption K_d s.

Following the assumptions listed above, a set of numerical experiments can be performed to compute K_d s for a material. The information needed for such calculations include: (a) initial radionuclide concentrations in solution; (b) groundwater chemistry (assumed to be unchanging); (c) thermodynamic reactions for all aqueous speciation and sorption reactions (e.g., Zavarin and Bruton, 2004a and b), and (d) most importantly, available reactive surface site concentrations of the surface complexation and ion-exchange sites at which sorption reactions will occur.

9.3.2 Directly Measured K_d

Although K_d may be computed from mechanistic processes, K_d can also be measured directly during laboratory sorption experiments. The experiments are generally designed with knowledge of the mechanistic processes that affect K_d , but with the goal of simply measuring it given some set of environmental controls. Measurements of K_d values for several radionuclides on multiple types of minerals and rock material have been collected in support of UGTA and YMP transport studies. Such studies generally provide information on the rock type (rock mineralogy) and the experimental conditions under which the experiment was performed. Such conditions include:

- Aqueous ion concentrations
- Temperature
- pH
- Eh (and/or other indicators of oxidation/reduction state such as oxygen fugacity)
- Solute concentration
- Rock characteristics
- Experimental atmospheric conditions (e.g., air or carbon dioxide to control pH)

Thus, each K_d measured is for a specific set of environmental conditions, albeit generally designed to represent *in situ* conditions. The information that would be necessary to scale mechanistic studies to reproduce measured K_d values is generally not available. Namely, the detailed trace mineral characterizations of the samples on which K_d s are measured do not exist. Thus, through analysis of large

numbers of K_d measurements, variation and uncertainty could be integrated through the use of probability distribution functions.

Although the experiments used to obtain K_d parameters are fast and easy, there are important limitations associated with the use of such parameters in transport models. Whereas transport processes are dynamic, the measurements with which the parameters are obtained are static. Likewise, the contact time between the radionuclides and aquifer materials in the CAU-scale model. The representativeness of K_d batch experiments to *in situ* rocks may be hard to assess because these experiments are usually performed on freshly created surfaces from crushed or sieved rocks. Experimentally determined K_d values that are very small or very large contain the greatest uncertainties, even for the static conditions in which they are measured, due to the subtraction of two large numbers necessary for the calculation. K_d values do not seek to describe the behavior of any particular species. Rather, they simply represent the total mass of the element of interest. However, if more detailed mechanistic understanding is desired, it is possible to derive the speciation given the environmental conditions describing the experiment. Finally, although the K_d parameter represents an integrated response of a sample brought in contact with the aqueous solute of interest, the sample size is still far smaller than the rock volume in the CAU-scale model that will be parameterized for flow and transport simulations.

9.3.3 Field Observations from the CAMBRIC Migration Experiment

The CAMBRIC RNM studied the radionuclide distribution in both the liquids and solid debris surrounding the cavity of a 0.75-kt nuclear test detonated in the alluvial aquifer, below the water table (Hoffman, 1979). With directly measured radionuclide partitioning in the test cavity and the aqueous phase, K_d s for Sr-90, Ru-106, Sb-125, Pm-147, and Pb-239 were calculated. This was accomplished by comparing the aqueous phase concentration of each radionuclide in the aquifer porewater to the expected, calculated concentrations based on the CAMBRIC source term.

9.4 Data Sources

9.4.1 Mechanistic K_d Values

Zavarin et al. (2004) calculated matrix K_d s for Ca, Sr, Cs, Am, Eu, Sm, Np, Pu, and U for Frenchman Flat alluvium in the presence of water consistent with groundwater ion concentrations near the CAMBRIC test. In addition, the K_d s for several regional HSUs were reported. The K_d s estimated by Zavarin et al. (2004) for alluvium match measured values much better than the tuff estimates for Pahute Mesa because the speciation-reaction database used to calculate the alluvium K_d values was validated against direct K_d measurements (Zavarin et al., 2002). Further details about the validation procedure can be found in Zavarin et al. (2004).

The mechanistic scaling study of Zavarin et al. (2004) is dependent upon multiple other data sources. The modeling is conducted in accordance with LLNL procedures. The information used as model input to predict the K_d values are available in LLNL reports.

9.4.2 Laboratory K_d Values

Alluvium. Primary sources of alluvium sorption data included Frenchman Flat specific laboratory values in Wolfsberg (1978a) and a memorandum written by Wolfsberg (1978b); however, mineralogy of the rock samples and water chemistries used during these experiments were not included in the documentation making these values difficult to interpret. Yucca Flat alluvial experiments were reported in Wolfsberg et al. (1983) and Zavarin et al. (2002). Additional data were available from the Beatty Low-Level Waste Storage Facility (Wolfsberg et al., 1983) and the YMP data discussed by Triay et al. (1997), DOE/ORD (2001), and DOE/ORD (2004) and stored in the YMP Technical Data Management System (TDMS).

Volcanic Rocks. The YMP has studied sorption of radionuclides on minerals and volcanic rocks for over two decades. These studies provide the majority of data and analyses relevant to radionuclide sorption on matrix material in Frenchman Flat volcanic aquifers. The data are discussed by Triay et al. (1997), DOE/ORD (2001), and DOE/ORD (2004) and stored in the YMP TDMS.

K_d measurements maintained in the YMP TDMS were collected under a stringent QA environment and are fully traceable with laboratory notebooks and data-tracking numbers. The analyses presented in this report incorporate data that meet all YMP QA requirements as of summer 2004; thus, these data will differ from those reported during previous data compilation for the UGTA program (e.g. Shaw, 2003a). These data are utilized in the present study to create new estimates of K_d distributions for Pu, Np, U, Sr, and Cs.

The NTS-UGTA Project has conducted a limited number of studies at DRI, primarily involving sorption of Pb, Sr, and Cs on a select number of rocks from Pahute Mesa and Rainier Mesa, and Frenchman Flat boreholes (Papelis and Um, 2002a and b; Decker et al., 2003). The results of these studies are used to supplement the data reported by the YMP. These studies are documented in DRI reports, and the experiments were conducted and documented under DRI QA protocol.

Other Rocks. Although most of the Frenchman Flat aquifers are comprised of alluvium and volcanic tuff, there are some CAs and aquitards within the CAU system as well as some basalt. Sorption data for radionuclides on carbonate material elsewhere, primarily in support of the WIPP Project, have been reported and summarized by Dosch and Lynch (1980), Stout and Carroll (1992), and Perkins et al. (1998). These studies provide primarily qualitative insight into the affinity of radionuclides for carbonate material; they do not represent specific NTS material or water chemistry.

9.4.3 Field K_d Values

The CAMBRIC RNM experiment studied the radionuclide distribution in both the liquids and solid debris surrounding the cavity of a 0.75-kt nuclear test detonated in the AA, below the water table (Hoffman, 1979). With directly measured radionuclide partitioning in the test cavity and the aqueous phase, K_d s for Sr-90, Ru-106, Sb-125, Pm-147, and Pb-239 were calculated. This was accomplished by comparing direct measurement of the ratio of each radionuclide detected in the liquid phase to the tritium in the water with the calculated ratio for the CAMBRIC source term.

Assumptions made in the calculation of K_d s are that all tritium is in the liquid phase and that the missing fraction of each radionuclide relative to the CAMBRIC source is the sorbed fraction. Usefulness in applying K_d s from the CAMBRIC RNM experiment is limited by these assumptions. K_d s reported from this experiment are static values that represent environmental conditions close to the test cavity and do not represent average K_d s throughout the Frenchmen Flat CAU-scale model. K_d s from CAMBRIC do not account for variations in aqueous ion concentrations, temperature, pH, Eh, solute concentration, or other conditions likely to vary away from the area effected by the test. Because transport is not expected to be large, these variations are unlikely to be large.

9.5 Data Transfer and Data Quality Protocol for Laboratory Distribution Coefficients

During the course of data compilation and evaluation, data quality flags and transferability weights were added to the dataset consistent with the general methodology suggested in SNJV (2004g). The following is a detailed description of the data transferability implementation for distribution coefficients. This approach differs for the transport parameter data analysis conducted for Pahute Mesa (Shaw, 2003a) by integrating data transfer weights and multipliers during the development of all probability functions for the sorption data.

9.5.1 Weights

Data weights are intended to describe the geologic context of the data in question. For distribution coefficients, information about the rock type and alteration is not sufficient to categorize the relevance of a data point to the appropriate CAU. To account for this situation, the generalized weighting scheme suggested by SNJV (2004g) was modified to account for the aqueous chemistry and the mineralogy of the rock used during the sorption experiments. This was done in an effort to use both information about the rock chemistry, rock alteration, and aqueous environment in predicting the extent of radionuclide sorption in the Frenchman Flat CAU.

9.5.1.1 Rock Type

If the rock type is different from the rocks observed in the CAU, the data should be rejected. Rock type definitions for the Frenchman Flat CAU were done according to the following classification criteria:

9.5.1.1.1 Alluvium

Generally, alluvium is considered the detrital deposits made by streams, flood plains, and alluvial fans. Alluvium at the NTS is almost exclusively the result of alluvial fan deposition. The upland areas around the alluvial basin should contain similar rocks/rock mineralogy to the CAU of interest. Alluvium tends to be highly heterogeneous; therefore, site-specific alluvial mineralogy is necessary to evaluate the transferability of other alluvium data.

9.5.1.1.2 Volcanic Rocks

Generally, volcanic rocks are classified by mineralogy and texture. The HSUs developed for CAU geologic models tend to emphasize the physical hydrologic significance of a unit, as opposed to the mineralogy. To account for this, the CAU transport model may require refinement to specifically identify volcanic rocks based on mineralogy. Class definitions for the volcanic rocks were selected to be consistent with the class definitions used for the YMP so that YMP data could be readily incorporated into the analysis for Frenchman Flat, where appropriate. These classes are defined as:

Vitric Tuff

High percentage of original glass in samples (not devitrified or altered to zeolites)

>40 percent glass
<10 percent clay
<10 percent zeolite

Devitrified Tuff

Composed primarily of quartz and feldspar

<10 percent clay
<10 percent zeolite

Zeolitic Tuff

Dominated by alteration assemblages of zeolites

>20 percent zeolite

<10 percent clay
<10 percent glass

9.5.1.1.3 Scores

1.0 - If the rock classification is the same and all reported minerals are within the 95-percent confidence interval of the rock classification.

0.9 - If the rock is the same type and the reported mineral content is within the 95-percent confidence interval of the rock classification, but not from the same CAU. This slightly lower score accounts for the un-measured differences in the rock deposition, pore structure, etc.

0.8 - If the rock type is the same, but the mineral chemistry is within the bounds of the 99-percent mineral confidence interval or meets the definition of the typical rock classification.

0.5 - If the rock classification is the same but outside the 99-percent confidence interval for the rock chemistry at the CAU, or if the rock mineralogy does not fit within the rock classification scheme above.

9.5.1.2 Deposition and Alteration History

Distribution coefficients are dependent on the deposition and alteration history of the rock; therefore, they should be the same for all transferred distribution coefficients. For this analysis a uniform weight of 0.7 is assigned.

9.5.1.3 Water Chemistry, Especially pH and Major Cation Concentrations

0.3 - pH within 95-percent confidence interval of observed variability within an HSU and major cation chemistry within 50 percent of reported values for Frenchman Flat CAU.

0.2 - pH within 95-percent confidence interval of observed variability within an HSU, but major cation concentrations in experiments appear to be outside 50 percent bounds of cation concentrations observed at the CAU (at this point there is no data to support an evaluation of minor cation effects on K_d measurements).

0.1 - pH outside 95-percent confidence interval or suspect cation concentrations that may lead to under or over estimation of distribution coefficients.

9.5.2 Multipliers

These values are used to reflect both the quality and uncertainty of the method and scale of the measurement. Ultimately, the use of these parameters allows for the appropriate use of data that are highly uncertain or documentation is poor without allowing these data to unduly skew a dataset.

9.5.2.1 Measurement Method Considerations

The measurement method considerations include the quality and uncertainty of the method as well as the scale of the measurement.

- Reported distribution coefficients less than 0 should be rejected because they reflect an unquantifiable level of uncertainty in the measurement and potentially poor data collection techniques.
- High-quality measurements that contain multiple concentration values, water to solid ratios of less than 4, and low detection limits for radionuclides in solution received a 1.2.
- Average-quality values that contain, at minimum, duplicate concentration values and detection limits at least an order of magnitude lower than observed concentration changes were scored 1.0.
- Low-quality values that have only one sample or poor detection limits relative to concentration changes were scored 0.5.

9.5.2.2 Data Reduction and Analysis Method

Data reduction and analysis methods are evaluated independently of the type of measurement being evaluated. However, the analyst must be familiar with state-of-the-art methods in order to make an evaluation. The following multipliers applied:

- Current and widely-accepted data reduction and analysis method with reputable and traceable calibration information - 1.0
- Good method, but calibration information is suspect or missing - 0.5
- Based on older or less widely-accepted methods, but calibration information is good - 0.5
- Both methods and calibration information are suspect or missing - 0.2

9.5.2.3 Quality Documentation

Documentation quality is also evaluated independently of the type of measurement being evaluated. The following multipliers were used for the Frenchman Flat dataset:

- Good (thorough, easy to follow, traceable) - 1.0
- Appearing in a reputable journal or peer-reviewed report, but otherwise lacking in thoroughness - 0.6
- Poor - 0.3

Note that it is often the case that poor documentation results in the inability to evaluate the data reduction and analysis method (including the calibration information) for a given dataset. Thus, poorly-documented estimates can, in effect, be doubly penalized as a result of both poor documentation scores and poor data reduction and analysis scores.

9.5.3 Overall Scores

The overall score for a given dataset is taken to be the sum of the weights multiplied by the product of the multipliers. This overall score is then able to be used in downstream analyses to calculate probability distribution functions for model sensitivity analyses.

9.6 K_d Derived From Scaled Mechanistic Models

Using component additivity, Zavarin et al. (2004) compute the effective K_d for a radionuclide for given bulk material as follows:

$$K_d = \sum_{i=1}^n K_{d,i} \phi_{m,i} \quad (9-2)$$

where:

$K_{d,i}$ = is the specific K_d for individual mineral i

$\phi_{m,i}$ = mass fraction of mineral i with respect to the total bulk medium

Using mineralogic characterizations by several authors on multiple samples from core from five Frenchman Flat alluvial wells, Zavarin et al. (2004) predicted bulk K_d values for each rock chemistry sample using one aqueous chemistry. [Table 9-2](#) reports the calculated mean and standard deviation based on a log-normal distribution from each dataset for nine different radionuclides. The mean K_d predicted using the datasets is very similar considering that there were differences among the mineralogic analyses with respect to detection limit, sampling method, sample interval, and sample area (Zavarin et al., 2004). Zavarin et al. (2004)

Table 9-2
Predicted Average Radionuclide Distribution Coefficients (Log K_d , mL/g)
for Frenchman Flat Alluvium Using Reported Radionuclide Sorbing Mineral Abundances

Drill Hole	Ramspott and McArthur (1977) and Beiriger (1977)	Warren et al. (2002)	Jones (1982)	Warren et al. (2002)	Daniels and Thompson (1984)	Warren et al. (2002)	Warren et al. (2002)	Sum of All Data
	Log K_d (mL/g)							
	UE-5n	UE-5n	U-11g-1	U-11g-1	RNM-1	ER-5-3	ER-5-4	All Drill Holes
Ca	2.74±0.57 ^a	2.28±0.28	2.93±0.24	2.94±0.05	2.18±0.47	2.79±0.26	2.28±0.31	2.54±0.45
Cs	3.93±0.12	3.91±0.12	2.91±0.22	3.86±0.04	3.56±0.22	3.80±0.27	4.03±0.21	3.82±0.39
Sr	2.52±0.58	2.01±0.30	2.70±0.25	2.71±0.06	1.93±0.48	2.56±0.28	2.00±0.34	2.29±0.47
Am	3.39±0.22	3.84±0.09	4.02±0.18	3.79±0.04	3.45±0.35	3.79±0.23	3.91±0.22	3.78±0.30
Eu	2.83±0.23	2.23±0.09	3.52±0.19	3.24±0.07	2.88±0.34	3.27±0.23	3.32±0.23	3.22±0.30
Sm	3.14±0.25	3.45±0.09	3.89±0.21	3.54±0.15	3.16±0.33	3.62±0.25	3.56±0.26	3.50±0.33
Np	0.18±0.30	0.51±0.08	0.90±0.22	0.61±0.13	0.21±0.36	0.65±0.23	0.61±0.24	0.54±0.32
U	-0.52±0.39	0.06±0.07	-0.07±0.19	0.03±0.12	-0.42±0.48	-0.14±0.21	0.09±0.16	-0.11±0.33
Pu ($O_2 = 10^{-5}$)	0.44±0.25	0.91±0.08	1.02±0.18	0.86±0.06	0.52±0.37	0.82±0.22	0.97±0.20	0.83±0.30
Pu ($O_2 = 10^{-10}$)	0.84±0.26	1.30±0.08	1.43±0.18	1.26±0.06	0.92±0.37	1.23±0.21	1.37±0.20	1.23±0.30
Pu ($O_2 = 10^{-15}$)	1.33±0.27	1.77±0.08	1.93±0.18	1.76±0.06	1.40±0.38	1.73±0.20	1.84±0.20	1.71±0.30

^a Log K_d values reported are mean ± one standard deviation.

report that the datasets suggest that heterogeneous distributions of sorbing mineral phases gives rise to a large range in K_d variability for Frenchman Flat alluvium.

Table 9-3 lists the matrix K_d value reported in Zavarin et al. (2004) for HSUs from the regional NTS model (DOE/NV, 1997). These data correspond with several HSUs in the Frenchman Flat model area (Table 2-4). The minimum and maximum values represent variations due to differences in mineral composition. Water chemistry (consistent with samples CHESHIRE Test, conducted on Pahute Mesa), surface site density on individual minerals, and mineral densities are assumed constant.

Table 9-3
Predicted Average Log K_d for Selected Regional Hydrostratigraphic Units
from Zavarin et al. (2004)^{a, b}

	TMA			TC			TCB			TBA			BCU			BAQ		
	E(x)	Min	Max	E(x)	Min	Max	E(x)	Min	Max	E(x)	Min	Max	E(x)	Min	Max	E(x)	Min	Max
Ca	3.44			3.37			3.57			2.99			2.94			3.74		
Cs	4.15	3.24		4.28	3.34		4.38	3.46		4.43	3.44		4.24	3.25		4.70	3.74	
Sr	3.22			3.14			3.35			2.73			2.67			3.50		
Am	4.05	3.77	4.40	4.19	3.90	4.54	3.47	3.18	3.81	4.62	4.35	4.96	4.62	4.35	4.97	5.08	4.81	5.42
Eu	3.60	3.14	4.06	3.73	3.27	4.20	3.04	2.56	3.52	4.18	3.72	4.65	4.18	3.72	4.65	4.65	4.19	5.12
Sm	3.79	3.32	4.26	3.92	3.46	4.39	3.23	2.76	3.72	4.41	3.94	4.89	4.41	3.94	4.88	4.90	4.43	5.38
Np	0.77	0.57	1.07	0.83	0.62	1.14	0.64	0.48	0.93	1.21	0.91	1.58	1.18	0.89	1.54	1.69	1.37	2.08
U	1.20	0.87	1.59	1.26	0.93	1.65	1.17	0.84	1.56	1.45	1.11	1.85	1.37	1.05	1.77	1.85	1.51	2.25
Pu ($O_2=10^{-5}$)	1.16	0.77	1.62	1.27	0.85	1.74	0.89	0.59	1.31	1.64	1.17	2.12	1.62	1.16	2.11	2.09	1.62	2.58
Pu ($O_2=10^{-10}$)	1.50	1.06	1.98	1.61	1.16	2.09	1.24	0.84	1.70	1.98	1.51	2.47	1.97	1.49	2.45	2.44	1.96	2.93
Pu ($O_2=10^{-15}$)	2.21	1.73	2.69	2.31	1.84	2.79	1.96	1.49	2.44	2.68	2.21	3.16	2.66	2.19	3.14	3.14	2.66	3.62

^aMin and Max based on variations in mineral abundances.

^bSee Table 2-4 for descriptions of the regional HSUs.

9.7 Probability Distributions from Laboratory K_d Values

9.7.1 Alluvium

Distribution coefficients were measured on samples collected from one Frenchman Flat site, two Yucca Flat sites, and one trench located at the Low-Level Waste Disposal Site located in Nye County, Nevada (Table 9-4). The whole rock mineralogy and radionuclides tested for each series of samples are listed in Table 9-4.

**Table 9-4
Whole Rock Mineralogy from Alluvium K_d Experiments**

Sample Location	Sample Site	Mass % Smectite	Mass % Mica	Mass % Zeolite	Mass % Hematite	Mass % Calcite	Radionuclides Tested
U-1a	Yucca Flat	30	3.4	1.3		18.2	Cs-137, Eu-152, Sm, Sr-85, U, Cs-137, Sm, Np-237
Trench 22	Beatty 1 Low-Level Waste Disposal Site-Nye County	3	1	3			Am-241, Cs-137, I-131, Ni-63, Pu-239, Sr-85, Tc-95m, U-235
Trench 22	Beatty 5 Low-Level Waste Disposal Site-Nye County	5.5	1	3			Am-241, Cs-137, I-131, Ni-63, Pu-239, Sr-85, Tc-95m, U-235
Trench 22	Beatty 2 Low-Level Waste Disposal Site-Nye County	3	1	3			Am-241, Cs-137, I-131, Ni-63, Pu-239, Sr-85, Tc-95m, U-235
U3hr	Yucca Flat	0	2.5	3			Am-241, Cs-137, I-131, Ni-63, Pu-239, Sr-85, Tc-95m, U-235
Ue-5n	Frenchman Flat	11.6	3.3	19.7	0.3	2.6	U, Sr-85, Cs-137, Sm, Np-237

9.7.1.1 Americium and Samarium

Americium batch-sorption experiments were conducted on alluvium samples collected from Trench 22 at the Low-Level Waste Disposal facility in Beatty, Nevada, and at borehole U3hr at Yucca Flat. The mineral content of the samples were evaluated as reported in [Section 9.5](#) and appropriate weights were recorded for each sample. The whole rock samples all had mineralogy within the range of observed values for Frenchman Flat alluvium (as reported by Zavarin et al., 2004); however, sieved fractions of the samples frequently altered the distribution of the sample mineralogy enough to require lower *rock type* weights. A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The ranked Am data were best fit by a gamma distribution that gave a 95-percent confidence interval of three orders of magnitude ([Figure 9-1](#)). The fit statistics and distribution shape parameters are reported in [Table 9-5](#).

Samarium batch-sorption experiments were conducted by Zavarin et al. (2002) on alluvium samples collected from an exposed section of the C alcove of the U-1a.102 drift on Yucca Flat. Mineral abundances of U-1a samples were slightly enriched in smectite relative to the expected range of mineral abundances for Frenchman Flat alluvium; however, all other mineral abundances were remarkably similar to Frenchman Flat alluvium indicating that sorption experiments conducted on this alluvium will supply a reasonable surrogate for the CAU study area. A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The ranked Sm data were best fit by a triangular distribution that

Figure 9-1
CDF Fit to ECDF for Americium (Top)
and Samarium (Bottom) Sorption onto Alluvial Material

Table 9-5
Distribution Coefficients Statistics and Shape Parameters for Laboratory Measurements of Radionuclide Sorption on Alluvium

	Radionuclide																					
	Am		Sr		Cs		Eu		I		Ni		Np		Sm		Tc		U		Pu	
	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit
Model Type		Gamma		Gamma		Weibull		Uniform		Log Logistic		Triangular		Inverse Gaussian		Triangular		Gamma		Log Normal (2)		Beta General
Number of Samples	24		73		56		34		14		24		30		18		17		48		24	
Mean	174,469	186,289	470	251	5,884	6,021	50,699	50,456	5.74	6.61	2,478.1	2,514.6	8.57	8.77	57,535	57,520	2.16	2.21	6.36	6.34	4,091.3	4,220.4
Standard Deviation	214,582	233,712	197	251	5,153	4,791	27,693	29,131	4.03	8.10	1,223.1	1,278	5.08	5.81	25,663	25,234	3.48	4.35	5.04	4.705	4,448.2	4,845.7
min	3,200		1		1,720		>640		0		672		1.83		13,946		0		0.9		230	
max	1,400,00		781		33,200		96,060		24.5		4,960		22		104,074		12		60		21,000	
95% CI Min		746		7		1,662		2,523		1.14		479		1.8333		12354		0.009		1.39		224
95% CI Max		839,530		911		20,255		95,867		21.79		5198		23.81		1.08E+05		14.96		18.65		17,578
RMS error		2.00E-03		5.63E-04		1.20E-03		0		2.72E-03		1.79E-03		1.30E-03		3.71E-03		1.21E-04		2.88E-04		2.06E-03
----- Model Shape Parameters -----																						
alpha (α)		1		1		0.86				2.48								0.26				
beta (β)		293,207		242		4,090.6				4.99								8.60				
gamma (γ)										0												
alpha 1 (α ₁)																					0.42	
alpha 2 (α ₂)																					2.26	
min								0				0				0					222.83	
max								100,913				6,020.8				122,874					25,837	
most likely												1,523.1				49,685						
mu (μ)														10.03					1.63			
lambda (λ)														29.90								
sigma (σ)																			0.66			

gave a 95-percent confidence interval of one order of magnitude (Figure 9-1). The fit statistics and shape parameters are reported in Table 9-5.

Sorption experiments were conducted with pH values ranging from 7.41 to 9.42. A plot of S_m sorption coefficients as a function of pH reveals that S_m sorption is dependent on pH and has a maximum adsorption coefficient at pH 8.4 under these experimental conditions (Figure 9-2). These changes in S_m sorption are likely to be the result of S_m - CO_3^{2-} complex formation, which tends to increase as pH increases. For Frenchman Flat basin, changes in pH within the AA may lead to considerable differences in S_m sorption, thus increasing the uncertainty in S_m transport predictions. Frenchman Flat alluvium pH has been measured at values ranging from 7.9 to 8.91 (Section 2.0), values consistent with the range of pH values examined in S_m sorption experiments.

Figure 9-2
 $S_m K_d$ as a Function of pH for Alluvium Samples Collected at Yucca Flat

Given the similar chemistry of S_m and A_m , we would expect better agreement between the K_d distributions for these two radionuclides. The 95-percent confidence interval for S_m is 1.24×10^4 to 1.08×10^5 mL/g compared to 7.46×10^2 to 8.40×10^5 mL/g for A_m . Although the S_m sorption experiments included a greater variety of ion concentrations for the water chemistry used in the experiments, there was considerably more variability in rock mineralogy of the samples in the A_m experiments. This may indicate that A_m and S_m sorption are more sensitive to rock chemistry than water chemistry.

9.7.1.2 Cesium and Strontium

Neither Cs nor Sr changes oxidation states under the solution compositions expected for Frenchman Flat groundwaters. Cesium and Sr should occur as cations with single and double, positive charges respectively. Behavior in the system will be predominantly ion exchange reactions with little dependence on pH but a large dependence on the concentration of competing ions in solution (e.g., Ca). Most ion exchange reactions will occur with clays and zeolites. Ion exchange reactions for Cs are dominated by illite and mica, while these reactions are dominated by zeolite and smectite for Sr.

Fifty-six measurements of Cs sorption onto alluvial rocks have been completed for alluvium collected at Frenchman Flat Well RNM-1, Yucca Flat (multiple wells), and the Low-Level Waste Disposal facility in Beatty, Nevada. Wolfsberg (1978b) reported a Frenchman Flat specific K_d of 8,000 milliliters per gram (mL/g) for alluvial material sampled at Well RNM-1 at 256 and 331 m depth. The data from all of the experiments were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Cs data were best fit by a Weibull distribution that gave a 95-percent confidence interval slightly less than one order of magnitude ([Figure 9-3](#)). The fit statistics and shape parameters are reported in [Table 9-5](#).

Strontium distribution coefficients were measured on 74 different alluvium samples collected at Frenchman Flat Well RNM-1, Yucca Flat (multiple wells), and the Low-Level Waste Disposal facility in Beatty, Nevada. Wolfsberg (1978b) reported a Frenchman Flat specific K_d of 220 mL/g for alluvial material sampled at Well RNM-1 at 256 and 331 m. The alluvial data from Frenchman Flat and other sites were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The Sr data were best fit by a gamma distribution that gave a 95-percent confidence interval of two orders of magnitude ([Figure 9-3](#)). The fit statistics and shape parameters are reported in [Table 9-5](#).

9.7.1.3 Neptunium

Under oxidizing conditions, Np tends to exhibit limited sorption on alluvium. Under reducing conditions, we would expect that Np would exhibit greater sorption and lower solubility. Frenchman Flat groundwater in the AA is oxidizing; however, if pockets of reducing conditions are present, these may result in greater sorption and less transport in the subsurface.

Distribution coefficients for Np have been measured in batch experiments from core samples obtained from three wells drilled into the alluvium near Yucca Mountain (borehole NC-EWDP-10SA to the north, NC-EWDP-22SA in the middle, and NC-EWDP-19IM1A to the south) spaced between 4 to 5 km apart (DOE/ORD, 2004). Samples were collected from below the water table at 5-ft intervals at two depths in wells NC-EWDP-19IM1A and NC-EWDP-10SA and at six depths in well NC-EWDP-22SA (DOE/ORD, 2004). For each core sample, batch experiments were run on three particle sizes: 500 to 2,000 μm , 75 to

Figure 9-3
CDF Fit to ECDF for Cesium (Top) and Strontium (Bottom)
Sorption onto Alluvial Material

500 μm , and < 75 μm . The greatest K_d values were observed on the smallest particle size fraction; most likely due to one or more of the following reasons: mineral sorting effects (however, no sample mineralogy data were reported with these distribution coefficients), increased surface areas of the particles, and increased cation-exchange capacity.

The data from all of the experiments were evaluated using the methodology presented in [Section 9.5](#). Because we were unable to assess whether the mineralogy of any of the three sieved fractions were most representative of Frenchman Flat alluvium, all samples were kept in the analysis without adding bias to the *rock type* weights. Distribution coefficient measurements were, however, weighted corresponding to the reported pH of the experiments to favor those experimental conditions most similar water from the Frenchman Flat AA. A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted N_p data were best fit by an inverse-gaussian distribution that gave a 95-percent confidence interval of 1.8 to 23.8 mL/g ([Figure 9-4](#)). The fit statistics and shape parameters are reported in [Table 9-5](#).

Figure 9-4
CDF Fit to ECDF for Neptunium Sorption onto Alluvial Material

9.7.1.4 Uranium

Based on the expected reduction/oxidation (redox) potential of Frenchman Flat groundwaters, U should be in the +6 oxidation state ([Section 2.0](#)). In this oxidation state, U will occur as a variety of carbonate complexes and, to a lesser extent, phosphate, fluoride, and sulfate complexes because these anions have a relatively low abundance in Frenchman Flat groundwaters (Triay et al., 1997). The complexation of U with carbonate species is dependent on the pH of the solution, where decreasing pH results in less complex formation, thus increasing U sorption (Triay et al., 1997 and DOE/ORD, 2001).

Wolfsberg (1978a) reported measured K_d s for alluvium samples collected at Well RNM-1 in the presence of RNM-2s groundwater of approximately 7 mL/g. When Wolfsberg (1978a) measured sorption of U on Frenchman Flat alluvium in the presence of deionized water, the K_d was approximately 60 mL/g. Clearly, the presence of ions in the RNM-2s groundwater resulted in a net reduction in the total sorption of U. Additional U sorption onto YMP cores obtained from three wells (10SA, 22SA, and 19IM1A) drilled into the alluvium (DOE/ORD, 2004) and from Trench 22 at the Low-Level Waste Disposal Site in Beatty, Nevada, (Wolfsberg et al., 1983) were used to supplement the two data points reported by Wolfsberg (1978a). The alluvial data from Frenchman Flat and the other sites where K_d s were measured on alluvium material were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The U data were best fit by a log-normal distribution that gave a 95-percent confidence interval of 1.4 to 18.7 mL/g ([Figure 9-5](#)). The fit statistics and shape parameters are reported in [Table 9-5](#).

Although we expect that U sorption to be pH dependent, this was not apparent in the dataset ([Appendix G](#)). It is likely that two competing processes are occurring: (1) pH changes resulting in changes in the net charge on the mineral surfaces and (2) carbonate complex formation. Increasing pH will tend to increase sorption and carbonate complexation, while decreasing pH will tend to decrease sorption and carbonate complexation. Depending on the solution conditions (i.e., the balance between hydrogen ion availability and aqueous carbonate species), an increase or decrease in sorption may occur (however, at very low pH, sorption will always decrease).

9.7.1.5 Europium

Europium is a member of the lathanide series of transition metals and is expected to behave similarly to Sm by occurring in the +3 oxidation state in Frenchman Flat groundwaters. The +2 oxidation state for Eu is more stable than the +2 oxidation state for Sm; however, the +2 oxidation state is limited to very reducing conditions at near neutral pH values (Krupka and Serne, 2002). Europium III tends to form strong aqueous complexes with dissolved hydroxide, phosphate, sulfate, carbonate, and fluoride, and weak complexes with chloride and nitrate (Krupka and Serne, 2002). The majority of these ligands occur in low concentrations in the Frenchman Flat AA.

Figure 9-5
CDF Fit to ECDF for Uranium Sorption onto Alluvial Material

Thirty-four measurements of Eu sorption onto alluvial rocks have been completed for alluvium collected at Frenchman Flat Well RNM-1 (Wolfsberg, 1978a) and Yucca Flat wells U-1a (Zavarin et al., 2002) and U3bv (Wolfsberg, 1978a). Wolfsberg (1978b) reports a recommended K_d for alluvium of greater than 5,000 mL/g.

The alluvium distribution coefficients from Frenchman Flat and Yucca Flat were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The Eu data were best fit by a uniform distribution that gave a 95-percent confidence interval of 2,522 to 98,390 mL/g ([Figure 9-7](#)). The fit statistics and shape parameters are reported in [Table 9-5](#).

Zavarin et al. (2002) report that the sorption of Eu on U-1a alluvium samples collected from Yucca Flat was dominated by sorption to calcite. As Zavarin et al. (2002) varied the pH of the solution, Eu sorption was reduced at low pH due to competition with Ca for calcite surfaces and at high pH due to Eu-carbonate complex formation in solution.

Given the similar chemistry of Eu and Sm, we would expect better agreement between the K_d distributions for these two radionuclides. The 95-percent confidence interval for Sm is 1.24×10^4 to 1.08×10^5 mL/g compared to 2.52×10^3

Figure 9-6
CDF Fit to ECDF for Europium Sorption to Alluvium

to 9.59×10^4 mL/g for Eu. Sm sorption experiments incorporated a greater variety of water and rock chemistries in the laboratory experiments, thus providing a greater range in measured K_d values. The sorption experiments for Eu, although more limited in number and scope, provide a more conservative estimate of transport.

9.7.1.6 Plutonium

In near neutral environments, like Frenchman Flat groundwater, the solution behavior of Pu is complicated (Triay et al., 1997). Plutonium may occur in many oxidation states in solutions similar to Frenchman Flat groundwater. In addition, it may also undergo complex formation with a variety of ligands. Plutonium sorption onto alluvium samples from Trench 22 at the Low-Level Waste Disposal Site in Beatty, Nevada, and Well U3hr at Yucca Flat (Wolfsberg et al., 1983) were measured in the presence of an ambient air atmosphere and water collected from the AA at the Waste Disposal Site and Frenchman Flat (U-5b), respectively. Additional data such as the oxidation state of the Pu in the aqueous solution and the initial Pu concentration were not reported.

The K_d s from 24 observations were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The Pu data were best fit by a beta general distribution that gave a

95-percent confidence interval of 224.3 to 17,578 mL/g (Figure 9-7). The fit statistics and shape parameters are reported in Table 9-5.

Figure 9-7
CDF Fit to ECDF for Plutonium Sorption onto Alluvial Material

9.7.1.7 Nickel

Nickel batch-sorption experiments were conducted using 24 samples collected from Trench 22 at the Low-Level Waste Disposal facility in Beatty, Nevada (Wolfsberg et al., 1983). The mineral content of the samples was evaluated as reported in Section 9.5, and appropriate weights and multipliers were recorded for each sample. The whole rock samples all had mineralogy within the range of observed values for Frenchman Flat alluvium; however, sieved fractions of the samples frequently altered the distribution of the sample mineralogy enough to require lower *rock type* weights. A CDF was fit to the weighted ECDF using BestFit software (see Appendix C). The ranked Ni data were best fit by a triangular distribution that gave a 95-percent confidence interval 479 to 5,198 mL/g with a most likely value of 1,523 mL/g (Figure 9-8). The fit statistics and shape parameters are reported in Table 9-5.

The distribution coefficient measured on alluvium samples collected in Beatty, Nevada, suggest that the approach by Thompson et al. (2004) of treating Ni as a conservative tracer in the Frenchman Flat flow system would result

Figure 9-8
CDF Fit to ECDF for Nickel Sorption onto Alluvial Material

in significantly more transport than would be expected for this metal. Wolfsberg et al. (1983) reports that Ni sorption occurs mostly on clays and zeolites (such as kaolinite, smectite, or clinoptilolite), which are minerals known to be present in Frenchman Flat alluvium in significant abundances (Warren et al., 2002).

9.7.1.8 Iodine and Technetium

Wolfsberg et al. (1983) measured both I and Tc sorption onto alluvium collected from Yucca Flat Well U3hr and Trench 22 at the Low-Level Waste Disposal facility in Beatty, Nevada. Wolfsberg (1978a) also reported a single Frenchman Flat specific K_d for I sorption of 24.5 mL/g for alluvial material sampled at Well RNM-1 at 256 m.

The data from all alluvium samples were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted I data were best fit by a log-logistic distribution that gave a 95-percent confidence interval of 1.1 to 21.8 mL/g ([Figure 9-9](#)). The weighted Tc data were best fit by a gamma distribution that gave a 95-percent confidence interval of 8.5×10^{-3} to 15.0 mL/g ([Figure 9-9](#)). The fit statistics and shape parameters are reported in [Table 9-5](#). For both of these

Figure 9-9
CDF Fit to ECDF for Iodine (Top) and Technetium (Bottom)
Sorption onto Alluvial Material

radionuclides, Thompson et al. (2004) approximate sorption of zero, suggesting that they are modeled as conservative tracers. Given the very small lower bound of the 95-percent confidence interval and that neither of these radionuclides result in ingrowth of radioactive daughter products (Thompson et al., 2003), treating these radionuclides as non-reactive tracers is a reasonable and conservative simplification that should be considered during CAU transport modeling efforts.

9.7.2 Volcanic Rocks

The largest set of K_d values applicable to Frenchman Flat for radionuclide sorption on volcanic rock is found in the YMP database, summarized primarily by Thomas (1987), Wilson et al. (1994), Triay et al. (1997), DOE/ORD (2001), and DOE/ORD (2004). These reports summarize more than two decades of studies examining radionuclide sorption to a variety of materials. All of these reports provide reviews of the mechanistic processes governing sorption of radionuclides and describe the experiments that were conducted by YMP. As more data became available, one finds an evolving understanding and interpretation of sorption of radionuclides on minerals and volcanic rocks. Thus, DOE/ORD (2004) provides the most current data and interpretations. However, Triay et al. (1997) provide greater detail for some experiments and background material not found in DOE/ORD (2004). As a result, the two reports provide complimentary sets of information and analyses.

Whereas the YMP reports provide detailed descriptions of experiments and mechanisms associated with the radionuclide sorption studies, the distributions presented do not capture the detail that is available in the datasets. The K_d distributions presented by DOE/ORD (2004) are meant to provide input to the YMP performance assessment, a process that does not explicitly seek to differentiate between stratigraphic units and water chemistry. Therefore, a significant difference between DOE/ORD (2004) and the present study is that the data have been reevaluated in this study and new distributions, relevant to volcanic rocks in the Frenchman Flat CAU, have been developed.

A limited number of DRI studies were conducted by Papelis and Um (2003a and 2003b) and Decker et al. (2003) to measure distribution coefficients for Pb, Cs, and Sr on tuff and devitrified lava samples from Rainier Mesa, Pahute Mesa, and Frenchman Flat. Equilibrium sorption, desorption, and diffusion experiments were conducted with a few samples from each CAU at the NTS. Based on sorption data with different solid and metal concentrations, linear sorption isotherms were derived for sorption at pH 8.3, representing a common NTS groundwater pH. Batch sorption experiments were conducted on crushed rock and diffusion/sorption experiments were conducted on intact core. The data collected in these experiments were used to augment the data collected for the YMP and provide some NTS-specific measurements. These data were fully integrated into each probability distribution using the data transfer protocol.

The data transfer methodology reported in [Section 9.5](#) was used to evaluate each of the radionuclides and rock types on which K_d experiments were conducted.

9.7.2.1 YMP Sorption Experiments

YMP Laboratory Sorption Data Obtained Prior to 1993. In 1993, the YMP conducted an expert elicitation regarding K_d values and distributions for various radionuclides and rock types (Wilson et al., 1994). The distributions developed in the elicitation are due substantially to a summary report by Thomas (1987). Thomas (1987) summarizes sorption experiment results performed by the YMP prior to the QA procedures that were required for the analysis and model report by DOE/ORD (2004).

YMP Laboratory Sorption Data Obtained After 1993. With new data collected after 1993, Triay et al. (1997) developed improved K_d distributions for multiple radionuclides on devitrified, vitric, zeolitic, and iron oxide rock types (iron oxides are important to YMP for assessing sorption in the vicinity of waste packages). These distributions were modified again by DOE/ORD (2004); during this modification, distributions of K_d s for vitric tuffs were eliminated. The DOE/ORD (2004) distributions are listed in [Table 9-6](#).

The distributions that Triay et al. (1997), DOE/ORD (2001), and DOE/ORD (2004) developed were in support of performance assessment modeling at Yucca Mountain, where the entire volcanic rock section was parameterized with a single K_d (TRW, 2000) or only three K_d s in any realization of the Monte Carlo analyses (DOE/ORD, 2004). For Frenchman Flat, sorption parameters are needed for individual HSUs and must be related to the rocks of Frenchman Flat by the data transfer protocol.

The data cited in DOE/ORD (2004) are available in the YMP TDMS, with appropriate data-tracking numbers and QA pedigrees linking to raw data and laboratory notebooks. These data provide most of the input to the distributions developed in the next sections.

YMP Water Chemistry. Nearly all of the YMP K_d experiments involving rock samples taken from the field were conducted with water from, or similar in composition to, either Well J-13 or Well UE25p#1 (p#1). Well J-13 samples the Topopah Spring Aquifer, a hydrologic unit also present in parts of Frenchman Flat. Well p#1 samples the CA below the volcanic tuffs at Yucca Mountain. The groundwater compositions of these two wells are listed in [Table 9-7](#). The composition of p#1 groundwater is similar to the groundwater composition observed in Well ER-5-3#2 (a well that samples the LCA on Frenchman Flat). Waters in the VAs of the Frenchman Flat testing area tend to more calcium poor than J-13 well water ([Figure 2-9](#)). Well J-13 water is most similar to some Frenchman Flat water samples from the TM-WTA, but in some cases J-13 water is still more enriched in Ca ([Table 9-7](#)). The pH of J-13 and p#1 groundwaters is lower than those found in the majority of Frenchman Flat wells. Many YMP sorption experiments using water with J-13 and p#1 compositions were conducted with atmospheric conditions (generally labeled as “air” or “bench” conditions) to obtain higher pH values between 8.5 and 9 (closer to the pH values observed in Frenchman Flat groundwater samples). Some YMP sorption experiments were also conducted with CO₂ overpressure inside of glove boxes to obtain pH values of

**Table 9-6
 K_d (mL/g) Distributions for YMP Reported by DOE/ORD (2004)**

Species	Unit	Distribution	Range				Confidence Interval	
			Minimum	Maximum	Mean	Standard Deviation	0.05	0.95
U	Zeolitic	Normal	5	20	12	3.6	---	---
	Devitrified	Normal	0	4	2	0.6	---	---
	Alluvium	Cumulative	---	---	---	---	2.9	6.3
Np	Zeolitic	Normal	0	6	2.88	1.47	---	---
	Devitrified	Exponential	0	2	0.69	0.707	---	---
	Alluvium	Cumulative	---	---	---	---	4.0	8.7
Pu	Zeolitic	Beta	50	300	100	15	---	---
	Devitrified	Beta	50	300	100	15	---	---
	Alluvium	Beta	50	300	100	15	---	---
Cs	Zeolitic	Exponential	4,000	42,000	16,942	14,930	---	---
	Devitrified	Normal	100	1,000	728	464	---	---
	Alluvium	Normal	100	1,000	728	464	---	---
Am	Zeolitic	Truncated Norm	1,000	10,000	5,500	1,500	---	---
	Devitrified	Truncated Norm	1,000	10,000	5,500	1,500	---	---
	Alluvium	Truncated Norm	1,000	10,000	5,500	1,500	---	---
Pa	Zeolitic	Truncated Norm	1,000	10,000	5,500	1,500	---	---
	Devitrified	Truncated Norm	1,000	10,000	5,500	1,500	---	---
	Alluvium	Truncated Norm	1,000	10,000	5,500	1,500	---	---
Sr	Zeolitic	Cumulative	---	---	---	---	5,000	---
	Devitrified	Uniform	20	400	---	---	---	---
	Alluvium	Uniform	20	400	---	---	---	---
Th	Zeolitic	Truncated Norm	1,000	10,000	5,500	1,500	---	---
	Devitrified	Truncated Norm	1,000	10,000	5,500	1,500	---	---
	Alluvium (same as devitrified)	Truncated Norm	1,000	10,000	5,500	1,500	---	---
Ra	Zeolitic	Truncated Log-Normal	1,000	250,000	100,000	31,420	---	---
	Devitrified	Uniform	100	1,000	---	---	---	---
	Alluvium	Uniform	100	1,000	---	---	---	---
C/Tc/I	Volcanic/Alluvium	Constant	0	0	0	0	---	---

YMP DTN: LA0310AM831341.002

about 7 or using a nitrogen atmosphere to stabilize pH during sorption experiments.

Because only a fraction of the citations in the database list the pH or the experimental atmosphere, the atmosphere is used sometimes to delimit high (~8 to 9) and low (~7) pH experiments in the proceeding analyses.

**Table 9-7
Chemical Composition (mg/L) of Water in J-13, p#1,
and Two Locations on Frenchman Flat**

Constituent	J-13 Water ^{a, b}	p#1 Water ^{a, b}	UE-5 PW-3 ^{c, d}	ER-5-3#2 ^{c, e}
Sodium	45	171	55.1	130
Potassium	5.3	13.4	4.3	17
Magnesium	1.8	31.9	5.8	29
Calcium	11.5	87.8	15.8	77
Silicon	30	30	65.2	30
Fluoride	2.1	3.5	1.09	1.2
Chloride	6.4	37	8.6	39
Sulfate	18.1	129	32.2	69
Bicarbonate	143	698	161	634.4
pH	6.9	6.7	8.28	6.67

^aYMP (1997) DTN: LAIT831361AQ95.003 (SEP Table S98491.002)

^bOgard and Kerrisk (1984) (In Meijer, 1992)

^cHershey et al. (2004)

^dExample TM-WTA water chemistry

^eExample LCA water chemistry

9.7.2.2 Distribution Generation

In the next several subsections, measured K_d data collected by YMP and DRI are evaluated. Distributions are developed by combining the YMP and DRI measurements and applying these to Frenchman Flat volcanic rocks using the data transfer protocol explained in [Section 9.5](#). Further, whereas previous distributions have been developed for YMP using the process of expert elicitation, here we focus on fitting K_d distributions to data. Cumulative distribution functions are developed for K_d values for Am, Pu, Np, U, Sr, and Cs. For each of the radionuclides, sorption measurements were conducted on multiple pure-phase minerals as well as on tuffs classified as vitric, devitrified, and zeolitic. Whereas the pure-phase mineral studies could serve to inform future mechanistic modeling studies, in this analysis, only the tuffs are considered because they can be correlated with Frenchman Flat HSUs.

Experiments on tuff samples were conducted with J-13 water and often with the higher ionic strength p#1 water ([Table 9-7](#)). Additionally, pH was often controlled by either conducting experiments with an air environment to achieve pH between 8 and 9, or with CO₂ overpressure to force the pH closer to 7. Finally, most experiments were conducted at 20 to 25°C, but many were conducted at temperatures up to 90°C. These different environmental conditions may or may not affect distributions developed from the data. Therefore, in the analyses that follow, the roles of the different environmental conditions are highlighted when necessary. Experimental conditions inconsistent with observed water

temperatures or water chemistries at Frenchman Flat are given a lower weight in the resulting probability distributions as per the data transfer protocol.

9.7.2.3 Americium

Americium sorption data for vitric tuffs, devitrified tuffs, and zeolitic tuffs in the presence of J-13 water are reported in the YMP TDMS. Triay et al. (1997) report results from Am sorption in the presence of p#1 water. These results suggest that all rocks in the presence of water saturated with calcite (like p#1 water) showed very large distribution coefficients. Triay et al. (1997) conclude that Am coprecipitated with carbonates or formed solid solutions on the surfaces of existing carbonates. Given that p#1 water is not similar to the water present in the VAs of Frenchman Flat due to the high Ca content of this water, sorption experiments in this water would likely overpredict the sorption of americium onto Frenchman Flat rocks. Therefore, only Am experiments conducted with J-13 water are considered here.

Vitric Tuff. Eight Am sorption experiments onto vitric-tuff rocks were reported in the YMP TDMS. All of these rocks were crushed and sieved prior to analysis, and the 75 to 500 μm sieve fraction was used for the experiments. These data were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Am data were best fit by a uniform distribution that gave a 95-percent confidence interval of 655 to 2,032 mL/g ([Figure 9-10](#)). The fit statistics and shape parameters are reported in [Table 9-8](#).

Devitrified Tuff. Thirty-five Am sorption experiments onto devitrified tuff rocks were reported in the YMP TDMS. All of these rocks were crushed and sieved prior to analysis, four different sieve fractions were used for the experiments. Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 parts per million (ppm) oxygen gas (O_2) and less than 20 ppm CO_2 to increase the pH from approximately 8.5 to 9.5 during the experiments. The measured distribution coefficients showed no trend with respect to pH. The dataset was evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Am data were best fit by an exponential distribution that gave a 95-percent confidence interval of 48 to 6,986 mL/g ([Figure 9-10](#)). The fit statistics and shape parameters are reported in [Table 9-9](#).

Zeolitic Tuff. Twenty-five Am sorption experiments onto zeolitic tuff rocks were reported in the YMP TDMS. All of these rocks were crushed and sieved prior to analysis, and the 75 to 500 μm and 106 to 250 μm sieve fractions were used for these experiments. These data were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Am data were best fit by an inverse-gaussian distribution that gave a 95-percent confidence interval of 612 to

Figure 9-10
CDF Fit to Weighted Americium Sorption Data
for Three Volcanic Rock Types

Table 9-8
Distribution Coefficients Statistics and Shape Parameters for
Laboratory Measurements of Radionuclide Sorption on Vitric Tuff

	Am		Sr		Cs		Np		U		Pu	
	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit
Model Type		Uniform		Weibull		Uniform		Log Logistic		Weibull		Exponential
Number of Samples	8	--	30	--	30	--	400	--	59	--	71	--
Mean (mL/g)	1,354	1,344	148	174	646	644	3.17	1.84	1.89	1.98	516	534
Standard Deviation (mL/g)	398	418	62	21	317	320	29	+infinity	1.70	1.91	472	534
Sample Minimum (mL/g)	860	--	23	--	109	--	0	--	0	--	23	--
Sample Maximum (mL/g)	2,050	--	220	--	1,061	--	526	--	12	--	1,810	--
95% CI Minimum (mL/g)	--	655	--	127	--	118	--	0.03	--	0.06	--	14
95% CI Maximum (mL/g)	--	2,032	--	208	--	1,170	--	8.6	--	7.1	--	1,969
RMS error	--	2.90E-03	--	7.23E-03	--	2.50E-03	--	7.51E-04	--	7.98E-04	--	2.70E-03
Model Shape Parameters												
alpha (α)	--	--	--	10	--	--	--	1.32	--	1.03	--	--
beta (β)	--	--	--	183	--	--	--	0.54	--	2.00	--	534
gamma (γ)	--	--	--	--	--	--	--	0	--	--	--	--

-- = No applicable data

42,028 mL/g (Figure 9-10). The fit statistics and shape parameters are reported in Table 9-10.

9.7.2.4 Cesium and Strontium

These two elements are grouped together, as in Triay et al. (1997), DOE/ORD (2001) and DOE/ORD (2004), because they show fairly simple solution behavior in typical groundwaters. Just as they are not subject to oxidation-state changes in the groundwater compositions of Yucca Mountain, we expect the same simplicity in Frenchman Flat groundwaters. Their sorption is primarily controlled by ion-exchange reactions, where the selectivity of most clays and zeolites for these elements should be larger than for major cations in solution. Distribution coefficients should be lower in higher ionic strength water (e.g., p#1) and should decrease with increasing solution concentrations. Sorption of these two elements has been extensively studied and reviewed by Daniels et al. (1983), Thomas (1987), and Meijer (1990), and summarized by Triay et al. (1997), DOE/ORD (2001), and DOE/ORD (2004). A limited number of DRI studies were conducted by Papelis and Um (2003a and 2003b) and Decker et al. (2003) to measure distribution coefficients for Cs, and Sr on tuff and devitrified lava samples from Pahute Mesa, Rainier Mesa, and Frenchman Flat. These data were used to supplement the data reported in the YMP TDMS.

Cesium

Vitric Tuff. Sorption experiments using vitric-tuff samples and predominantly J-13 water were reported in the YMP TDMS. All rock samples were crushed and sieved prior to analysis, and the 75 to 500 μm and less than 500 μm sieve fractions were used for the experiments. These data were evaluated using the methodology presented in Section 9.5. A CDF was fit to the weighted ECDF using BestFit software (see Appendix C). The weighted Cs data were best fit by a uniform distribution that gave a 95-percent confidence interval of 118 to 1,170 mL/g (Figure 9-11). The fit statistics and shape parameters are reported in Table 9-8.

Devitrified Tuff. Among all of the data sources, a total of 159 experiments measuring Cs sorption on devitrified tuff rocks are reported. All the rock samples were crushed and sieved prior to analysis, several different sieve fractions were used for the experiments (Appendix G). Most experiments were conducted in the presence of an ambient air atmosphere; however, and several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O_2 and less than 20 ppm CO_2 to increase the pH during the experiments. The measured distribution coefficients showed no trend with respect to pH. The dataset was evaluated using the methodology presented in Section 9.5. A CDF was fit to the weighted ECDF using BestFit software (see Appendix C). The weighted Cs data were best fit by an exponential distribution that gave a 95-percent confidence interval of 25 to 2,187 mL/g (Figure 9-11). The fit statistics and shape parameters are reported in Table 9-9. The distribution coefficients, used to develop this distribution, were measured with essentially the same initial concentrations for all experiments. If field concentrations are greater than those used in the experiments supporting

Table 9-9
Distribution Coefficients Statistics and Shape Parameters for
Laboratory Measurement of Radionuclide Sorption on Devitrified Tuffs

	Am		Sr		Cs		Np		U		Pu	
	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit
Model Type		Exponential		Log Logistic		Exponential		Log Logistic		Log Logistic		Log Normal (2)
Number of Samples	35	--	154	--	159	--	421	--	75	--	118	--
Mean (mL/g)	1,845	1,894	101	101	645	601	19	12	2.51	2.76	125	142
Standard Deviation (mL/g)	1,834	1,894	141	+Infinity	656	590	166.37	+infinity	2.29	4.46	168	237
Sample Minimum (mL/g)	79	--	9	--	10	--	0	--	0	--	6	--
Sample Maximum (mL/g)	12,000	--	1,200	--	3,800	--	2,353	--	15	--	1,900	--
95% CI Minimum (mL/g)	--	48	--	18	--	25	--	0.02	--	0.4	--	8
95% CI Maximum (mL/g)	--	6,986	--	402	--	2,187	--	17.34	--	9.75	--	701
RMS error	--	1.60E-03	--	1.30E-03	--	2.10E-03	--	6.69E-04	--	9.42E-04	--	8.35E-04
Model Shape Parameters												
alpha (α)	--	--	--	2	--	--	--	1.04	--	2.29	--	--
beta (β)	--	1,894	--	48	--	590	--	0.51	--	1.97	--	--
mu (μ)	--	--	--	--	--	--	--	--	--	--	--	4
sigma (σ)	--	--	--	--	--	--	--	--	--	--	--	1
gamma (γ)	--	--	--	12	--	--	--	0	--	0	--	--

-- = No applicable data

Table 9-10
Distribution Coefficients Statistics and Shape Parameters for
Laboratory Measurement of Radionuclide Sorption on Zeolitic Tuffs

	Am		Sr		Cs		Np		U		Pu	
	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit	Sample	Fit
Model Type		Inverse Gaussian		Weibull		Log Normal (2)		Gamma		Log Normal (2)		Weibull
Number of Samples	25	--	83	--	86	--	430	--	176	--	110	--
Mean (mL/g)	5,204	6,037	39,277	40,278	16,747	17,762	3	3	45	17	260	255
Standard Deviation (mL/g)	7,757	14,863	54,882	65,354	13,710	19,440	2	1	423	22	242	205
Sample Minimum (mL/g)	470	--	1,200	--	2,700	--	0	--	0	--	19	--
Sample Maximum (mL/g)	33,000	--	246,085	--	72,000	--	22	--	9,423	--	2,000	--
95% CI Minimum (mL/g)	--	612	--	1,492	--	3,495	--	1	--	3	--	14
95% CI Maximum (mL/g)	--	42,028	--	221,800	--	67,375	--	6	--	70	--	778
RMS error	--	3.10E-03	--	3.58E-04	--	--	--	3.45E-04	--	3.82E-03	--	1.37E-03
Model Shape Parameters												
alpha (α)	--	--	--	1	--	--	--	3	--	--	--	1
beta (β)	--	--	--	27,023	--	--	--	1	--	--	--	273
mu (μ)	--	5,573	--	--	--	9	--	--	--	2	--	--
lambda (λ)	--	784	--	--	--	--	--	--	--	--	--	--
sigma (σ)	--	--	--	--	--	1	--	--	--	1	--	--

-- = No applicable data

Figure 9-11
CDF Fit to Weighted Cesium Sorption Data for
Three Volcanic Rock Types

these distributions, then K_d s will likely be lower, favoring the lower end of the distribution.

Zeolitic Tuff. Eighty-six Cs sorption experiments with zeolitic tuff rocks were reported in the YMP TDMS. All of these rocks were crushed and sieved prior to analysis, and particles sized from 75 to 500 μm were used for these experiments, but not necessarily all of the particles that fell within this range. These data were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Cs data were best fit by a log-normal (2) distribution that gave a 95-percent confidence interval of 3,495 to 67,375 mL/g ([Figure 9-11](#)). The fit statistics and shape parameters are reported in [Table 9-10](#).

Strontium

Vitric Tuff. Distribution coefficient experiments using vitric-tuff samples and predominantly J-13 water were reported in the YMP TDMS. All of these rocks were crushed and sieved prior to analysis, and the 75 to 500 μm and less than 500 μm sieve fractions were used for the experiments. These data were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Sr data were best fit by a Weibull distribution that gave a 95-percent confidence interval of 127 to 208 mL/g ([Figure 9-12](#)). The 95-percent confidence interval for Sr sorption on vitric tuffs is similar to the distribution calculated for cesium. The fit statistics and shape parameters are reported in [Table 9-8](#).

Devitrified Tuff. Experiments measuring the sorption of Sr onto devitrified tuffs are reported in the YMP TDMS and by Papelis and Um (2003 a and b). All of these rocks were crushed and sieved prior to analysis, and several different sieve fractions were used for the experiments ([Appendix G](#)). Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O_2 and less than 20 ppm CO_2 to increase the pH. Papelis and Um (2003a and b) leached the natural Sr out of the rock samples prior to their analyses; this procedure is likely to overestimate the sorption of Sr onto the devitrified rocks *in situ* at Frenchman Flat. The reported values for the Papelis and Um (2003a) study for sorption onto rocks collected from Frenchman Flat well ER-5-3 #2 are 237 to 686 mL/g. The data from YMP and Papelis and Um (2003a, b) were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Sr data were best fit by a log-logistic distribution that gave a 95-percent confidence interval of 18 to 402 mL/g ([Figure 9-12](#)). The fit statistics and shape parameters are reported in [Table 9-9](#).

Zeolitic Tuff. Eighty-three Sr sorption experiments onto zeolitic-tuff rocks were reported in the YMP TDMS. All of these rocks were crushed and sieved prior to analysis, and particles sized from 75 to 500 μm were used for these experiments, but not necessarily all of the particles that fell within this range. These data were evaluated using the methodology presented in [Section 9.5](#). A

Figure 9-12
CDF Fit to Weighted Strontium Sorption Data for
Three Volcanic Rock Types

CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Sr data were best fit by a Weibull distribution that gave a 95-percent confidence interval of 1,492 to 221,800 mL/g ([Figure 9-12](#)). The fit statistics and shape parameters are reported in [Table 9-10](#).

Several Sr sorption experiments for the YMP were conducted with temperatures ranging from 20 to 80°C. [Figure 9-13](#) shows the relationship between Sr sorption

Figure 9-13
Strontium Sorption as a Function of Temperature (°C)
Measured During YMP Distribution Coefficient Experiments

and temperature for the three volcanic rock types. Although there may be an increase in Sr sorption with increasing temperature, the distribution coefficients measured at higher temperatures were not outside the range of values measured at 20°C. This result suggests that the variability in rock chemistry or aqueous chemistry creates as much uncertainty as temperature for this dataset.

9.7.2.5 Neptunium

Neptunium has been one the most studied radionuclides by the YMP. It is important due to its abundance in nuclear waste packages, its long half-life, and its relative low affinity for immobile minerals. Yet, the exact mechanisms controlling

Np sorption are still only partially understood. Triay et al. (1997) and DOE/ORD (2001) describe in detail the history and results of Np sorption studies for YMP. The sorption behavior of Np on apparently similar rock types varies between samples, indicating that minor primary or secondary phases such as calcite, hematite, or trace quantities of ferrous iron may govern the exact sorption process. Thus, mechanistic predictions of Np adsorption would require detailed knowledge of the surface areas of these trace minerals in the various hydrologic units.

An unexpected result of the YMP sorption studies involving Np are the relatively low K_d associated with zeolitic tuff. Whereas a strong cation exchange reaction was expected, the low values indicate that perhaps the neptunyl cation is too large relative to the zeolite cage sizes to come into contact with the exchange sites.

The complexities of Np sorption observations still present multiple challenges to decipher the precise governing mechanisms. The large number of distribution coefficient observations collected by YMP provides input to the present process of developing distributions of the parameter. It is expected that variability in K_d values represents variability in the processes controlling sorption (e.g., trace mineral quantities or reactive mineral surface area).

The distribution parameters developed by YMP for a 90-percent confidence interval are reported in [Table 9-6](#). The Np sorption data from the YMP TDMS are reevaluated to incorporate the data transfer protocol reported in [Section 9.5](#).

Vitric Tuff. Distribution coefficient experiments for Np using vitric-tuff samples in both J-13 and p#1 water were reported in the YMP TDMS. Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O_2 and less than 20 ppm CO_2 to increase the pH during the experiments. Changes in pH between 7 and 9 appear to make no apparent difference in Np sorption to vitric tuff, nor does changes in water chemistry between J-13 and p#1 water ([Appendix G](#)). As stated previously, p#1 water is not similar to the water composition of the volcanic rock aquifers present at Frenchman Flat; therefore, these data have been excluded from the dataset prior to the development of a K_d distribution. A total of 400 distribution coefficients have been measured using J-13 water and vitric-tuff rocks. A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Np data were best fit by a log-logistic distribution that gave a 95-percent confidence interval of 0.03 to 8.6 mL/g ([Figure 9-14](#)). The fit statistics and shape parameters are reported in [Table 9-8](#).

Devitrified Tuff. As with vitric tuff, Np sorption to devitrified tuff is generally characterized with low K_d s. For the J-13 water experiments, pH and temperature do not appear to exert specific influence on the K_d values. The weighted Np data were best fit by a log-logistic distribution that gave a 95-percent confidence interval of 0.02 to 17.3 mL/g ([Figure 9-14](#)). The fit statistics and shape parameters are reported in [Table 9-9](#).

Figure 9-14
CDF Fit to Weighted Neptunium Sorption Data
for Three Volcanic Rock Types

Zeolitic Tuff. Five hundred seventy-eight Np sorption experiments onto zeolitic-tuff rocks were reported in the YMP TDMS. Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O₂ and less than 20 ppm CO₂ to increase the pH during the experiments. Changes in pH between 7 and 9 appear to make no apparent difference in Np sorption to zeolitic tuff. However, the presence of high Ca content present in p#1 causes a decrease in the total sorption to the zeolitic rocks ([Appendix G](#)). As stated previously, p#1 water is not similar to the water composition of the volcanic rock aquifers present at Frenchman Flat; therefore, these data have been excluded from the dataset prior to the development of a K_d distribution. These data were evaluated using the methodology presented in [Section 9.5](#). A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The weighted Np data were best fit by a gamma distribution that gave a 95-percent confidence interval of 1 to 6 mL/g ([Figure 9-14](#)). The fit statistics and shape parameters are reported in [Table 9-10](#). Although the lower bound of the 95-percent confidence interval was 1 mL/g, a number of experiments reported negative distribution coefficients. As a result, it is suggested that the lower bound of this distribution be set equal to 0 mL/g to account for the uncertainty associated with the lower bound of sorption for Np.

9.7.2.6 Uranium

This section provides a summary of the evaluation of YMP U sorption data (Triay et al., 1997; DOE/ORD, 2001; DOE/ORD, 2004) followed by results of the current analyses of the same dataset.

Triay et al. (1997) summarize U sorption analyses indicating that it will likely be affected by pH, carbonate content, and concentrations of Ca and Mg. Complexation with carbonate species in solution will likely reduce the sorption coefficients for U. Thus, if pH decreases with carbonate concentration, one would expect reduced distribution coefficients. However, in the presence of zeolite minerals, decreasing pH would lead to an increase in uranyl ion concentrations and an increase in sorption coefficients. Data supporting this conclusion are cited in DOE/ORD (2001) in which sorption to zeolites in pH 9 water is near zero, but increases to approximately 25 mL/g at pH of 6 in J-13 water. In p#1 water, K_ds are generally smaller than in J-13 water due to increased complexes with carbonate and will not be used in this analysis because they are not representative of the water in the VAs of Frenchman Flat.

Vitric Tuff. Distribution coefficient experiments using vitric tuff samples in both J-13 and p#1 water were reported in the YMP TDMS. Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O₂ and less than 20 ppm CO₂ to increase the pH during the experiments. Changes in pH between 7 and 9 appear to make no apparent difference in U sorption to vitric tuff in the presence of J-13 water ([Appendix G](#)). A total of 59 distribution coefficients have been measured using J-13 water and vitric tuff rocks. A CDF was fit to the weighted ECDF using BestFit software (see [Appendix C](#)). The

weighted U data were best fit by a Weibull distribution that gave a 95-percent confidence interval of 0.06 to 7.08 mL/g (Figure 9-15). The fit statistics and shape parameters are reported in Table 9-8. Although the lower bound of the 95-percent confidence interval is 0.06 mL/g, a number of experiments reported negative distribution coefficients, as a result it is suggested that the lower bound of this distribution be set equal to 0 mL/g to ensure that the predictions at the lower bound are conservative.

Devitrified Tuff. As with vitric tuff, U sorption to devitrified tuff is generally characterized with low K_d s. For the J-13 water experiments, pH and temperature do not appear to exert specific influence on the K_d values. The weighted U data were best fit by a log-logistic distribution that gave a 95-percent confidence interval of 0.4 to 9.8 mL/g (Figure 9-15). The fit statistics and shape parameters are reported in Table 9-9. Consistent with the observations for vitric tuffs, the lower bound of the 95-percent confidence interval is small (0.4 mL/g) and a number of experiments reported negative distribution coefficients; as a result, it is suggested that the lower bound of this distribution be set equal to 0 mL/g to ensure that the predictions at the lower bound are conservative.

Zeolitic Tuff. One hundred seventy-six U sorption experiments onto zeolitic-tuff rocks were reported in the YMP TDMS. Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O_2 and less than 20 ppm CO_2 to increase the pH during the experiments. Changes in pH between 7 and 9 appear to make no apparent difference in U sorption to zeolitic tuff. The presence of high Ca content present in p#1, however, causes a decrease in the total sorption to the zeolitic rocks (Appendix G). The distribution coefficients measured in the presence of J-13 water were evaluated using the methodology presented in Section 9.5. A CDF was fit to the weighted ECDF using BestFit software (see Appendix C). The weighted U data were best fit by a log-normal (2) distribution that gave a 95-percent confidence interval of 3 to 70 mL/g (Figure 9-15). The fit statistics and shape parameters are reported in Table 9-10.

Refinement of the distributions by pH was not specifically conducted for uranium sorption. Both Triay et al. (1997) and DOE/ORD (2001) indicate that pH may play an important role in controlling uranyl species formation. However, for the specific groundwater types used in these experiments, we do not see a clear trend in pH dependence.

9.7.2.7 Plutonium

Triay et al. (1997) provide a detailed discussion of the physiochemical processes affecting Pu speciation and sorption. The exact nature of Pu sorption is not well understood. Most importantly, sorption and desorption of Pu on the volcanic rocks considered is clearly not an equilibrium process. A possible explanation provided by DOE/ORD (2001) is that Pu^{+5} must undergo reduction prior to sorbing as Pu^{+4} . A result of this conclusion is that laboratory experiments conducted under oxidizing conditions should lead to smaller K_d s than exist in less oxidizing field

Figure 9-15
CDF Fit to Weighted Uranium Sorption Data
for Three Volcanic Rock Types

conditions. This may not be the case, however, because the use of only one oxidation state during laboratory experiments may bias the results. A plausible scenario is one in which the oxidation state of Pu in the field may vary within the same water resulting in sorption of Pu in several other oxidation states that may be less likely to sorb than Pu⁺⁵. Kersting et al. (2002b) have recently addressed the question of Pu⁺⁵ reduction to Pu⁺⁴ during sorption (see [Section 11.0](#)). Further, DOE/ORD (2001) concludes that K_d s derived from laboratory batch experiments would likely lead to conservative transport predictions (due to the short time scales associated with the laboratory Pu K_d measurements – longer contact with immobile minerals leads to increased sorption).

Thomas (1987) found that sorption of Pu onto zeolitic rock samples had lower K_d values than vitric and devitrified tuffs due possibly to the lack of reduction sites. In that study, the largest K_d values were measured for samples with calcite and clays. Thomas (1987) also observed the strong dependence of K_d values on water composition, but not on pH. It was observed that the high bicarbonate concentration in p#1 water might actually lead to coprecipitation of Pu rather than surface complexation or ion exchange.

For Pu sorption on various rock and mineral types, DOE/ORD (2001) discusses results for both J-13 and p#1 water. Modifying the conclusions of Thomas (1987) and Wilson et al. (1994), DOE/ORD (2001) analysis indicates that the most important factors controlling Pu sorption in oxidizing water are the abundance of montmorillonite clays, zeolite minerals, and possibly calcite. Thus, zeolitic tuffs should sorb Pu strongest, followed closely by vitric tuffs. Devitrified tuffs sorb Pu less strongly for both types of water, but the values are non-negligible. The data discussion provided by DOE/ORD (2001, Section 6.4.4) is not consistent with the distribution of K_d values provided in DOE/ORD (2004), where the reported distributions for devitrified and zeolitic tuffs are identical ([Table 9-6](#)). Therefore, the data in the YMP TDMS have been reevaluated for the present study with the data transferability methodology used to evaluate the data with respect to Frenchman Flat. A likely explanation for this discrepancy is that the ion radius of Pu is too large to enter the sorption sites on zeolitic materials, thus decreasing the total possible sorption of Pu onto zeolitic rocks. Additionally, the higher sorption of Pu on some volcanic rocks may be driven by the presence of secondary metal-oxide minerals; however, neither DOE/ORD 2001 nor 2004 addresses this issue.

Thomas (1987) and DOE/ORD (2001) note that water composition has a significant impact on Pu K_d distributions. That conclusion was used to support the decision to eliminate experiments in the presence of p#1 in the following analyses because p#1 is not similar to groundwater chemistries observed in Frenchman Flat volcanic aquifers. Atmospheric conditions affecting pH in the experiments are included in this analysis. DOE/ORD (2001) points out that the pH of J-13 and p#1 groundwater in contact with atmospheric carbon dioxide levels is generally in the range of 8.2 to 8.5. Therefore, in some experiments, the pH was adjusted down to near 7.0 by imposing an overpressure of CO₂ to address lower pH values observed among some saturated zone waters in the Yucca Mountain flow system.

Probability distributions are developed for Pu on each different rock type for J-13 groundwater. All data used to fit new distributions in this analysis are found in the YMP TDMS system.

Vitric Tuff. Seventy-one YMP sorption experiments were conducted with Pu, J-13 water, and vitric-tuff material. Figure 9-16 shows the distribution for Pu K_d on vitric tuff in J-13 water. A CDF was fit to the weighted ECDF using BestFit software (see Appendix C). The weighted Pu data were best fit by a exponential distribution that gave a 95-percent confidence interval of 13.5 to 1,969 mL/g (Figure 9-16). The fit statistics and shape parameters are reported in Table 9-8.

Figure 9-16
CDF Fit to Weighted Plutonium Sorption Data for Vitric Tuff

Shaw (2003a) demonstrated a clear relationship between pH and K_d from data from a series of experiments that have been subsequently archived and removed from the current YMP database. The three values reported for the lower pH conditions were associated three lowest K_d values in the distribution. However, the next set of K_d values in the distribution were only a factor of two larger and they were obtained with pH values of 8.4 (Shaw, 2003a). The current dataset has a limited number of samples with reported pH values and a more narrow range of pH values, between 8.28 and 9.26, and no obvious trend in K_d as a function of pH (Appendix G).

Devitrified Tuff. Most experiments were conducted in the presence of an ambient air atmosphere; however, several experiments were conducted in a nitrogen atmosphere with less than 0.2 ppm O₂ and less than 20 ppm CO₂ to increase the pH from approximately 8.5 to 9.5 during the experiments. However, there is an overlap between the air and nitrogen experiments and the values are weakly correlated to the duration of the experiments, so separate distributions are not established. Figure 9-17 shows the relationship between the experiment duration and K_d for air atmosphere experiments. This disequilibrium behavior for Pu sorption highlights the need for special care in parameter assignment and interpretation of results. If more data are collected for small duration experiments, the distribution is skewed to lower K_d s, which will lead to conservative Pu mobility estimates.

Figure 9-17
Distribution Coefficient (mL/g) for Plutonium Sorption onto
Devitrified Tuff as a Function of Experiment Duration

One hundred eighteen YMP sorption experiments were conducted with Pu, J-13 water, and devitrified tuff material. Figure 9-18 shows the distribution for Pu K_d on vitric tuff in J-13 water. A CDF was fit to the weighted ECDF using BestFit software (see Appendix C). The weighted Pu data were best fit by a log-normal (2) distribution that gave a 95-percent confidence interval of 8 to 701 mL/g (Figure 9-18). The fit statistics and shape parameters are reported in Table 9-9.

Figure 9-18
CDF Fit to Weighted Plutonium Sorption Data for Devitrified Tuff

Zeolitic Tuff. The relative affinities for Pu on specific minerals are, in decreasing order, hematite > montmorillonite > clinoptilolite > calcite > gibbsite > albite > quartz (DOE/ORD, 2001). Although this generalization does not take into account water chemistry, it is expected that rocks containing large abundances of secondary metal-oxide minerals should also show relatively strong affinities for Pu. Sorption of Pu to devitrified and zeolitic tuff in J-13 water is not strong for these rock samples, as shown in Figure 9-19. The weighted Pu data were best fit by a Weibull distribution that gave a 95-percent confidence interval of 14 to 778 mL/g (Figure 9-19). The fit statistics and shape parameters are reported in Table 9-10.

The large values in the data range are not as large as those for Pu sorption to vitric tuff, indicating that such sorption reactions may be dominated by the presence or absence of a few key minerals such as clay, which may determine the overall sorption capacity of a particular rock. There does not appear to be a strong correlation between pH and K_d values for Pu sorption to zeolitic tuffs.

9.7.3 Carbonate Rocks

Although K_d s for radionuclides and carbonate rock material have not been measured for NTS or YMP projects, three studies provide insight into these

Figure 9-19
CDF Fit to Weighted Plutonium Sorption Data for Zeolitic Tuff

sorption reactions. Dosch and Lynch (1980) report dolomite K_d s for Cs, Sr, Eu, Pu, and Am, examining differences in initial solute concentration and groundwater composition. Stout and Carroll (1992) summarize several studies from the literature up to 1992, and Perkins et al. (1998) provide K_d estimates for Pu and Am determined from a flowing column experiment. [Table 9-11](#) summarizes the measured carbonate K_d s from these studies.

9.7.4 Summary of Laboratory Distribution Coefficient Data

Laboratory measurements of distribution coefficients on rocks representative of Frenchman Flat alluvium, vitric tuff, devitrified tuff, and zeolitic tuff are available for Am, Cs, Sr, Np, U, and Pu. Depending on the specific interaction between the radionuclide and the rock, different Frenchman Flat rocks will have different distribution coefficients. [Figures 9-20 through 9-25](#) show the mean of all of the laboratory values (blue diamonds) for the radionuclides with laboratory measurements for all FF rock types, the upper and lower bound of the 95-percent confidence interval (yellow and pink blocks, respectively), and the minimum and maximum sample values (black bars) for each radionuclide with each rock type. For Am and Pu, the highest distribution coefficients are observed in alluvium; therefore, we would expect to see a smaller fraction of the Am and Pu mobile in

**Table 9-11
Carbonate Sorption K_d (mL/g) Ranges**

Radionuclide	Dosch and Lynch (1980)	Stout and Carroll (1992)	Perkins et al. (1998)	Total Range
Cs	Range(4,101)	-	-	Range(4, 101)
Sr	Range(5,16)	-	-	Range(5, 16)
Eu	Range(1E4, 4E5)	-	-	Range(1E4, 4E5)
Pu	Range(2E3,7E3)	Range(1E2, 1E4)	275	Range(1E2, 1E4)
Am	Range(2E3, 2E4)	Range(2E3, 3E5)	Range(150, 350)	Range(150, 3E5)
U	Range(2,132)	Range(1E-5, 0.3)	-	Range(0, 132)
Np	-	Range(<1E2, 5E3)	-	Range(<1E2, 5E3)

the subsurface for the nine Frenchman Flat tests conducted in the AA. Likewise, any transport of Cs, Sr, and U into a zeolitic-tuff unit would be expected to reduce the total fraction of these radionuclides mobile in the groundwater.

9.8 K_d from Field Observations

Table 9-12 provides a summary of K_d s derived from field measurements taken during the CAMBRIC RNM experiment. Hoffman (1979) reports that 10 years after the nuclear test, most of the radionuclides were still located in the original explosion cavity. At 50 m below the detonation cavity, there was no radioactivity above background levels (Hoffman, 1979). The large distribution coefficients reported for the cavity region likely indicate the fused nature of the debris located in the cavity. Hoffman (1979) speculates that the decreased K_d for Cs and Sr in the cavity region are the result of their movement in the cavity as gaseous species and their adsorption onto the surface of the alluvium.

**Table 9-12
Observed K_d s (mL/g) from Hoffman (1979)**

Zone	Sr-90	Ru-106	Sb-125	Cs-137	Pm-147	Pu-239
Lower Cavity	2,100	100	290	25,000	>1,000,000	>32,000,000
Upper Cavity	1,600	190	360	18,000	ND	>19,000,000
Chimney	39	ND	ND	660	ND	ND
Adjacent to Chimney	310	ND	ND	1,100	ND	ND

ND = Radionuclide not detected

Figure 9-20
Comparison of Americium K_d (mL/g) for Frenchman Flat Alluvial
and Volcanic Rocks. Rock Alteration Decreases to the Right

Figure 9-21
Comparison of Cesium K_d (mL/g) for Frenchman Flat Alluvial
and Volcanic Rocks. Rock Alteration Decreases to the Right

Figure 9-22
Comparison of Strontium K_d (mL/g) for Frenchman Flat Alluvial
and Volcanic Rocks. Rock Alteration Decreases to the Right

Figure 9-23
Comparison of Neptunium K_d (mL/g) for Frenchman Flat Alluvial
and Volcanic Rocks. Rock Alteration Decreases to the Right

Figure 9-24
Comparison of Uranium K_d (mL/g) for Frenchman Flat Alluvial
and Volcanic Rocks. Rock Alteration Decreases to the Right

Figure 9-25
Comparison of Plutonium K_d (mL/g) for Frenchman Flat Alluvial
and Volcanic Rocks. Rock Alteration Decreases to the Right

9.9 Data Limitations

The compiled alluvium data, DRI data, and YMP TDMS data make up a dataset of sorption K_d s of Pu, Np, Cs, Sr, and U that contains an extensive set of laboratory-experimentally-determined K_d values with which cumulative distribution functions can be developed. However, the uncertainty in the laboratory-measured K_d values and the uncertainty in field K_d values may not be governed by the same processes, this is an inherent limitation of this approach. Multiple rock samples are associated with the K_d distributions for most of the radionuclides providing some insight into spatial variability within a given rock type. All K_d values determined from laboratory sorption studies are specific to the small sample of aquifer material and the experimental conditions. Many times the experimental conditions include increasing the surface area and reactive surfaces of the rock by crushing the rock samples. Thus, applying the measured K_d values to field simulations involves the assumptions that the rock samples encompass the full range of variability in the aquifer, that groundwater conditions in the field are similar to those in the experiments and unchanging, or at least that the CDF represents variability that may exist in the field. The K_d s used in this analysis are not correlated with such physical parameters as hydraulic conductivity, although other studies (e.g., Tompson et al., 1996) have suggested correlation between physical and chemical parameters for porous media systems. Correlations for physical and chemical properties of matrix material in fractured rock have not been developed.

9.10 Summary of K_d Data

The K_d data described in this chapter are from direct laboratory measurements, mechanistic model predictions, and field observations. Comparing the direct measurements and mechanistic model predictions for HSUs in the Frenchman Flat CAU domain is difficult. The measured data are for particular types of rock alteration in the presence of a particular water chemistry, while the mechanistic model is calculated for a particular rock chemistry and one water chemistry. Although the mechanistic model conditions are similar to many of the laboratory experiments, they are not identical. A direct comparison between these two methods is, however, warranted so that these values can be appropriately incorporated into the CAU transport model.

To compare the direct measurements of radionuclide sorption with the mechanistic model reported by Zavarin et al. (2004), the mineralogy of the laboratory samples was substituted for the mineralogies reported in Zavarin et al. (2004) and the sorption values were calculated for each rock sample for which a mineralogy was reported. The mechanistic model calculations are dependent on the quality of the rock mineralogical analysis because many trace minerals are an important for radionuclide sorption. Therefore, poor quality mineralogical analyses will result in poor agreement between the laboratory distribution coefficients and those calculated using the mechanistic model. Additionally, better comparison between the laboratory values and mechanistic model would be accomplished if the exact chemistry of the aqueous solution used during the experiment were used for the

mechanistic model calculations; however, many times the aqueous chemistry is not reported with the distribution coefficient.

The calculated K_d values from the mechanistic model were fit with a CDF. Both the laboratory measured and mechanistic calculated mean K_d and the range of the 95-percent confidence interval are plotted for each radionuclide in Figure 9-26.

Figure 9-26
Comparison of mean and 95-percent confidence interval for laboratory K_d s measured in alluvium to mechanistic model K_d s calculated using laboratory mineralogy values.
(Note: Triangle points show the sorption values reported by Hoffman [1979] for the area adjacent to the CAMBRIC chimney)

The comparison for the alluvium includes laboratory measurements from U-1a samples that have an identical water chemistry to the one used in the mechanistic model. For Cs, Sr, Am, Eu, Sm, Np, and U the mechanistic model provides values for K_d that generally encompass the entire distribution calculated for the direct measurements; however, the mechanistic model tends to overpredict the uncertainty in these values. This is likely because the number of experiments for which complete mineralogies were reported is relatively small compared to the entire set of laboratory measurements, thus increasing the uncertainty in the CDF. For Pu, the mechanistic model tends to under predict the distribution coefficient, this will result in conservative transport simulations, but may need to be further examined during transport model sensitivity analyses. A likely interpretation is that Pu in the mechanistic model is being simulated at an oxygen fugacity that is too oxidizing (mechanistic model oxygen fugacity ranged from 10^{-5} to 10^{-15}); adjusting this fugacity to be more reducing may result in improved agreement

between the mechanistic model and laboratory experiments. Figure 9-26 also shows the observed K_d s associated with the area adjacent to the chimney for the CAMBRIC RNM experiment.

Similar analyses were done to compare the Zavarin et al. (2004) mechanistic model developed for regional volcanic rock HSUs to those volcanic rocks used in laboratory experiments by YMP and DRI. As with the alluvial analysis, the rock chemistries reported for the laboratory experiments were used rather than the mineralogies reported by Zavarin et al. (2004). Figures 9-26 through 9-29 show the plots of K_d for each radionuclide available with the Zavarin et al. (2004) model. Generally, the vitric tuffs and devitrified tuffs matched well; however, the mechanistic model tended to under predict sorption to zeolitic rocks. In all cases, the mechanistic model predictions for Pu in the presence of an oxygen fugacity of 10^{-15} bars under predicted the laboratory measurements. Using the mechanistic model will result in conservative predictions for Pu transport, but sensitivity analyses in the CAU transport model will need to account for this uncertainty.

In each case, the data are correlated to HSU characteristics, as described in Section 2.0. Table 9-13 lists the K_d distributions developed for each radionuclide class identified by Tompson et al. (2003) from direct measurements relevant to each HSU based upon alteration of material where laboratory measurements were available. When laboratory values were not available, mechanistic model values from Zavarin et al. (2004) were used as a surrogate.

Pu-5, Pu-10, Pu-15 represent mechanistic model results at oxygen fugacity values of 10^{-5} , 10^{-10} , and 10^{-15} , respectively.

Figure 9-27
**Comparison of mean and 95-percent confidence interval for laboratory K_d s to
mechanistic model K_d s calculated using laboratory mineralogy values for vitric tuffs**

Pu-5, Pu-10, Pu-15 represent mechanistic model results at oxygen fugacity values of 10^{-5} , 10^{-10} , and 10^{-15} , respectively.

Figure 9-28
**Comparison of mean and 95-percent confidence interval for laboratory K_d 's to
mechanistic model K_d 's calculated using laboratory mineralogy values for devitrified tuffs**

Pu-5, Pu-10, Pu-15 represent mechanistic model results at oxygen fugacity values of 10^{-5} , 10^{-10} , and 10^{-15} , respectively.

Figure 9-29
**Comparison of mean and 95-percent confidence interval for laboratory K_d 's to
mechanistic model K_d 's calculated using laboratory mineralogy values for zeolitic tuffs**

Table 9-13
Summary of Matrix Distribution Coefficients for Frenchman Flat HSUs
 (Page 1 of 2)

Data are reported as a range of values (minimum, maximum); when only one value is reported, this value should be used as the minimum.

HSU Name	Regional HSU (Zavarin et al., 2004)	HGUs ^a	Representative Alteration ^a	Ca ^b	Cs	Sr	Am	Eu ^c	Sm ^c	Np	U	Pu	Ni
LCCU		CCU	-	-	-	-	-	-	-	-	-	-	-
LCA		CA	-	-	-	-	-	-	-	-	-	-	-
UCCU		CCU	-	-	-	-	-	-	-	-	-	-	-
LCA3		CA	-	-	-	-	-	-	-	-	-	-	-
VCU	TC	TCU, minor AA and CA	zeolitic	(2344)	Range (1662, 67375)	Range (1492, 221800)	Range (612, 42028)	Range (1862, 15849)	Range (2884, 24547)	Range (1, 6)	Range (3, 70)	Range (14, 778)	-
WCU	TC	TCU, minor LFA	zeolitic, minor lava	(2344)	Range (3495, 67375)	Range (1492, 221800)	Range (612, 42028)	Range (1862, 15849)	Range (2884, 24547)	Range (1, 6)	Range (3, 70)	Range (14, 778)	-
LTCU	TC	TCU, minor WTA	zeolitic	(2344)	Range (3495, 67375)	Range (1492, 221800)	Range (612, 42028)	Range (1862, 15849)	Range (2884, 24547)	Range (1, 6)	Range (3, 70)	Range (14, 778)	-
LVTA	TC	VTA	minor fractures, non-welded, vitric	(2344)	Range (118, 1170)	Range (127, 208)	Range (655, 2032)	Range (1862, 15849)	Range (2884, 24547)	Range (0.03, 8.6)	Range (0.06, 7.1)	Range (14, 1969)	-
TSA	TMA	WTA	welded, mostly vitric, limited devitrified	(2754)	Range (25, 2187)	Range (18, 402)	Range (48, 6986)	Range (1380, 11482)	Range (2089, 18197)	Range (0.02, 17.3)	Range (0.06, 9.8)	Range (8, 1969)	-
UTCU	TC	TCU	zeolitic	(2344)	Range (3495, 67375)	Range (1492, 221800)	Range (612, 42028)	Range (1862, 15849)	Range (2884, 24547)	Range (1, 6)	Range (3, 70)	Range (14, 778)	-
TM-LVTA	TC	VTA	minor fractures, non-welded, vitric	(2344)	Range (118, 1170)	Range (127, 208)	Range (655, 2032)	Range (1862, 15849)	Range (2884, 24547)	Range (0.03, 8.6)	Range (0.06, 7.1)	Range (14, 1969)	-
TM-WTA	TMA	Mostly WTA, minor VTA	welded, mostly vitric, limited devitrified	(2754)	Range (25, 2187)	Range (18, 402)	Range (48, 6986)	Range (1380, 11482)	Range (2089, 18197)	Range (0.02, 17.3)	Range (0.06, 9.8)	Range (8, 1969)	-
PCU1		PCU	alluvium	Range (123, 977)	Range (1661, 20255)	Range (7, 911)	Range (746, 839530)	Range (2523, 95867)	Range (12354, 1.08x10 ⁵)	Range (18.3, 23.8)	Range (1.4, 18.7)	Range (224, 17578)	Range (479, 5198)

Table 9-13
Summary of Matrix Distribution Coefficients for Frenchman Flat HSUs
 (Page 2 of 2)

Data are reported as a range of values (minimum, maximum); when only one value is reported, this value should be used as the minimum.

HSU Name	Regional HSU (Zavarin et al., 2004)	HGUs ^a	Representative Alteration ^a	Ca ^b	Cs	Sr	Am	Eu ^c	Sm ^c	Np	U	Pu	Ni
OAA		AA	alluvium	Range (123, 977)	Range (1661, 20255)	Range (7, 911)	Range (746, 839530)	Range (2523, 95867)	Range (12354, 1.08x10 ⁵)	Range (18.3, 23.8)	Range (1.4, 18.7)	Range (224, 17578)	Range (479, 5198)
BLFA ^b	TMA^d	LFA	lava	(2754)	Range (25, 2187)	Range (18, 402)	Range (48, 6986)	Range (1380, 11482)	Range (2089, 18197)	Range (0.02, 17.3)	Range (0.06, 9.8)	Range (8, 1969)	-
AA		AA	alluvium	Range (123, 977)	Range (1661, 20255)	Range (7, 911)	Range (746, 839530)	Range (2523, 95867)	Range (12354, 1.08x10 ⁵)	Range (18.3, 23.8)	Range (1.4, 18.7)	Range (224, 17578)	Range (479, 5198)
PCU2		PCU	alluvium	Range (123, 977)	Range (1661, 20255)	Range (7, 911)	Range (746, 839530)	Range (2523, 95867)	Range (12354, 1.08x10 ⁵)	Range (18.3, 23.8)	Range (1.4, 18.7)	Range (224, 17578)	Range (479, 5198)

- ^aHGUs and Representative Alteration are used to relate the laboratory sorption data and the mechanistic sorption model to each HSU. In most cases an HSU is dominated by an HGU or Representative Alteration, when more than one HGU or alteration is a large fraction of the rocks in the HSU two sorption datasets were used to include the full range of possible sorption values.
- ^bCa sorption values from Zavarin et al. (2004) mechanistic model.
- ^cEu and Sm sorption values for volcanic rocks from Zavarin et al. (2004) mechanistic model for matrix distribution coefficients for regional model HSUs.
- ^dRetardation factors extrapolated from TMA regional HSU parameters

Bold Font = Prominent material type encountered-basis for consideration
 Italic Font = Estimated using other HSU as a surrogate
 -- = No applicable data

9.11 Scaling Considerations

Frenchman Flat CAU transport simulations for contaminant boundary assessment will be conducted over various spatial scales. Volumes in the computational model represented with a single set of transport parameters could be larger than 25 m³ in some portions of the model domain. Scaling should address how well measurements conducted on less than 0.5 m³ of aquifer material represents the integrated sorptive behavior of a much larger volume in the CAU-scale model. One method for addressing this would be to use the data presented in this documentation report as representative of the small-scale system behavior. Scaling simulations could be designed to identify the effective K_d of a CAU-scale model block using multiple realizations of spatially distributed values from this study. Correlations between K_d and rock permeability will be likely to continue to provide uncertainty in transport simulations. It is likely that such an analysis will produce tighter distributions, filtering out both the small and large values in the laboratory-scale distributions.

10.0 Fracture Sorption Parameter

This section describes the fracture sorption process and the methods for parameterizing it in the CAU models.

10.1 The Role of Fracture Sorption in Contaminant Transport

As with matrix sorption, fracture sorption is the physiochemical process at mineral-water interfaces that controls solute mobility and, hence, solute retardation in fractures within flowing groundwater systems. Fracture sorption is treated separately from matrix sorption because it strictly involves the sorption of radionuclides to minerals coating fracture surfaces, prior to diffusion into the matrix material, where matrix sorption may occur. Further, fracture sorption is not considered for matrix material in which fractures are not present and porous media flow controls fluid and solute mass transport. Where fractures are present, the CAU-scale parameter of interest is the solute retardation factor in fractures.

[Section 9.0](#) highlights measurements of radionuclide sorption to matrix material; however, observational data have not been collected to isolate and parameterize the process of radionuclide sorption to fracture minerals. Thus, estimates of this retardation process are based upon mechanistic modeling studies, utilizing the same reaction principals described in the previous chapter for matrix sorption.

Retardation factors (R parameters) for solutes in fractures are the simplest method with which to represent sorption to fracture minerals. Although easily derived from each other, R is preferable to K_d because the K_d is based upon a volumetric sample of material, as appropriate for matrix material. In the fracture, all of the reactive processes leading to solute retardation are represented per unit length of fracture, rather than per unit volume of rock. As with the K_d , R is straightforward to apply in transport models.

Use of the R parameter requires the assumption of local equilibrium. Reactions that are kinetic in nature must be assumed to occur fast enough that R captures the process either adequately or conservatively in field-scale simulations. Further, the R parameter does not allow for changing sorption behavior due to changes in water chemistry or mineral surfaces. It can vary spatially, but is not capable of representing dynamic system changes during the course of a simulation.

10.2 Data Compilation and Evaluation

The fracture sorption data types and sources of data are described in this section.

10.2.1 Data Types

The modeling studies seeking to upscale mechanistic processes to larger-scale retardation factors are based upon the same processes as those described for mechanistic models of matrix K_d in the previous section. The key components to estimating reactions with fracture coatings are as follows:

- The effective reactive surface area of fracture-coating minerals available to solutes flowing in the fracture
- The mineralogic composition of the fracture coatings
- The distribution (existence) of fracture-coating minerals in fractures

Once estimated, these three factors can be used to parameterize mechanistic models, which ultimately provide effective fracture retardation factors.

A benefit of the mechanistic modeling approach is that it specifically represents which reactions control and affect sorption to fracture-coating minerals. Due to the complete representation of all reactions, the mechanistic modeling approach can also describe how groundwater chemistry changes such as pH affect sorption reactions, as well as how sorption reactions may affect groundwater chemistry.

A limitation of the mechanistic modeling approach is that, although a detailed set of reactions may be simulated, parameters for those reactions may not be available, particularly at the CAU scale. This is particularly important for estimating fracture retardation factors where spatial variation of fracture-coating materials will have first-order effects on the estimated parameters.

Two recent approaches within the UGTA project have begun to assess fracture retardation. Wolfsberg et al. (2002, Chapter 7 and Appendix F) used estimates of fracture-coating thickness, distribution, mineral content, and availability in conjunction with surface complexation thermodynamic data reported by Pawloski et al. (2001) to predict fracture retardation factors. They find that the primary factor controlling fracture retardation is how much of the fracture coating is accessible to solutes migrating in the fracture. Zavarin et al. (2004) extends upon developments made by Pawloski et al. (2001), with estimates of fracture retardation using mechanistic processes. Zavarin et al. (2004) attempts to link effective porosity, fracture density, and aperture measurements with a mechanistic conceptual model by requiring a relationship between the effective porosity and the volume of reactive minerals in contact with the flowing fluid. Thus, if the effective porosity is 1 percent and the porosity associated with open fractures is less than 1 percent, some of the flowing fluid was required to be associated with flow within the matrix. Diffusion between fractures and matrix material is not explicitly modeled. Rather, this method seeks to capture the effect of some diffusion into the matrix near the fracture wall with the increased effective porosity. Thus, the method also combines the effects of sorption to matrix material and fracture minerals with a single set of parameters. Although, if the matrix sorption and fracture retardation need to be separated for the CAU-scale flow and transport model, this method can be modified. Additional diffusion into

the matrix beyond the matrix reactive zone can be simulated, understanding that the first portion of reactive matrix minerals is wrapped up in the fracture effective porosity abstraction with this method.

Using thermodynamic databases for sorption reactions to specific minerals and measurement of specific mineral compositions in field samples, these theoretical methods provide estimates of retardation resulting from radionuclides sorbing to reactive minerals surrounding flowing fractures.

10.2.2 Data Sources

Wolfsberg et al. (2002) and Zavarin et al. (2004) have provided estimates of fracture retardation factors for various rock types on Pahute Mesa. Pahute Mesa volcanic aquifers have reasonably similar water composition to those observed in Frenchman Flat volcanic aquifers; therefore, when HSUs from Pahute Mesa crosswalk to Frenchman Flat HSUs this data can be used directly (refer to [Table 2-4](#) for BN crosswalk). To date, there is no site specific Frenchman Flat data available to describe fracture sorption.

Wolfsberg et al. (2002) and Zavarin et al. (2004) modeling studies seek to incorporate information regarding specific reactions and estimates of fracture-coating properties. Coupled with other processes of matrix diffusion, matrix reaction, and colloid-facilitated transport, the expected values of fracture retardation factors were used by Wolfsberg et al. (2002) in predicting radionuclide concentrations in Wells ER-20-5 #1 and ER-20-5 #3. In those simulations, the radionuclides with large R values in fractures were shown to have minimal mobility in the absence of colloids. Zavarin et al. (2004) also demonstrate the increased predicted mobility when colloids are present and compete with immobile reactive minerals for radionuclide sorption.

10.3 Data Evaluation

This section includes a description of the data available for the fracture retardation factor, followed by a discussion covering their limitations and range of values.

10.3.1 Dataset Descriptions

Two recent UGTA Project studies have sought to derive fracture retardation factors using mechanistic modeling approaches.

10.3.1.1 Derivation by Wolfsberg et al. (2002)

Wolfsberg et al. (2002, Chapter 7 and Appendix F) apply a semi-mechanistic approach for estimating fracture retardation factors. They assume invariant water chemistry representative of Pahute Mesa groundwater and group radionuclides

into the classes shown in [Table 10-1](#). Their derivation shows the dependence of the fracture retardation factor on the uncertain fracture-coating properties listed in [Section 10.2.1](#). The method is based on three major assumptions: (1) a fixed percent coverage of fractures with coatings, (2) a fixed coating thickness where they exist, and (3) fixed availability of reactive minerals within the coatings. Wolfsberg et al. (2002) ignored the ion exchange reactions with fracture coatings, which may be significant contributors to fracture sorption for Sr^{2+} , Cs^+ , P^{4+} , and UO_2^{2+} . Variability in fracture retardation factors associated with variability in mineral content in the coatings calculated using this method are presented in [Table 10-2](#) as the low, base, and high cases. Wolfsberg et al. (2002, Appendix F) noted that uncertainty in percent fracture-coating coverage and the percent of the coatings available for reactions can add up to three orders of magnitude uncertainty on these values.

10.3.1.2 Derivation by Zavarin et al. (2004)

Zavarin et al. (2004) apply a mechanistic model using the thermodynamic reaction databases of Zavarin et al. (2002) to predict fracture retardation factors for several regional model HSUs. [Table 10-3](#) provides the estimated retardation factors from that study under the assumption that the primary metal-oxide present in the rocks is an iron-oxide. The reported range of uncertainty is only related to uncertainty in mineralogic composition of the fracture coatings, not of their abundance or the accessibility of those minerals to solutes in the fracture water.

**Table 10-1
Radionuclide Classes in Wolfsberg et al. (2002)**

Class	Radionuclide	Symbol
Class I	Tritium	H-3
	Carbon	C-14
	Chloride	Cl-36
	Krypton	Kr-85
	Technetium	Tc-99
	Iodine	I-129
Class II	Samarium	Sm-151
	Americium	Am-241
	Europium	Eu-152
	Europium	Eu-154
Class III	Strontium	Sr-90
	Cesium	Cs-137
Class IV	Uranium (D&S)	U-234
	Uranium (D&S)	U-238
	Neptunium	Np-237
Class V	Plutonium	Pu-239
	Plutonium	Pu-240

**Table 10-2
Fracture Retardation Factors from Wolfsberg et al. (2002)
(Class I has R=1)**

Radionuclide Class	Range	Rock Type						
		Bedded	Non-welded	Welded	Lava	Altered	Fractured Non-welded	Bedded-Altered
Class II	low	N/A	N/A	63	163	22	192	N/A
	base	N/A	N/A	195	207	25	223	N/A
	high	N/A	N/A	837	231	129	265	N/A
Class III	low	N/A	N/A	1.01	1.04	1	1.04	N/A
	base	N/A	N/A	1.07	1.05	1	1.05	N/A
	high	N/A	N/A	1.23	1.06	1.01	1.07	N/A
Class IV	low	N/A	N/A	1.13	1.35	1.03	1.43	N/A
	base	N/A	N/A	3.5	2.7	1.43	2.7	N/A
	high	N/A	N/A	13.5	4.9	2.5	5.5	N/A
Class V	low	N/A	N/A	2.7	9.2	1	8.4	N/A
	base	N/A	N/A	13.6	10.3	3.9	9.6	N/A
	high	N/A	N/A	39	13	6.8	15	N/A

N/A - Not applicable

**Table 10-3
Fracture Retardation Factors, Log(R), Estimated for Regional HSUs by Zavarin et al. (2004)**

Regional HSU ^a	TMA			TC			TBA			BAQ		
Nuclide	E(x) ^b	Min ^c	Max	E(x)	Min	Max	E(x)	Min	Max	E(x)	Min	Max
Ca	3.34			2.95			3.24			3.36		
Cs	4.04	3.13		3.19	2.4		4.30	3.34		3.27	2.66	
Sr	3.12			2.72			2.99			3.14		
Am	2.03	1.99	2.06	1.92	1.88	1.94	2.64	2.61	2.65	2.26	1.94	2.50
Eu	2.06	1.98	2.08	1.98	2.03	1.89	2.69	2.59	2.73	2.60	2.49	2.65
Sm	2.14	2.11	2.16	2.06	2.02	2.11	2.74	2.70	2.78	2.98	2.92	3.02
Np	0.80	0.57	1.13	1.08	0.74	1.49	1.72	1.35	2.15	1.61	1.15	2.09
U	1.18	0.85	1.54	1.77	1.37	2.17	2.46	2.05	2.86	0.19	0.19	0.20
Pu (O ₂ =10 ⁻⁵)	1.12	0.74	1.51	1.36	0.93	1.77	2.04	1.57	2.46	1.46	1.03	1.87
Pu (O ₂ =10 ⁻¹⁰)	1.43	1.03	1.79	1.74	1.31	2.11	2.43	1.98	2.80	1.81	1.37	2.18
Pu (O ₂ =10 ⁻¹⁵)	1.94	1.62	2.12	2.31	1.97	2.50	3.00	2.66	3.20	2.34	2.00	2.54

^aCorrelations between the regional HSUs and the FF HSUs are provided in [Table 2-4](#).

^bE(x) is the mean Log (R) for each HSU-radionuclide pair.

^cMin and Max values incorporate the uncertainty associated with the mechanistic model reaction constants.

10.3.2 Fracture Retardation Factor Summary and Integration

The two studies described in this section present approaches for estimating retardation in fractures due to reactions with fracture-coating minerals. Although they highlight methodologies to account for processes that may affect migration rates and groundwater concentration of reactive radionuclides, these approaches are theoretical. The two methods yield different results due to conceptual model differences and assumptions about the processes that lead to fracture retardation. One of the largest differences is that Zavarin et al. (2004) include reactions with matrix minerals as well as with fracture-coating minerals. This leads to substantial increases in the estimated retardation factors. Wolfsberg et al. (2002) only consider reactions with the minerals coating the fracture. Reactions with matrix minerals is considered in conjunction with the matrix diffusion component of their model. The Zavarin et al. (2004) model may require modification to be implemented in the FF CAU transport model.

Within the Frenchman Flat CAU-scale groundwater flow and transport model, fracture sorption can potentially be of concern in fractured, volcanic-rock units. In these units an initial assessment that identifies the expected time scale of water flow with respect to the time scale associated with matrix diffusion will be essential in determining the importance of fracture sorption. In systems where the time scale of water flow is significantly greater than matrix diffusion, contaminant retardation will be dominated by interactions between contaminants and matrix. In systems where the time scale of water flow is significantly smaller (or the same order of magnitude) than the time scale of matrix diffusion, fracture sorption will dominate.

Table 10-4 summarizes the results from the two different approaches and correlates the results with HSUs in the Frenchman Flat CAU groundwater flow and transport model domain. Considering the two different approaches, the range of uncertainty is large due to the strictly theoretical nature of the estimation methods. Although, the results from Wolfsberg et al. (2002) are more directly applicable to the representation of fracture sorption in the CAU model, the results by Zavarin et al. (2004) are presented for comparison.

Table 10-4
Summary of Fracture Retardation Factors for HSUs
 (Page 1 of 2)

Data is reported as a range of values (minimum, maximum), when only one value is reported this value should be used as the minimum.

HSU Name	Regional HSU (Zavarin et al. 2004)	HGUs	Representative Alteration	Ca	Cs	Sr	Am	Eu	Sm	Np	U	Pu (10 ⁻⁵)	Pu (10 ⁻¹⁰)	Pu (10 ⁻¹⁵)
LCCU		CCU												
LCA		CA												
UCCU		CCU												
LCA3		CA												
VCU	TC	TCU, minor AA and CA	altered	(891)	Range (1, 1.01) ^a Range (251, 1549)	Range (1, 1.01) (525)	Range (22, 129) Range (76, 87)	Range (22, 129) Range (78, 107)	Range (22, 129) Range (105, 129)	Range (1.03, 2.5) Range (5.5, 31)	Range (1.03, 2.5) Range (23, 148)	Range (1, 6.8) Range (8.5, 59)	Range (20, 129)	Range (93, 316)
WCU	TC	TCU, minor LFA	altered, minor lava	(891)	Range (1, 1.06) Range (251, 1549)	Range (1, 1.06) (525)	Range (22, 231) Range (76, 87)	Range (22, 231) Range (78, 107)	Range (22, 231) Range (105, 129)	Range (1.03, 4.9) Range (5.5, 31)	Range (1.03, 4.9) Range (23, 148)	Range (1, 13) Range (8.5, 59)	Range (20, 129)	Range (93, 316)
LTCU	TC	TCU, minor WTA	altered	(891)	Range (1, 1.01) Range (251, 1549)	Range (1, 1.01) (525)	Range (22, 129) Range (76, 87)	Range (22, 129) Range (78, 107)	Range (22, 129) Range (105, 129)	Range (1.03, 2.5) Range (5.5, 31)	Range (1.03, 2.5) Range (23, 148)	Range (1, 6.8) Range (8.5, 59)	Range (20, 129)	Range (93, 316)
LVTA	TC	VTA	minor fractures, non-welded, vitric	(891)	Range (1.04, 1.07) Range (251, 1549)	Range (1.04, 1.07) (525)	Range (192, 265) Range (76, 87)	Range (192, 265) Range (78, 107)	Range (192, 265) Range (105, 129)	Range (1.43, 5.5) Range (5.5, 31)	Range (1.43, 5.5) Range (23, 148)	Range (8.4, 15) Range (8.5, 59)	Range (20, 129)	Range (93, 316)
TSA	TMA	WTA	welded, mostly vitric, limited devitrified	(2188)	Range (1.01, 1.23) Range (1349, 10965)	Range (1.01, 1.23) (1318)	Range (63, 837) Range (98, 115)	Range (63, 837) Range (95, 120)	Range (63, 837) Range (129, 145)	Range 1.13, 13.5) Range (3.7, 13)	Range (1.13, 13.5) Range (7.1, 35)	Range (2.7, 39) Range (5.5, 32)	Range (11, 62)	Range (42, 132)
UTCU	TC	TCU	altered	(891)	Range (1, 1.01) Range (251, 1549)	Range (1.04, 1.07) (525)	Range (22, 129) Range (76, 87)	Range (22, 129) Range (78, 107)	Range (22, 129) Range (105, 129)	Range (1.03, 2.5) Range (5.5, 31)	Range (1.03, 2.5) Range (23, 148)	Range (1, 6.8) Range (8.5, 59)	Range (20, 129)	Range (93, 316)
TM-LVTA	TC	VTA	minor fractures, non-welded, vitric	(891)	Range (1.04, 1.07) Range (251, 1549)	Range (1.04, 1.07) (525)	Range (192, 265) Range (76, 87)	Range (192, 265) Range (78, 107)	Range (192, 265) Range (105, 129)	Range (1.43, 5.5) Range (5.5, 31)	Range (1.43, 5.5) Range (23, 148)	Range (8.4, 15) Range (8.5, 59)	Range (20, 129)	Range (93, 316)
TM-WTA	TMA	Mostly WTA, minor VTA	welded, mostly vitric, limited devitrified	(2188)	Range (1.01, 1.23) Range (1349, 10965)	Range (1.01, 1.23) (1318)	Range (63, 837) Range (98, 115)	Range (63, 837) Range (95, 120)	Range (63, 837) Range (129, 145)	Range (1.13, 13.5) Range (3.7, 13)	Range (1.13, 13.5) Range (7.1, 35)	Range (2.7, 39) Range (5.5, 32)	Range (11, 62)	Range (42, 132)
PCU1		PCU		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 10-4
Summary of Fracture Retardation Factors for HSUs
 (Page 2 of 2)

Data is reported as a range of values (minimum, maximum), when only one value is reported this value should be used as the minimum.

HSU Name	Regional HSU (Zavarin et al. 2004)	HGUs	Representative Alteration	Ca	Cs	Sr	Am	Eu	Sm	Np	U	Pu (10 ⁻⁵)	Pu (10 ⁻¹⁰)	Pu (10 ⁻¹⁵)
OAA		AA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BLFA ^b	<i>TMA</i>	LFA	lava	(2188)	Range (1.04, 1.06) Range (1349, 10965)	Range (1.04, 1.06) (1318)	Range (163, 231) Range (98, 115)	Range (163, 231) Range (95, 120)	Range (163, 231) Range (129, 145)	Range (1.35, 4.9) Range (3.7, 13)	Range (1.35, 4.9) Range (7.1, 35)	Range (9.2, 13) Range (5.5, 32)	Range (11, 62)	Range (42, 132)
AA		AA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PCU2		PCU		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

^aUpper range in each cell represents retardation to fracture minerals only from [Table 10-2](#) (Wolfsberg et al., 2002)

^bLower range in each cell represents retardation due to sorption to fracture minerals and matrix minerals from [Table 10-3](#) (Zavarin et al. 2004)

^bRetardation factors extrapolated from TMA regional HSU parameters in [Table 10-3](#)

Bold Font = Prominent material type encountered-basis for consideration

Italic Font = Estimated using other HSU as a surrogate

11.0 Colloid-Facilitated Transport Parameters

This section includes descriptions of the role of colloids in contaminant transport in groundwater, the available data, and the data evaluation and associated results.

11.1 Role of Colloids in Contaminant Transport

Colloids can facilitate the transport of strongly sorbing contaminants in groundwater systems by providing mobile surface area onto which the contaminants can sorb. Colloid-facilitated transport of radionuclides depends on the colloid types, concentrations and size distributions, the radionuclide distribution coefficients, and the colloid filtration and retardation parameters.

Colloid types are important because contaminant sorption and colloid mobility are strong functions of colloid surface mineralogy. Colloid concentrations and size distributions are important because these parameters determine the available surface area and ultimately the contaminant sorption capacity offered by mobile colloids. Colloid size distributions are also important in determining the mobility of colloids.

Colloid filtration and retardation parameters are important because colloid-facilitated contaminant transport can occur to a significant degree only if colloids remain mobile over relatively long distance and time scales.

Actinide distribution coefficients and sorption/desorption rates onto colloids are important because these parameters govern how strongly and reversibly actinides adsorb to colloids. Strong, irreversible sorption will tend to increase the probability of significant colloid-facilitated transport in a groundwater system.

11.2 Colloid Mineralogy, Concentrations, and Size Distributions

This section includes descriptions of the data available on colloid types, concentrations, and size distributions. The associated data analysis and results are also described including a discussion on the limitations of the data and scaling considerations.

11.2.1 Data Compilation and Evaluation

Colloid types, concentrations, and size distributions were obtained for the NTS, either for the UGTA Program or the YMP. LLNL determined colloid types from mineralogic analyses of colloid samples by XRD. Colloid concentrations and size distributions were measured using high-sensitivity liquid *in situ* particle spectrometry (HSLIS) at LANL. Colloid sizes reported when using this method are the diameter of an equivalent sphere (based on light-scattering intensity). Colloid mineralogy, concentrations, and size distribution data are described in [Appendix H](#).

11.2.2 Colloid Mineralogy

Mineralogy of natural colloids have not been analyzed routinely at the NTS. Brachmann and Kersting (2002), however, conducted significant mineralogical analysis on colloid samples collected from Wells ER-20-5 #1 and #3 and from U20n PS1 DDH (in and near the CHESHIRE cavity) in Area 20 of the NTS. Some of their conclusions were:

- Among the NTS groundwater samples, colloids are mineralogically similar, although the actual abundances of each mineral may vary from aquifer to aquifer.
- The colloidal material is composed primarily of clays (smectite and illite) and zeolites (mordenite and clinoptilolite/heulandite). Cristobalite (SiO_2) was also identified in XRD spectra of colloids from ER-20-5 #1 (HSU = TSA). These results suggest that potentially important radionuclide-sorbing minerals are clays and zeolites for groundwater in silicic volcanic units. This does not rule out the importance of minor colloidal minerals (i.e., those present at less than 10 percent). Note that the relative percentages of the different minerals in the colloid samples were not reported.
- The same clays and zeolites identified in the groundwater samples are also present in the host rock aquifers at ER-20-5 (HSU = TSA). The colloid minerals mimic the host rock from which they originated.

For the purposes of radionuclide transport modeling, it is recommended that natural colloids be considered to consist primarily of clays and zeolites with some silica (either amorphous or crystalline). Refractory colloids generated at the time of nuclear test detonations or resulting from alteration of the resulting melt glass (probably mostly clays) cannot be ruled out as a potentially significant contributor to colloid-facilitated transport at the NTS.

11.2.3 Colloid Concentrations and Size Distributions

Colloid concentrations and size distributions have been measured in groundwater samples taken from two wells on Frenchman Flat and several wells at other NTS CAUs, Nye County Early Warning Drilling Program and Yucca Mountain in the past several years (Kung, 2000 and 2002; Abdel-Fattah et al., 2003).

Concentration and size distribution data from 84 samples collected from 47 different wells sites were evaluated and classified by HSU in order to construct distributions for both colloid concentrations and sizes for Frenchman Flat HSUs.

Most of the sampled wells are located on Pahute Mesa, in the vicinity of the YMP, or at the Nye County Early Warning Drilling Program. As a result, to augment data for Frenchman Flat, it was necessary to transfer data from the HSUs of Pahute Mesa CAU or the NTS regional model to the equivalent HSUs for Frenchman Flat. [Table 2-4](#) shows the correlation between the HSUs for Pahute Mesa and the NTS regional model HSUs with Frenchman Flat HSUs. [Table 11-1](#) lists the wells, the sampled HSU, the equivalent HSU for Frenchman Flat if the sample was collected in another CAU, and the primary rock alteration for each unit.

11.2.3.1 Colloid Concentrations

Of the 17 HSUs associated with Frenchman Flat, only two HSUs have site-specific colloid data. When Frenchman Flat site-specific data was available, concentrations were calculated for both the site-specific data and the entire dataset with transferred data from other wells in and around the NTS. [Table 11-2](#) contains colloid concentrations for Frenchman Flat and the NTS regional model area on a HSU basis.

Samples analyzed for mean colloid concentration of the alluvial aquifer of Frenchman Flat are an order of magnitude smaller than the colloid concentration observations for the NTS regional area. This suggests that colloids are less abundant in Frenchman Flat alluvium than in the NTS region. There may be some bias in the Well RNM-2s, tending to be lower in concentration, because the well has been thoroughly developed and was pumped extensively as part of the CAMBRIC RNM experiment. In some cases, low colloid concentrations are indicative of stable groundwater conditions because both strong flow gradients and changes in groundwater chemistry are thought to enhance colloid mobilization (detachment) from rock surfaces.

An appropriate initial value for colloid concentrations during transport modeling would be the mean concentration of colloids for each HSU. For HSUs with no colloid concentration data, modelers should consider using data from the most comparable HSU for which data exists. For example, the OAA is similar to the AA, so AA values would be a reasonable approximation.

To allow for a model sensitivity analysis on colloid concentrations within the Frenchman Flat CAU transport model, two cumulative density functions (CDF) were calculated using Best Fit® software (see [Appendix C](#)). Both graphical and quantitative evaluations were used to judge the goodness of fit for each CDF.

**Phase II Contaminant Transport Parameters for the Groundwater Flow and
Contaminant Transport Model of CAU 98: Frenchman Flat, Nye County, Nevada**

Table 11-1
Wells Sampled For Colloid Concentrations and Distributions
(Page 1 of 2)

Well Name	Sampled HSU ^a	FF equivalent HSU ^b	Primary Rock Alteration on Frenchman Flat (Alluvium, Zeolitic, Vitric, Devitrified)
ER-EC-5	TMCM	NP	
ER-EC-8	FCCM/ TMCM	NP	
ER-EC-7	FCCM	NP	
ER-EC-1	BA/UPCU/TCA/LPCU/TSA/CHCU/CFCM	UTCU	Zeolitic
ER-EC-4	TMA/FCCM/TCVA	TM-WTA	Vitric
ER-EC-6	BA/UPCU/TCA/LPCU/TSA/CHCU/CFCM	UTCU	Zeolitic
ER-EC-2A	FCCM/TMCM	NP	
ER-18-2	AA	AA	Alluvium
ER-20-5 #1	TSA	TSA	Vitric
ER-20-5 #3	TSA	TSA	Vitric
UE-18r	TMCM	NP	
UE-20bh #1	CHZCM	NP	
U-19q	BFCU	LTCU	Zeolitic
U-20n	CHZCM	NP	
UE-19h	BRA	NP	
Water Well 8	AA	AA	Alluvium
U-20 Water Well	LFA/TCU	L/UTCU	Zeolitic
J-13 WW	80% TSA/20% zeolitic Tram units	TSA	Vitric
UE-25c #3	VA	TM-LVTA/TM-WTA/UTCU/TSA/LVTA	Devitrified and Vitric
UE-29a #1	UNK	NP	
UE-29a #2	YMCFCM	NP	
UE-25 WT #3	VA	TM-LVTA/TM-WTA/UTCU/TSA/LVTA	Devitrified and Vitric
UE-25 WT #17	VA	TM-LVTA/TM-WTA/UTCU/TSA/LVTA	Devitrified and Vitric
USW SD- 6	UKN		
RNM-2S	AA	AA	Alluvium
ER-7-1	LCA	LCA	
ER-6-1#2	LCA	LCA	
ER-12-2	LCA	LCA	
ER-5-4-2	LTCU	LTCU	Zeolitic
U-19-v	BFCU/CFCU/CHUTA/PLFA/PVTA/FMA	LTCU	Zeolitic
U-20n ps#1 ddh	CHZCM	NP	
ER-2-1	TM-LVTA	TM-LVTA	Vitric
U-4u ps2a	AA	AA	Alluvium
NC-EWDP-19D, zones 1, 2, 3, and 4	AA	AA	Alluvium
NC-EWDP-19IM-2-A	AA	AA	Alluvium
NC-EWDP-19IM-2-B	AA	AA	Alluvium

Table 11-1
Wells Sampled For Colloid Concentrations and Distributions
(Page 2 of 2)

Well Name	Sampled HSU ^a	FF equivalent HSU ^b	Primary Rock Alteration on Frenchman Flat (Alluvium, Zeolitic, Vitric, Devitrified)
NC-EWDP-19IM1 zones 1, 2, 3, 4	AA	AA	Alluvium
NC-EWDP-5SB	AA	AA	Alluvium
NC-EWDP-7S	AA	AA	Alluvium
NC-EWDP-12PA	AA	AA	Alluvium
NC-EWDP-12PB	AA	AA	Alluvium
NC-EWDP-12PC	AA	AA	Alluvium
NC-EWDP-15P	AA	AA	Alluvium
NC-EWDP-4PB	AA	AA	Alluvium
NC-EWDP-4PA	AA	AA	Alluvium
NC-EWDP-01S	AA	AA	Alluvium
NC-EWDP-03S	AA	AA	Alluvium
NC-EWDP-09SX	AA	AA	Alluvium

^aSampled HSU was determined by identifying the screened interval(s) for each well.

^bFrenchman Flat equivalent HSU determined using [Table 2-4](#).

UNK = Unit at screened interval unknown.

NP = Not Present

All other HSU abbreviations, refer to [Section 2.0](#).

Graphical evaluations included comparing the ECDF with the CDF of the fitted probability distribution and, to a lesser extent, comparing the histogram of observed values with the density function of the fitted distribution. Quantitative evaluation measures included the Kolmogorov-Smirnov (K-S) statistic, which measures the goodness of fit across the entire scale of observations. CDFs were calculated based on all NTS data irrespective of HSU and only for those HSUs occurring in the Frenchman Flat CAU model area ([Figure 11-1](#)). The Frenchman Flat CDF represents data from wells on FF or wells completed in units comparable to FF HSUs. The best fit to the NTS log-colloid concentration data was a Pearson5 distribution ($\alpha = 72.76$, $\beta = 859$), while the best fit to the Frenchman Flat log colloid concentration data was a normal distribution ($\mu = 8.28$, $\sigma = 1.51$) (see [Appendix C](#) for CDF equations).

Given that there are only four colloid concentration measurements for Frenchman Flat, the correlation of colloid concentrations to water chemistry was not evaluated. The water chemistry of the sampled wells was, however, quite similar (typically sodium bicarbonate waters with a pH of 7 to 8.5 and relatively low concentrations of divalent cations). [Figure 11-2](#) shows colloid concentrations in wells completed in saturated alluvium south and southwest of Yucca Mountain as a function of divalent cation concentrations in the groundwater (SNJV, 2004b). In this case, there is significant variability in the divalent cation concentrations and it is clear that colloid concentrations are correlated with these concentrations.

Table 11-2
Summary of Log₁₀ Colloid Concentrations (colloids/mL) for Frenchman Flat HSUs

Frenchman Flat HSUs	FF Colloid Samples				NTS Regional Model Area Samples			
	Number of Observations	Min	Mean ^a	Max	Number of Observations	Min	Mean	Max
AA	2	5.69	5.70	5.71	37	5.69	8.47	11.77
PCU	ND ^b				ND			
BLFA	ND				ND			
OAA	ND				ND			
PCU (older)	ND				ND			
TM-WTA	ND				2	6.15	6.83	7.51
TM-LVTA	ND				4	6.89	9.05	10.09
TCU	2	8.61	8.61	8.61	12	5.24	8.57	10.82
TSA	ND				5	6.02	7.74	10.15
WCU	ND				ND			
VCU	ND				ND			
LCA	ND				6	6.57	6.89	7.13
U/L CCU	ND				ND			
All HSUs	4	5.69	7.15	8.61	84 ^c	5.26	8.17	11.77

^aArithmetic mean

^bND = No data available

^cIncludes all NTS area colloid samples regardless of HSU or FF transferability

Correlations of colloid concentrations from these wells with total ionic strength and monovalent cation concentrations were not nearly as good as the correlation with divalent cation concentrations. This result is consistent with colloid stability theory and the Schulze-Hardy Rule (Hiemenz, 1986). Although Figure 11-2 does not represent groundwater samples taken from Frenchman Flat, it suggests that it may be appropriate to adjust colloid concentrations reported above when waters are found to be significantly different (based on divalent cation concentration) from those in the sampled wells (which have Log [(Ca) + (Mg)] values of approximately 1.3).

11.2.3.2 Colloid Size

Normalized colloid size distributions were determined from the 66 samples taken from wells on Frenchman Flat or wells completed in units comparable to Frenchman Flat HSUs (Figure 11-3). Size analyses were completed using a HSLIS-50 and -100 (Kung, 2000). This instrument has lower and upper size (diameter) limits of 50 and 1,000 nm, respectively. Only diameters up to 250 nm are shown in Figure 11-3 because there are very few colloids at larger sizes. The

Figure 11-1
CDF of Log₁₀ Colloid Concentrations for All Sampled NTS HSUs and Frenchman Flat HSUs (FF HSU Data is a Subset of the NTS HSU Data)

size distributions in [Figure 11-3](#) are normalized by dividing the number of colloids in each size “bin” by the total number of colloids in all bins. This allows the shapes of the distributions to be compared directly. The concentration of colloids in each size bin is represented by “C”, and the total concentration of colloids in all size bins is represented by “C_T.”

It is apparent from [Figure 11-3](#) that all of the size distributions are qualitatively similar in shape. As indicated by the two bold lines, however, distributions with higher concentrations of larger sizes tend to have lower concentrations of smaller sizes (an expected result of the normalization process). To simplify the parameterization of the size distributions, all of the colloid size distributions for a HSU were lumped together and an ECDF was calculated. The ECDFs were evaluated using BestFit. Log-normal CDFs provided the best overall fit to all of the HSUs ([Figure 11-4](#)). [Table 11-3](#) contains the log-normal fit statistics describing the CDF distributions for each HSU (see [Appendix C](#) for equations). These distributions can be used to directly during sensitivity analysis of the Frenchman Flat groundwater flow and transport model.

Figure 11-2
Log₁₀ Colloid Concentrations (no./mL) Versus Log [(CA)+[Mg)] (M)
in Saturated Alluvium near Yucca Mountain

11.2.3.3 Data Limitations

Colloid samples obtained from pumped wells have potential artifacts resulting from necessary stressing of the aquifer to obtain the samples and also from residual foreign materials that are introduced during drilling (e.g., drilling muds, polymer additives) or from corrosion of well construction materials (e.g., metallic casing, concrete). Colloids that are mobile under pumping conditions may not necessarily be mobile under nonpumping conditions.

It is always best to purge a borehole extremely well before sampling for colloids. Unfortunately, well purging was not done in a consistent manner for the samples reported in [Table 11-1](#). Some of the samples came from wells that had been producing large volumes of water at high flow rates for years before they were sampled (e.g., UE-25 J-13 and UE-25c#3), and others could only be bailed or pumped very minimally before sampling. The impact of these sampling inconsistencies on the colloid data cannot be specifically quantified and incorporated in the data analysis.

In addition, when sampling for colloids, it is best to pump the well at low flow rates to minimize the perturbations to the ambient flow system. High flow rates during sampling may lead to concentrations that are higher in the samples than in the formation under ambient conditions. Sampling at the ER wells was conducted at pumping rates that are considered high for representative colloid sampling. The

Figure 11-3
Normalized Size Distributions of Colloids in Wells
Located on the Nevada Test Site and Vicinity

colloid concentrations reported from the ER wells may be greater than ambient, unperturbed concentrations.

11.2.3.4 Scaling Considerations

Colloid concentrations and size distributions appropriate to CAU-scale transport modeling are not expected to vary appreciably when compared to samples collected from wells. Scaling of colloid transport, mobilization and deposition mechanisms, and colloid-facilitated contaminant transport are probably far more important.

11.3 Colloid Transport Parameters

This section includes descriptions of the data available on colloid filtration and retardation parameters. The associated data analysis and results are also described, including a discussion on the limitations of the data and scaling considerations.

Figure 11-4
CDF of Colloid Diameter (nm) for All Sampled NTS HSUs and Frenchman Flat HSUs

Table 11-3
Log-Normal CDF Shape Parameters of Colloid Size Distributions for Frenchman Flat

	All NTS HSUs	Alluvium	TSA	TM-LVTA	TM-WTA	TCU	LCA
μ (nm)	47.3	50.4	40.5	56.2	56.2	38.7	55.6
σ (nm)	22.5	40.0	34.3	55.7	55.7	41.4	51.8
+shift (nm)	17.9	28.1	33.9	31.5	30.9	36.0	28.2
Lower 95% CI (nm)	35.5	38.1	41.3	38.8	38.8	40.8	36.9
Upper 95% CI (nm)	121.4	183.5	164.5	233.0	233.0	182.3	219.9

11.3.1 Data Compilation and Evaluation

Colloid filtration and retardation parameters were obtained primarily from analyses of colloid tracer responses in laboratory and field tracer transport experiments involving inorganic colloids or fluorescent polystyrene microspheres as tracers.

11.3.2 Data Evaluation

Colloid filtration and detachment rate constants have been derived from colloid responses in tracer tests by using the advection-dispersion equation with appropriate terms for a single reversible first-order reaction to account for mass transfer between mobile water and immobile surfaces (filtration and detachment) to fit the data:

$$\frac{\partial C}{\partial t} + V \frac{\partial C}{\partial x} - D \frac{\partial^2 C}{\partial x^2} + k_{\text{filt}} C - k_{\text{det}} S = 0 \quad (11-1)$$

$$\frac{1}{b} \frac{\partial S}{\partial t} - k_{\text{filt}} C + k_{\text{det}} S = 0 \quad (11-2)$$

Where:

- C = Colloid concentration in solution, number of colloids/L³
- S = Colloid concentration on rock or fracture surfaces, number of colloids/L²
- V = Flow velocity in pores or fractures, L/T
- D = Dispersion coefficient, L²/T
- k_{filt} = Filtration rate constant (1/T) = λV, where λ = filtration coefficient (1/L)
- k_{det} = Detachment rate constant, 1/L-T
- x, t = Independent variables for distance and time, respectively.
- b = Fracture half aperture (L)

The values for V and D in [Equation \(11-1\)](#) and [Equation \(11-2\)](#) were always obtained from interpretations of nonsorbing solute tracer responses; therefore, the filtration and detachment rate constants were the only parameters adjusted to match the colloid responses. Colloid filtration and detachment rate constants have been derived from colloid responses in tracer tests by using the advection-dispersion equation with appropriate terms for a single reversible first-order reaction to account for mass transfer between mobile water and immobile surfaces (filtration and detachment) to fit the data. [Equation \(11-1\)](#) and [Equation \(11-2\)](#) apply to colloid filtration in alluvium, volcanic, and carbonate units. Details of the interpretation procedure are provided in Reimus et al. (1999b).

11.3.3 Development of Parameter Distributions

Colloid filtration rate constants and retardation factors have been estimated in a number of laboratory and field experiments conducted for UGTA and other projects. All of the field measurements have involved fluorescent microspheres ranging in size from 280 to 640 nm diameter. Laboratory alluvium and fracture experiments have been conducted using silica, montmorillonite, and clinoptilolite colloids in addition to CML microspheres. In one study, silica colloid transport

(approximately 100 nm diameter) was compared directly with CML microsphere transport (330 nm diameter), and it was found that the microspheres transported with little retardation relative to the silica colloids in saturated, fractured volcanic rocks (Anghel, 2001). This result suggests that colloid filtration and retardation parameters derived from CML microsphere responses in field tracer tests should be conservative if used to predict natural, inorganic-colloid transport in fractured systems. Conversely, in alluvium, CML microspheres do not appear to be conservative when compared to natural, inorganic colloids.

11.3.3.1 Colloid Filtration Rate Constants

Alluvium. Colloid filtration rate constants and retardation factors for alluvial material have been estimated in a number of laboratory experiments for the YMP. Field tests of colloid filtration in the alluvium have not been done; therefore, data from Schijven et al. (1999) were used in conjunction with laboratory measurements to obtain colloid filtration and detachment rates at the field scale.

Schijven et al. (1999) measured filtration and detachment rates for bacteriophages in alluvial material under natural gradient conditions. They used bacteriophages denoted as MS-2 and PRD-1 that are in the same size range as colloids. These bacteriophages were chosen because they attach less than most pathogenic viruses and are relatively persistent during transport through the subsurface (Schijven et al., 1999). The groundwater at the site studied by Schijven et al. (1999) had somewhat higher divalent cation concentrations than most alluvium at Frenchman Flat (90 to 100 mg/L Ca^{2+} and 10 to 15 mg/L Mg^{2+} compared to 7 to 44 mg/L Ca^{2+} and 1.5 to 8 mg/L Mg^{2+} at Frenchman Flat) (GEOCHEM04.mbd). Based on this data, colloids would be expected to be less stable at their site. The alluvium material at their study site was also a bit coarser, with more sand, less clay, and more organic carbon than the alluvium material of Frenchman Flat, all of which would tend to result in enhanced colloid transport relative to Frenchman Flat conditions. Thus, the combination of colloid selection, groundwater chemistry, and alluvium characteristics at the site studied by Schijven et al. (1999) is sufficiently similar, suggesting that there are no obvious reasons why their reported colloid filtration and detachment rate constants would not be conservative when applied to Frenchman Flat alluvium (although there are uncertainties associated with doing so).

Filtration rate constants obtained from interpretations of several laboratory tracer tests and the Schijven et al. (1999) field test conducted in saturated alluvium as a function of the mean solute residence time in the tests are compared in [Figure 11-5](#). The filtration rate constants reflect the fraction of colloids that were not filtered during the tests (i.e., the rate constant is constrained primarily by the magnitude of the early arrival of colloids).

There is an apparent trend of decreasing filtration rate constant with residence time in laboratory column experiments even though different sizes and types of colloids were used in the different tests ([Figure 11-5](#)). The experiments involving the two colloids with the largest filtration rate constants, the 330-nm CML microspheres and the 100-nm silica colloids, were conducted in columns in which air bubbles

Figure 11-5
Colloid Filtration Rate Constants as a Function of Mean Residence Time in
Several Laboratory Experiments and a Field Study in Saturated, Alluvium Material
(Viswanathan and Reimus, 2003)

became apparent during the experiments. Later alluvium column experiments that involved the 190-nm and 500-nm CML microspheres, as well as the natural colloids, were conducted much more carefully to avoid air bubbles. It is certainly possible that the air bubbles in the earlier tests could have been at least partly responsible for the greater filtration rate constants. Figure 11-6 shows the normal cumulative probability distribution fit to the log of the colloid filtration rate constants in alluvium during laboratory and field-scale transport. The CDF has a mean value of -1.49 (log 1/hr) and standard deviation of 0.98 (log 1/hr) (95-percent confidence interval: -3.40 to 0.43 log 1/hr) (see Appendix C for normal distribution equation).

Fractured Volcanic Rocks. Figure 11-7 shows a plot of filtration rate constants obtained from interpretations of several field and laboratory tracer tests conducted in saturated fractured volcanic rocks as a function of the time to reach peak nonsorbing tracer concentrations in the tests. The results (Figure 11-7) are presented as a plot of CML microsphere and inorganic colloid filtration rate constants as a function of time to tracer peak concentration. The data were obtained from several field and laboratory tracer tests conducted in saturated, fractured volcanic rocks. These tracer tests include:

- The BULLION Forced-Gradient Experiment (Reimus and Haga, 1999) referred to as “ER-20-6” in Figure 11-7

Figure 11-6
**Normal CDF Fit to ECDF of Colloid Filtration Rate Constants for
Colloid Transport in Alluvium (Viswanathan and Reimus, 2003)**

Figure 11-7
**CML Microsphere and Inorganic Colloid Filtration Rate Constants
as a Function of Time to Tracer Peak Concentration**

- Tracer tests in the Bullfrog Tuff (Member of the Crater Flat Group) at the UE25c Wells at NTS (Reimus et al., 1999b) referred to as “C-Wells BF” in [Figure 11-7](#)
- Tracer tests in the Prow Pass Tuff (Members of the Crater Flat Group), at the UE25c Wells at NTS (Reimus et al., 1999b) referred to as “C-Wells PP” in [Figure 11-7](#)
- Laboratory experiments conducted at LANL using fractured cores from Pahute Mesa at the NTS (Kersting et al., 2002b)

It is important to emphasize that different CML microspheres were used in the different field tests, and also that groundwater chemistry varied slightly from site to site or test to test.

The filtration rate constants reflect the fraction of colloids that were not filtered during the tests (i.e., the rate constant is constrained primarily by the magnitude of the early arrival of colloids). [Figure 11-7](#) shows that, even though different sizes and types of colloids were used in the different tests, there is an apparent trend of decreasing filtration rate constant with residence time. The line drawn through the data (not a fit) has a slope of -1, which implies an inverse time dependence of the filtration rate constant. Schijven et al. (1999), however, observed no change in filtration rate constants as a function of distance (proportional to time in their system) for bacteriophage transport in a sandy alluvial aquifer.

The trend shown in [Figure 11-7](#) suggests that some fraction of colloids may always transport through a fracture flow system regardless of the time or length scale of the observations. It is tempting to draw the conclusion that filtration rate constants will continually decrease with increasing time scales. However, it may be more appropriate to consider the possibility that, while the majority of colloids might be filtered quickly, there is a small fraction that are resistant to filtration and, therefore, capable of traveling large distances over long time periods. This statement implies that there may be a distribution of colloid filtration rate constants rather than a fixed rate constant that applies to all colloids. The appearance of a small fraction of colloids at about the same time as nonsorbing solutes in tracer tests, regardless of the overall time scale of the test, forces filtration rate constants to decrease with time when a single-rate constant is assumed to apply to all colloids.

Ignoring the possible scale effect for the moment, it is possible to construct a cumulative PDF for the filtration rate constants derived from all of the experiments represented in [Figure 11-7](#). In doing so, filtration rate constants derived from field tests were weighted twice that of rate constants from laboratory tests. The rationale for this weighting was that the field tests (10- to 100-m scales) are one- to two-orders of magnitude closer to CAU scales (10,000+ m) than the laboratory tests (0.1- to 1-m scales). Also, one additional data point does not come from a tracer test, but rather comes from the observation(s) of colloid-facilitated Pu transport in the ER-20-5 wells that originated from the BENHAM nuclear test cavity. To estimate a filtration rate constant for this observation, several assumptions were made. First, it was assumed that the Pu in the ER-20-5 wells

was irreversibly sorbed to colloids, which means that Pu concentrations in the wells reflect colloid transport parameters reasonably well. Second, it was assumed that the concentrations measured in ER-20-5 #1 (on the order of 10^{-13} M Pu) represent a 5 order-of-magnitude decrease from concentrations at the source. Thus, colloid filtration is assumed to result in a 5 order-of-magnitude decrease in colloid concentrations. Third, it was assumed that any colloids that were filtered would never make it to the observation wells (i.e., they were effectively irreversibly filtered). Finally, the travel time from the source to the ER-20-5 wells was approximately 30 years, which represents an upper bound estimate. No assumptions were required about the travel distance. Although these assumptions cannot be verified directly, they allow us to estimate a filtration rate constant using the following expression:

$$1 \times 10^{-5} = \text{Exp} [-(t)k_f] \quad (11-3)$$

Where:

k_f = Filtration rate constant
 1×10^{-5} = Fraction of colloids traveling from the source to the ER-20-5 wells
 t = Travel time in hours = (30)(365.25)(24)=262,980.

Note that Equation (11-3) is obtained by assuming plug flow for a batch system in which there are no advection and dispersion terms. In addition, the detachment rate is assumed to be zero, thus yielding Equation (11-3) after solving the resulting ODE with the initial condition ($C_0 = 10^5$). Solving for k_f yields a filtration rate constant of $4.4 \times 10^{-5} \text{ hr}^{-1}$. This estimate is not very sensitive to the fraction of colloids assumed on the left-hand side of Equation (11-3). If the fraction is changed to 1×10^{-8} , the filtration rate constant becomes $7 \times 10^{-5} \text{ hr}^{-1}$. The filtration rate constant is inversely proportional to the assumed travel time, so if the travel time is decreased by a factor of 3 (to 10) years, the filtration rate constant increases by a factor of 3 (to $1.3 \times 10^{-4} \text{ hr}^{-1}$).

Figure 11-8 shows the resulting ECDF of filtration rate constants that includes the data point corresponding to the ER-20-5 observations (which was weighted the same as the field tracer test results). Both axes in Figure 11-8 are logarithmic. Note that data points associated with the two alternative assumptions (shown as two squares) discussed above for the ER-20-5 observations are also shown to illustrate the insensitivity of the overall cumulative distribution to these assumptions. Another approach is to assume that a very small fraction of the source term travels unfiltered or unretarded through the flow system.

The line fitted to the data in Figure 11-8 can be used to obtain a representative filtration rate constant for use in a transport model given a random number sampled from a uniform distribution that ranges from 0 to 1. The procedure is as follows:

1. Generate the random uniform number.
2. Take the $\log_{10}$ of that number.

3. Insert the result into the regression equation for y and solve for x.
4. Use 10^x as the filtration rate constant in the transport model.

The apparent scale effect of Figure 11-7 was implicitly incorporated into the cumulative probability distribution of Figure 11-8 by weighting the field-derived filtration rate constants twice as much as the laboratory-derived ones. Information is lacking to provide any further recommendations on how the apparent scale effect should be accounted for in CAU-scale modeling. At a minimum, transport simulations at the CAU scale should include sensitivity analyses to determine the sensitivity of radionuclide transport predictions to assumed values of colloid filtration rate constants.

11.3.3.2 Colloid Retardation Factors

Colloid retardation factors, R_{col} , can be calculated from colloid filtration and detachment rate constants using the following expressions:

For alluvium:

$$R_{col} = 1 + \frac{\rho\alpha}{\theta} \frac{k_f}{k_{det}} \quad (11-4)$$

For fractured rocks:

$$R_{\text{col}} = 1 + \frac{k_f}{bk_{\text{det}}} \quad (11-5)$$

where ρ_a is the bulk density of alluvium (M/L^3), θ is the porosity of alluvium (L^3/L^3). All other symbols are the same as those used in Equation (11-2) and Equation (11-3)

Alluvium. Colloid retardation factors, R_{col} , can be calculated from colloid filtration and detachment rate constants using Equation (11-4). Using the calculated values reported in Figure 11-5, a cumulative probability distribution for $\text{Log } R_{\text{col}}$ can be generated. This uniform distribution is shown in Figure 11-9, the 95-percent confidence interval is -0.02 to 3.76 for R_{col} (Appendix C contains the uniform CDF equation: $\text{min} = -0.12$, $\text{max} = 3.84$). This distribution consists of the best-fitting R_{col} values obtained from RELAP as reported by Viswanathan and Reimus (2003). Note that the filtration rate constants and retardation factors from Schijven et al. (1999) are weighted the same as all lab experimental data when generating probability distributions of filtration rate constants and retardation factors in the alluvium. Although the Schijven et al. (1999) data were obtained at field scales, the flow system and aquifer materials are different from Frenchman Flat and, therefore, justifies assigning no greater weight to these data than to data obtained from lab experiments using NTS-specific materials.

Fractured Volcanic Rocks. Using the interpretive results from all of the tests represented in Figure 11-7, with the exception of the ER-20-5 observations and two of the three CML microsphere responses from the BULLION FGE, a cumulative probability distribution for R_{col} can be generated. The distribution is shown in Figure 11-10 (log scale on x axis), which has the field test results weighted a factor of 2 greater than the laboratory test results. Figure 11-10 also shows a fit of a log-normal distribution to the retardation factors. This fit has a mean of 1.5, which corresponds to a mean colloid retardation factor of 31.6, and a standard deviation of 0.65 (log units). The ER-20-5 observations were included in Figure 11-10 by assigning a probability of 0.00001 to a retardation factor of 1.0, which assumes that 0.001 percent of the colloids from the source cavity moved unretarded to the ER-20-5 wells (consistent with the above analysis of filtration rate constants). The results from the two microsphere responses in the BULLION FGE production well were omitted because there was a significant increase in microsphere concentrations in the tails of the responses that apparently resulted from a flow transient in the production well (this increase prevented an unbiased estimate of bk_{det}). The maximum retardation factor assumed for any of the colloid datasets was 1,000. For any of these datasets, the factor of 1,000 could effectively not be distinguished from an infinite retardation factor (because the colloid responses could be fitted equally well assuming no detachment at all). Thus, the distribution of Figure 11-8 is probably conservative at the high end because of this somewhat arbitrary maximum value.

Figure 11-9
Cumulative Probability Distribution of Colloid Retardation Factors for Alluvium
(data as reported by Viswanathan and Reimus, 2003)

Figure 11-10
Cumulative Probability Distribution of Log Colloid
Retardation Factors for Fractured Volcanic Rocks

11.3.4 Data Limitations

Colloid filtration rate constants and retardation factors from sites with different lithology and chemistry and those derived from polystyrene microsphere transport data must be used with caution and carefully qualified when applied to colloid-facilitated transport modeling because of the obvious physical and chemical differences when compared to site-specific conditions.

11.3.5 Scaling Considerations

Figure 11-8 and the associated discussion suggest that there may be an important scale dependence of colloid filtration rate constants and retardation factors. However, rather than an explicit scale dependence, it is possible that there may be a wide distribution of colloid filtration rate constants associated with any colloid population and fracture flow system. As a result of this distribution, there may always be a small percentage of colloids that are resistant to filtration and capable of traveling over large distances at essentially the rate of water flow in any given groundwater flow system. This possibility should be seriously considered when modeling colloid-facilitated transport at CAU scales.

11.4 Summary

An approach for modeling colloid transport in groundwater using both colloid filtration rates and colloid retardation factors is presented in this section.

The approach is initiated by randomly sampling a retardation factor from [Figure 11-9](#) and [Figure 11-10](#) for alluvium and fractured volcanic rocks, respectively. This value is then inserted into the advection-dispersion equation modified to account for colloid retardation to calculate colloid travel times. However, even if retardation factors are generally large, the ER-20-5 observations suggest that a small fraction of colloid mass may have slow enough filtration rate constants that they can travel large distances effectively unretarded. To allow for this possibility, the following approach is suggested for colloid transport modeling at the CAU scale:

1. Sample CDF associated with the rock type of interest.
2. Given a mean travel time, τ , to the CAU boundary (possibly calculated from randomly sampled values of specific discharge, effective porosity, and travel distance), calculate a critical filtration rate constant, k_{crit} , as $k_{crit} = 1/\tau$.
3. Calculate the fraction of colloid mass that travels with $R = 1.0$ based on the CDFs reported ([Figure 11-6](#) and [Figure 11-8](#)) for alluvium and volcanic rocks, respectively.

In steps 2 and 3, the critical filtration rate constant is the rate constant that yields $-k_{crit} t = -1$, which, when inserted as the appropriate equation in step 3, yields a probability of a colloid traveling for time t without being filtered. Colloids with this filtration rate constant, or less, will not tend to be filtered over the time scale in question. In contrast, a large fraction of colloids with filtration rates larger than k_{crit} will be filtered (once k_{crit} is exceeded by a factor of 5, less than 1 percent of the colloids will be transported without filtering). Thus, all colloids with filtration rate constants greater than k_{crit} can be assumed to travel with the effective retardation factor sampled from [Figure 11-9](#) and [Figure 11-10](#).

A refinement of this approach could be made by assigning the distribution of [Figure 11-9](#) and [Figure 11-10](#) to the entire population of colloids in each CAU-scale model simulation rather than sampling a single retardation factor from the distribution. In this case, a small number of colloids will travel essentially unretarded while the majority of the colloids are retarded.

11.5 Actinide Distribution Coefficients and Sorption Rates onto Colloids

This section includes descriptions of the data available on actinide distribution coefficients and sorption rates (forward and reverse) onto colloids. The associated data analysis and results are also described including a discussion on the limitations of the data and scaling considerations.

11.5.1 Data Compilation and Evaluation

Actinide distribution coefficients and sorption/desorption rates onto colloids were obtained from batch sorption and desorption experiments as well as fracture transport experiments conducted at both LANL and LLNL. All of the YMP experiments and the UGTA fracture transport experiments were conducted at LANL.

Batch sorption/desorption experiments have been conducted for both the UGTA program (focusing on Pu only) and the Yucca Mountain Project (Pu, Am, Np, and U), and fracture-transport experiments have been conducted for the UGTA program (Pu only). Actinide distribution coefficients and sorption/desorption rates onto colloids were checked by LANL personnel prior to tabulation, and they were also checked for consistency after tabulation. Actinide distribution coefficients and sorption/desorption rates onto colloids are described in [Appendix H](#) (distribution coefficients) and in [Table 11-4](#) of this section (rates).

11.5.2 Development of Parameter Distributions

The available data were assessed to derive distribution coefficients (K_d values) and radionuclide desorption rates from colloids.

11.5.2.1 Distribution Coefficients (K_d values)

Between 1997 and 2000, Lu et al. (1998a and b, 2000) conducted several batch sorption and desorption experiments to measure the sorption of Pu^{+4} , Pu^{+5} , Am^{+3} , Np^{+5} , and U^{+6} onto hematite, goethite, montmorillonite, and silica colloids using filtered waters from Well J-13 in Area 25 at the NTS (near Yucca Mountain) and synthetic J-13 water. The Pu^{+4} was always introduced as a polymeric colloid (≤ 10 nm diameter) because Pu^{+4} is not stable as a solute at near-neutral pH, except at very low concentrations. The solubility of Pu^{+4} at near-neutral pH is less than 10^{-8} M. The measurements of Pu^{+4} polymeric colloid sorption are, therefore, likely to be valid because the concentrations of Pu in solution were very low after equilibration, even though the kinetics of precipitation, colloid formation, and oxidation are not well known.

The hematite and goethite were selected to represent colloids that could form as a result of the corrosion of iron-containing waste package materials in the potential Yucca Mountain repository. Experiments were conducted at different colloid concentrations, temperatures, and ionic strengths. The reader is referred to the Lu et al. (1998a, b, and 2000) for details of the experiments.

[Figure 11-11](#) depicts the ranges of radionuclide partition coefficients (K_d values, mL/g) measured for the various radionuclide-colloid combinations at colloid concentrations of 200 mg/L at 20°C in natural J-13 water (ambient LANL temperature of about 20°C) (Lu et al., 1998a, b, and 2000; Reimus et al., 2002b; Kersting et al., 2002a and b). UGTA results for Pu^{+5} distribution coefficients onto

**Table 11-4
Ranges of Rate Constants for Sorption and Desorption of Actinides Onto Colloids
(Assuming Only a Single Type of Sorption Site) from UGTA and Yucca Mountain Experiments**

Colloids/Actinides	Batch k_f (hr ⁻¹)	Batch k_b (hr ⁻¹)	Fracture k_f (hr ⁻¹)	Fracture k_b (hr ⁻¹)
Montmorillonite				
Pu ⁺⁴	0.2-0.5	0.0001-0.01		
Pu ⁺⁵	0.005-0.04	0.0001-0.01	0.005-0.04	0.1-2
Np ⁺⁵	0.02-0.1	ND		
Am ⁺³	0.04-0.1	ND		
U ⁺⁶	0.02-0.1	ND		
Silica				
Pu ⁺⁴	0.2-0.5	0.01-0.2		
Pu ⁺⁵	0.01-0.06	0.01-0.2	0.01-0.06	0.5-1.5
Np ⁺⁵	0.02-0.1	ND		
Am ⁺³	0.04-0.1	ND		
U ⁺⁶	0.02-0.1	ND		
Hematite				
Pu ⁺⁴	1-50	0.00001-0.0001		
Pu ⁺⁵	0.04-0.1	0.00001-0.0001		
Np ⁺⁵	0.02-0.1	ND		
Am ⁺³	1-5	ND		
U ⁺⁶	0.02-0.1	ND		
Goethite				
Pu ⁺⁴	1-50	0.00001-0.001		
Pu ⁺⁵	0.06-0.1	0.00001-0.001		
Clinoptilolite				
Pu ⁺⁴	1-50	0.001-0.03	1-50	0.001-0.03
Pu ⁺⁵	0.001-0.01	ND		
Birnessite				
Pu ⁺⁵	1-50	ND		

k_f = Sorption rate constant
 k_b = Desorption rate constant
 ND = Not determined

silica and montmorillonite colloids in well water from U-20WW (Reimus et al., 2002b) and for Pu⁺⁴ distribution coefficients onto clinoptilolite colloids in a synthetic J-13 well water (Kersting et al., 2002a) are shown as extensions of the bars for the J-13 K_d values in Figure 11-11. Some of the key observations in the J-13 experiments, including the effects of changing the temperature, ionic strength, and colloid concentrations are listed in brief summary fashion for each radionuclide and each colloid below.

Figure 11-11
Ranges of K_d Values Measured for Actinide Sorption Onto Colloids

Pu⁺⁴ and Pu⁺⁵ Sorption to Hematite Colloids:

- Pu⁺⁴ sorption much faster than Pu⁺⁵ sorption, although final K_d s were quite similar
- K_d range 2×10^4 to 2×10^5 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 5×10^6 mL/g as temperature increases to 80°C
- K_d increase to 1×10^7 mL/g as ionic strength increases to 0.07 M or greater
- Slight K_d increase (about a factor of 2) at low colloid concentrations (down to 10 mg/L)
- Desorption K_d comparable to sorption K_d s, so tests appear to indicate reversibility

Pu⁺⁴ and Pu⁺⁵ Sorption to Goethite Colloids:

- Pu⁺⁴ sorption much faster than Pu⁺⁵ sorption, although final K_d s were quite similar
- No significant effect of ionic strength on K_d values; K_d increase to 3×10^4 mL/g at low colloid concentrations
- Desorption K_d comparable to sorption K_d s, so tests appear to indicate reversibility

Pu⁺⁴ and Pu⁺⁵ Sorption to Silica Colloids:

- Pu⁺⁴ sorption much faster than Pu⁺⁵ sorption, although final K_ds were quite similar
- K_d range 10³ to 10⁴ mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d upper limit of 10⁴ mL/g as temperature increases to 80°C
- K_d lower limit of 10³ mL/g as ionic strength increases to 0.1 M
- K_d increase to 3 x 10⁴ mL/g at low colloid concentrations
- Desorption K_d is comparable to sorption K_ds so tests appear to indicate reversibility

Am⁺³ Sorption to Hematite Colloids:

- K_d range 10⁵ to 10⁷ mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- No significant effect of temperature, although slightly higher K_ds at higher temps
- K_ds approach lower end of K_d range as ionic strength increases to 0.1 M
- Upper end of K_d range is approached at low colloid concentrations
- Desorption K_d is at lower end of range of sorption K_ds, so tests appear to indicate reversibility

Am⁺³ Sorption to Montmorillonite Colloids:

- K_d range 10⁴ to 10⁵ mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 3 x 10⁵ mL/g as temperature increases to 80°C.
- K_d values approach lower end of K_d range as ionic strength increases to 0.1 M
- K_d increase to 10⁶ mL/g at low colloid concentrations (10 mg/L)
- Desorption K_d is within range of sorption K_ds, so tests appear to indicate reversibility

Am⁺³ Sorption to Silica Colloids:

- K_d range 2×10^3 to 2×10^4 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 6×10^4 mL/g as temperature increases to 80°C.
- K_d values approach lower end of K_d range as ionic strength increases to 0.1 M
- K_d increase to 10^5 mL/g at low colloid concentrations (10 mg/L)
- Desorption K_d is comparable to sorption K_d s, so tests appear to indicate reversibility

Np⁺⁵ Sorption to Hematite Colloids:

- K_d range 10^2 to 10^3 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 4×10^3 mL/g as temperature increases to 80°C
- K_d values approach upper end of K_d range as ionic strength increases to 0.1 M
- Desorption was not measurable, but this is not conclusive because of low amount of sorption

Np⁺⁵ Sorption to Montmorillonite Colloids:

- K_d range 10 to 200 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 3×10^3 mL/g as temperature increases to 80°C
- No significant effect of ionic strength on K_d values
- Desorption was not measurable, but this is not conclusive because of low amount of sorption

Np⁺⁵ Sorption to Silica Colloids:

- K_d range 30 to 1,000 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 2×10^3 mL/g as temperature increases to 80°C
- K_d values approach lower end of K_d range as ionic strength increases to 0.1 M

- Desorption was not measurable, but this is not conclusive because of low amount of sorption

U⁶ Sorption to Hematite Colloids:

- K_d range 100 to 500 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to upper end of K_d range as temperature increases to 80°C
- U precipitated at higher ionic strengths
- Desorption was not measurable, but this is not conclusive because of low amount of sorption

U⁶ Sorption to Montmorillonite Colloids:

- K_d range 30 to 200 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 700 mL/g as temperature increases to 80°C
- U precipitated at higher ionic strengths
- Desorption was not measurable, but this is not conclusive because of low amount of sorption

U⁶ Sorption to Silica Colloids:

- K_d 300 to 600 mL/g at 20°C, J-13 water, 200 mg/L colloid concentration
- K_d increase to 2×10^3 mL/g as temperature increases to 80°C
- U precipitated at higher ionic strengths
- Desorption was not measurable, but this is not conclusive because of low amount of sorption

The results of the Pu⁴ and Pu⁵ experiments are consistent with at least partial reversibility of sorption, but the results are also consistent with very slow desorption kinetics or irreversible sorption of a fraction of the Pu.

Separate Pu⁴ and Pu⁵ sorption experiments onto colloids were recently conducted by Kersting et al. (2002a and b) at LLNL. Pu⁴ sorption onto clinoptilolite colloids was very fast and exhibited K_d values of 15,000 to 25,000 mL/g at 20°C over a pH range of 7 to 9.5 (Kersting et al., 2002a). Pu⁵ experiments were conducted using seven different colloids. The resulting K_d values for Mn-oxide, birnessite and pyrolusite; calcite; zeolite, clinoptilolite; Fe-oxide, goethite; clay, montmorillonite; and silica are depicted in [Figure 11-12](#) (Kersting et al., 2002b). The data in [Figure 11-12](#) are in good agreement with the

Pu K_d values from LANL experiments shown in Figure 11-11. The K_d values for goethite are slightly higher in the LLNL experiments compared to the range in LANL experiments, although both datasets indicate very strong sorption of Pu⁺⁵ to goethite. These are the only types of mineral colloids for which comparisons are possible.

Figure 11-12
Distribution Coefficient Calculated for Pu⁺⁵ Sorbed
Onto Various Mineral Colloids (Kersting et al., 2002b)

It is recommended that K_d values for actinide sorption onto mineral colloids be sampled from the ranges shown in Figure 11-11 for iron oxide, montmorillonite, and silica colloids if these colloids are expected in the HSU of interest. For calcite, birnessite, clinoptilolite, and pyrolusite colloids, the K_d values in Figure 11-12 are the only ones currently available for UGTA modelers to use if these are anticipated in the HSU.

11.5.2.2 Radionuclide Sorption Rates Onto Colloids

Sorption rates of Pu⁺⁴ and Pu⁺⁵ onto colloids have been measured in experiments at both LANL and LLNL. Pu⁺⁴ polymeric colloid sorption rates onto colloids are typically very rapid, with maximum (or equilibrium) sorption levels being attained within a few hours to at most a day. In experiments conducted at LANL for the UGTA program, Pu⁺⁵ sorption rates onto silica colloids were initially faster than rates onto montmorillonite colloids, although final sorption K_d values tended to be somewhat higher on montmorillonite colloids. Maximum sorption levels were attained within a day or so on silica colloids, while they took 5 to 10 days on montmorillonite colloids. In sorption experiments conducted at LLNL, the sorption rates of Pu⁺⁵ onto birnessite and goethite colloids were very rapid (on the

order of hours), but rates of Pu^{+5} sorption onto clinoptilolite colloids were extremely slow. In the latter case, it did not appear that equilibrium sorption levels were attained even after 50 days (Kersting et al., 2002b). These experiments were conducted in a synthetic water mimicking J-13 well water from near Yucca Mountain. The results were attributed to the ability of the birnessite and goethite surfaces to reduce Pu^{+5} to Pu^{+4} , followed by rapid subsequent sorption of the Pu^{+4} onto the colloids. In contrast, Pu^{+5} reduction to Pu^{+4} in the presence of clinoptilolite colloids was interpreted to occur only in the solution phase, a much slower process that was considered to be a necessary precursor to sorption onto the colloids. An alternative interpretation is that surface reduction is still occurring, but at a much slower rate due to less effective reductants on the surfaces of the colloids. Spectroscopic methods confirmed that Pu^{+4} , not Pu^{+5} , was sorbed to the surfaces of all the colloids studied (Kersting et al., 2002a and b).

Sorption rates of U^{+6} , Np^{+5} , Pu^{+4} , Pu^{+5} , and Am^{+3} onto various types of inorganic colloids have been measured in experiments conducted at LANL for the YMP (Lu et al., 1998a and b; 2000). The results are summarized as follows (all at approximately 20°C, 200 mg/L colloids, and ambient LANL atmosphere):

- Pu^{+4} (colloidal) sorbed very quickly (hours) to hematite, goethite, montmorillonite, and silica colloids in J-13 well water.
- Pu^{+5} sorbed more slowly to all of these colloids, taking 1 to 3 days to reach maximum sorption levels in J-13 water. Sorption tended to be somewhat faster (just a few hours) onto hematite and goethite colloids in a synthetic J-13 water that consisted of only sodium bicarbonate in solution.
- Am^{+3} sorbed rapidly (within a few hours) and quite strongly onto hematite, montmorillonite, and silica colloids.
- Np^{+5} sorbed relatively slowly onto hematite, montmorillonite, and silica colloids, taking a day or two to reach maximum sorption levels. Sorption of Np^{+5} onto these colloids was also much lower (lower K_d values) than for Pu and Am.
- U^{+6} sorbed relatively weakly to hematite, montmorillonite, and silica colloids, although maximum sorption levels were reached within a day or so.

Interestingly, Pu^{+5} sorption rates onto montmorillonite colloids in Well U-20WW water seem to be significantly slower (5 to 10 days) than sorption rates onto these same types of colloids in Well J-13 water (1 to 3 days). We have no explanation for this result because the two well waters are quite similar in composition. There may be a significant influence of a minor constituent present in one of the waters that is not present in the other, or there could be some differences in the montmorillonite colloids used in the different experiments.

From a practical standpoint, radionuclide sorption rates onto colloids are probably less important for CAU-scale modeling than distribution coefficients (K_d values)

and desorption rates. Transport predictions will be relatively insensitive to whether sorption occurs over a matter of hours or a matter of weeks when time scales of interest are many years. However, relative sorption rates onto different colloids may be important from the standpoint of determining which types of colloids radionuclides tend to be associated with. If several different types of colloids are present, radionuclides will, for a while, tend to be preferentially sorbed onto colloids that they sorb onto fastest, even if there are other colloids present that ultimately have larger distribution coefficients (because of slower desorption rates). It is recommended that sensitivity studies be conducted using CAU-scale models to determine how sensitive transport predictions are to relative radionuclide sorption and desorption rates onto colloids.

11.5.2.3 Radionuclide Desorption Rates from Colloids

Far fewer studies have been conducted to determine radionuclide desorption rates from colloids than sorption rates onto colloids. UGTA and Yucca Mountain data exist only for Pu starting as either Pu⁺⁴ or Pu⁺⁵. Kersting et al. (2002a and b) report very slow desorption rates of Pu⁺⁴ from clinoptilolite colloids at pHs ranging from 4 to 10. Total desorption over a 7-month period was 2 to 8 percent of the Pu that had sorbed.

In UGTA experiments at LANL, desorption rates were measured for Pu⁺⁵ sorbed onto montmorillonite and silica colloids, and also for Pu⁺⁴ sorbed onto clinoptilolite colloids (obtained from LLNL). These experiments were conducted at approximately 20°C in well water from U-20WW. In all cases, desorption rates were slow, although the results were mixed as to exactly how slow for the montmorillonite colloids (Reimus et al., 2002b). In some experiments, approximately 25 percent of the sorbed Pu desorbed in 7 to 11 months, and in other experiments only approximately 1 to 2 percent desorbed in 1 to 4 months. Desorption of Pu from silica colloids ranged from 20 to 30 percent in 7 to 11 months. Desorption of Pu⁺⁴ from clinoptilolite was slow, consistent with the LLNL results, with only 3 to 4 percent of the Pu desorbing in approximately 4 months. The inconsistencies in the montmorillonite results may be the result of using several different batches of montmorillonite colloids that were prepared from two different sources. Some of the differences might also be the result of starting desorption after different time periods of sorption in different experiments. Montmorillonite desorption experiments started after longer sorption time periods tended to have lower amounts and rates of desorption.

Montmorillonite, silica, and clinoptilolite colloids with Pu sorbed onto them were injected into naturally-fractured cores from Pahute Mesa in experiments at LANL between 1999 and 2001 (Reimus et al., 2002b). Interestingly, apparent Pu desorption rates from both montmorillonite and silica colloids were one to two orders of magnitude faster in the fractures than in the batch experiments described in the previous paragraph (the same Pu-colloid solutions were used in both experiments) (Reimus et al., 2002b). Pu desorption from the clinoptilolite colloids, on the other hand, was essentially undetectable, consistent with the batch experimental results. The enhanced desorption rates for the montmorillonite and silica colloids were interpreted as being the result of collisions between the

colloids and the fracture surfaces, which offered opportunities for direct transfer of Pu from the colloids to the fracture surfaces, a process that was absent in the batch experiments (Reimus et al., 2002b). The fracture surfaces, which were coated with manganese-oxides in two of the four fractures and had other mineral coatings in the other two, apparently had a greater affinity for the Pu than the montmorillonite and silica colloids. However, in the case of the clinoptilolite colloids, the Pu apparently had a greater affinity for the colloids than the fracture surfaces. These results indicate that results from batch sorption and desorption experiments may not necessarily be directly transferable to modeling of colloid-facilitated transport in real fracture systems.

In YMP experiments, desorption rates have been measured for Pu⁺⁵ and Pu⁺⁴ (colloidal) from hematite, goethite, montmorillonite, and silica colloids over a 268-day period (Lu et al., 1998a). These experiments were conducted at approximately 20°C, with 200 mg/L colloids in J-13 well water, and in ambient LANL atmosphere. The experiments were also conducted with sequential additions of fresh Pu-free water to the colloids at 2, 15, 50, 86, 107, 128, 150, 212, and 268 days (with removal and analyses of the solutions that had been in contact with the colloids at each of these times). This experimental method is in contrast to the methods used for the UGTA batch experiments where fresh solution was never added to the colloids after extracting water for a desorption measurement (i.e., only one desorption step, although measurements were made for several different contact periods). [Figure 11-13](#) presents the results of Yucca Mountain Pu desorption experiments in which Pu⁺⁵ was sorbed onto smectite and silica colloids for six days, the Pu was then desorbed in multiple batch steps in which Pu-free water was placed in contact with the colloids. The experiments were conducted at room temperature in J-13 well water (Lu et al., 1998b) and Pu was initially introduced as Pu⁺⁵ in solution. The Yucca Mountain results are summarized as follows:

- Less than 0.02 percent of the sorbed Pu⁺⁵ and Pu⁺⁴ desorbed from the hematite colloids.
- Less than 1 percent of the sorbed Pu⁺⁵ and Pu⁺⁴ desorbed from the goethite colloids.
- Pu⁺⁵ desorption from montmorillonite colloids was less than 1 percent after 268 days, but Pu⁺⁴ desorption from these colloids exceeded 10 percent after 150 days.
- Much of the desorption of Pu⁺⁵ and Pu⁺⁴ from silica and smectite colloids occurred early in the experiments, with a tendency to reach a desorption plateau later in the experiments (see [Figure 11-13](#)). Extrapolation of the results could lead one to conclude that some of the Pu sorption may be irreversible, even onto silica colloids that have relatively low measured K_d values.

The last bullet suggests that a multiple sorption site model may be appropriate for Pu sorption onto colloids. Some of the sites appear to be associated with relatively rapid desorption, while others may essentially behave as irreversible or very

Figure 11-13
Yucca Mountain Pu Desorption Experiments using Smectite and Silica Colloids
(Lu et al., 1998b)

slowly reversible sites. The time-scale of transport should dictate if the reverse rate is treated as effectively irreversible or slowly reversible. A two-site sorption model resulted in significantly improved model fits to the sorption and desorption data from the UGTA batch experiments, particularly in the case of the montmorillonite and silica colloids (Reimus et al., 2002b). Desorption experiments reported by Lu and Reimus (2003) indicate that long-term desorption rates of 0.35 yr^{-1} for smectite colloids and 0.12 yr^{-1} for silica colloids would be appropriate for systems with relatively long transport time scales.

The data of Lu et al. (1998a and b) are consistent with at least partial reversibility of actinide sorption onto colloids. However, the data of [Figure 11-13](#) suggest that much of the sorbed Pu may either be irreversibly sorbed or have very slow desorption kinetics. The fracture data are probably more applicable than the batch data because of the presence of minerals that can compete with the colloids for sorption, which is consistent with the real system.

11.5.2.4 Recommendations for Radionuclide Sorption and Desorption Rates From Colloids

In this section, we present ranges of recommended rate constants for actinide sorption onto and desorption from inorganic colloids in NTS waters (either J-13 or U-20WW well waters) at approximately 20°C. Normally, the sorption rate constants, k_p , would be expressed in units of (g water)/(g colloid-hr), and the actual rates would then be a function of colloid concentrations and actinide concentrations in solution (a linear dependence on both assuming a first order reaction in each). However, we abandon this convention in favor of presenting rate constants in units of 1/hr so that the reader can gain an immediate appreciation of approximate time scales of sorption ($1-e^{-1}$ of the radionuclide mass should be sorbed after $1/k_p$ hrs). Rate constants can be quickly converted between the two conventions by simply multiplying the conventional rate constant by the colloid mass concentration in solution or dividing the latter rate constant by the colloid concentration.

Table 11-4 provides ranges of actinide sorption and desorption rate constants onto colloids from batch experiments and fracture transport experiments (Pu only) conducted for the UGTA and Yucca Mountain projects. It is apparent that the Pu desorption rate constants for montmorillonite and silica colloids are significantly greater in the fracture experiments than in the batch experiments, as discussed in the previous section.

11.5.3 Data Limitations

It is important to recognize that the data in Figure 11-11 and Table 11-4 reflect only general trends observed in sorption and transport experiments; they do not account for the possibility of multiple types of sorption sites with different sorption strengths on colloids. The desorption rate constants in Table 11-4 should be considered upper bounds because it is possible that some sites may behave as essentially irreversible sites with very low or zero desorption rates. The vast majority of batch experiments conducted to date have not been designed to explicitly investigate this possibility, although the desorption results shown in Figure 11-13 clearly suggest it. A small amount of desorption occurring early in a batch test will tend to skew estimates of desorption rate constants to large values that may apply to only a small percentage of sorption sites.

On the other hand, batch experiments conducted to date also do not account for potential desorption that may occur when other natural mineral surfaces are present to compete with the colloid surfaces for actinides (as in the fracture transport experiments or a real fracture system). We recommend that sensitivity studies using CAU-scale models be conducted using desorption rate constants that extend well beyond the ranges in Table 11-4.

11.5.4 Scaling Considerations

An important scaling consideration for actinide distribution coefficients and sorption/desorption rates onto colloids is the question of how desorption rate constants scale with time (or alternatively, how reversible actinide sorption onto colloids is). The experimental results shown in [Figure 11-13](#) suggest that there may be a significant fraction of Pu that desorbs much more slowly from colloids than the initial desorbing mass fraction. In effect, the Pu desorption rates appear to decrease with time, although the observed behavior could also be explained by multiple sorption sites with different sorption strengths or degrees of reversibility. Such desorption behavior could have a profound impact on predictions of colloid-facilitated transport at CAU scales.

Another important “scaling” consideration is actinide sorption and desorption behavior on colloids in the presence of sorbing fracture surfaces (as opposed to being in the presence of only nonreactive test tube walls in batch sorption/desorption experiments). The significant differences between the batch and fracture transport experimental results indicated in [Table 11-4](#) clearly suggest that batch sorption/desorption test results should be very cautiously applied in field-scale fracture transport modeling exercises.

12.0 References

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Appendix A

Hydrostratigraphic Model Supporting Information and Groundwater Aqueous Geochemistry Data

A.1.0 Description of the Frenchman Flat Alternative HSU Models

Multiple hydrostratigraphic models have been created to address uncertainties within the Frenchman Flat flow system. The flow system contains the Frenchman Flat CAU (the site of 10 underground nuclear tests) along with the HSUs through which the radionuclides from these tests could potentially leave the Frenchman Flat underground test areas. The flow system includes areas in and immediately east of the NTS. A summary description is provided here. The report titled: *A Hydrostratigraphic Model for the Groundwater Flow and Contaminant Transport Model of Corrective Action Unit 98: Frenchman Flat, Nye County, Nevada* (BN, 2004) provides more detail.

Each of the alternative hydrostratigraphic models honor the data available, with differences between the models representing differences in interpretations of various features described by the data. Thus, each alternative model can be considered a possible representation of reality. The original list of alternatives was developed by an alternative scenario working group, under the auspices of the TWG. The complete list included 30 “alternative scenarios” (Table A.1-1). The list of 30 “alternative scenarios” was then distilled into four groups based upon the action deemed needed. The four groups were as follows:

- Group A: Recommended changes to the base model.
- Group B: Viable alternative scenarios.
- Group C: Proposed alternatives that would be better addressed during the hydromodeling phase rather than as alternatives to the geologic framework model.
- Group D: Suggested alternatives that were deemed to be of low priority or not necessary to model at this time.

The final listings for Group A, B, and C, based on the work of the alternative scenario working group, were as follows (note that because Group D scenarios are considered to be of lesser consequence to the potential mobility of the radionuclides from the Frenchman Flat test sites, they are not presented in this report).

Group A - Recommended Changes to the Base Model

- Subdivide the alluvial section.
- Portray the basalt lava flow aquifer as smaller and discontinuous flows.

Table A.1-1
Abridged List of Alternative Scenarios for the Frenchman Flat 3-D Hydrostratigraphic Model
(Page 1 of 3)

Alternative	Priority Group	Comment
1.0 HYDROSTRATIGRAPHY-RELATED ALTERNATIVES		
1.1 Alternatives to Simplify Hydrostratigraphy		
1.1.1 Simplify HSUs above the water table	D ^a	Can HSUs in the unsaturated zone be lumped, simplified, or ignored? This would affect the outcrop area in the northern portion of the model.
1.1.2 Decrease the depth of the model	D	Is there any merit in raising the bottom of the model? Work on the regional model demonstrated that even after removing the lowest 2 km (1.2 mi) from the bottom of the model, there was no difference in the outcome compared to the original model. Conductivity below about 3,000 m may be negligible. The elevation of the bottom of the framework model is now consistent with the regional model.
1.2 Alternatives to Add Hydrostratigraphic Detail		
1.2.1 Differentiate units of the Lower Tuff Confining Unit (LTCU)	D	Hydraulic conductivity of the several interbedded ash-flow tuff units within the LTCU may be worth considering (e.g., the Bullfrog Tuff at ER-5-4#2).
1.2.2 Subdivide the alluvium based on relative abundance of reactive minerals	C ^b	Is there enough information (e.g., in Carle et al., 2002; Warren et al., 2002; Zavarin et al., 2004), and are the differences significant and/or predictable enough to warrant subdividing these units? Perhaps this should be a separate sub-CAU-scale model.
1.2.3 Subdivide the Volcaniclastic Confining Unit (VCU) in the southern portion of the model	C	Although dominated by fine-grained clastics, the VCU also includes lenses of gravel and thin freshwater carbonate beds. It might be possible to add more geologic detail (in a conceptual manner), but almost no subsurface data and no hydrologic data are available.
1.2.4 Maximize detail within 1,000 m (3,280 ft) of the water table	D	Will small differences at, or just beneath the water table make significant differences in the flow and transport modeling results (e.g., raise or lower an HSU, or, add or remove HSUs)?
1.2.6 Vary the Paleozoic stratigraphy	D	Would occurrences of the Dunderberg Shale or Eureka Quartzite alter flow in the LCA?
1.2.7 Basalt-flow geometry	A ^c D	a. The basalt is modeled as a continuous unit from ER-5-3 to the basin-forming faults to the east (a "worst-case scenario"). What if this basalt is dissected by erosion, faulted, or composed of separate lobes? b. How would a basalt dike affect groundwater flow? What is the geometry and nature of a basalt flow source? Can we define the hydrologic properties of such a thin tabular body?
1.3 Alternatives Addressing Different Distributions for Pre-Tertiary HSUs		
1.3.1a Outcrop of Paleozoic carbonate rocks; LCA versus LCA3?	D	These outcrops are currently modeled as LCA. Should/could they be LCA3?
1.3.1b Vary the occurrence of the LCA3 and UCCU	D	Could the LCA3 and UCCU be present in other parts of the model area (e.g., south of the Cane Spring fault)?
2.0 STRUCTURE-RELATED ALTERNATIVES		
2.1 Simplify the structural model	D	Omit all but the most profound structures and faults.
2.2 Remove faults along edge of model	D	Remove faults in the southeast corner of the model.
2.3 Add More Structural Detail		
2.3.1 Faults	C	Add width to faults, modifying them from simple two-dimensional surfaces to a 3-D feature having some width. Can we predict where and why they might be a barrier and/or conduit to groundwater flow?

Table A.1-1
Abridged List of Alternative Scenarios for the Frenchman Flat 3-D Hydrostratigraphic Model
(Page 2 of 3)

Alternative	Priority Group	Comment
2.3.2 Add more Tertiary faults or fault zones	D	Perhaps begin by adding more of the mapped faults (shown on Slate et al. [1999] or the individual USGS quadrangle maps). (Although, most reviewers thought that structurally the model contained the appropriate level of detail.)
2.3.3 Extend the CP thrust fault south of the Cane Spring fault	D	A component of 1.3 above. The CP thrust is a poorly characterized, west-to-northwest-vergent thrust fault, that appears to be mostly outside the boundaries of the model area. Is it critical to add this complexity to the northwest corner of the model? Could the fault be elsewhere, too? See 1.3.1a and 1.3.1b.
2.3.4 Explore fault related groundwater pathways	B ^d (also C)	Consider increasing or decreasing fault displacements so aquifers are juxtaposed across faults. Conversely, if aquifers are juxtaposed, adjust relative fault displacement to prevent aquifer-aquifer juxtaposition. Deliberately juxtapose aquifer units across faults. Candidates for such adjustments would include the basin-forming faults in the east.
2.3.5 Other fault variations	C	Model faults as a zone with multiple planes. Typically, faults have been modeled as a single plane.
2.4 Develop Different Structural Scenarios		
2.4.1 Vary fault dips	C	The basin-and-range normal faults are modeled using an 75-degree dip. Varying fault dips would present more consequences in the source areas, where fault proximity to working points is important. This might be better addressed in sub-CAU-scale models.
2.4.3 Vary the depth to basement rocks	D	The uncertainty in depth to basement based on geophysical data (gravity) is roughly 300 m (1,000 ft). This may not be geologically permissible in some areas. And where it is possible, what units would be thinned or thickened?
2.4.4 Explore variations of the Cane Spring fault	B	This strike-slip fault bounds the southeast side of the CP basin. It seems to end at the Massachusetts Mountain/CP Hogback juncture. Could it control deep inter-basin flow from Yucca Flat, or relatively shallow recharge from Barren Wash?
2.4.5 Vary the geometry/position of the Rock Valley fault	D	This northeast-southwest striking strike-slip fault is intimately related to basin formation. Does it also control groundwater flow out of Frenchman Flat?
2.4.6 Vary displacement on basin-forming faults	D	Distribute displacements along basin-forming faults along east side to better fit gravity data. The emphasis here (as apposed to 2.3.4) is to more closely match the gravity data.
2.5 Other Structure-Related Alternatives		
2.5.1 "Smooth" versus "rough" HSU surface	D	Computer idiosyncracies have produced "hills" and "indentations" on HSU surfaces where none were intended. Does it matter? A rough surface might better approximate the effect of faulting (not represented now in the model).
2.5.2 Consider defining basin/slopes with faults	D	The UGTA base model portrays many of the central basin gravity lows as a moncline-type structure and not half-grabens related to basin-and-range extension (e.g., northeast of the Well Cluster ER-5-4). Are there more faults (possibly hydrologically significant) that are not discernable with geophysics?
2.5.4 Explore variations of the accommodation zone between Frenchman and Yucca Flat	C	This feature appears as a gravity high between two extensional basins. How does this area effect inter-basin groundwater flow?
2.5.5 Remove the detachment fault	B	Model volcanics in the northern portion of basin as moderately dipping surfaces to the south.
3.0 HYDROLOGIC ALTERNATIVES		
3.1 Account for lower hydraulic heads at Water Wells 5a and 5c	B	These two wells show a significant downward gradient. This scenario will be addressed with alternative 2.3.4.

Table A.1-1
Abridged List of Alternative Scenarios for the Frenchman Flat 3-D Hydrostratigraphic Model
(Page 3 of 3)

Alternative	Priority Group	Comment
3.2 Consider effect on the CAU boundary of contaminated water flowing into Frenchman Flat from Yucca Flat	C	Model the case in which contaminated water is already present in the regional carbonate aquifer, and is flowing into the Frenchman Flat CAU from Yucca Flat.
3.3 Consider the effect of significant groundwater flux from the northwest	C	Groundwater levels in CP basin are considerably higher than in Yucca or Frenchman Flat. Model the inflow of significant uncontaminated water from the CP basin northwest of Frenchman Flat (ultimately from Mid Valley via Barren Wash).
3.4 Consider the effect of significant groundwater from the east	C	The Phase I Regional Model indicates significant interbasin flow from the east and into Frenchman Flat. Model the inflow of significant uncontaminated water from the east (e.g., Pahrnagat Valley).

^aSuggested alternatives that were deemed to be of low priority or not necessary to make at this time.

^bProposed alternatives that would be better addressed during the hydro modeling phase rather than as alternatives to the geologic framework model.

^cRecommended and implemented changes to the base model.

^dViable alternative scenarios.

- Use the gravity inversion model only as a rough guide.
- Modify CP basin.

Group B - Viable Alternative Scenarios

- Portray the basalt HSU as a single, extensive, continuous lava flow extending eastward to the basin-forming fault (1.2.7, in [Table A.1-1](#)).
- Remove the detachment fault (2.5.5).
- Vary displacement of the basin-forming faults to force juxtaposition of HSUs (2.3.4).

Group C - Alternatives to Address During the Hydrologic Modeling

- Vary hydraulic properties for the alluvial HSUs (1.2.2).
- Model faults as 3-D features having the same width (2.3.1 and 2.3.5).
- Subdivide the volcanoclastic confining unit (VCU) (1.2.3).
- Explore variation of the accommodation zone between Frenchman Flat and Yucca Flat (2.5.4).
- Consider effect of contaminated interbasin flow from Yucca Flat (3.2).
- Consider effect of groundwater influx from the northwest (3.3).

- Consider effect of groundwater influx from the east (3.4).
- Vary hydraulic properties for the HSUs.

The alternatives listed in Group A were considered to be of high priority and reflected the need to update the HSU model in order to examine the influence of the alternative interpretations on radionuclide mobility. The Frenchman Flat section of the base HSU model has been refined and modified by applying to it the recommendations presented in Group A. The regional flow model, updated to include the changes in structure associated with the updated Frenchman Flat geology, has been calibrated using the ModFlow 2000 in conjunction with PEST.

The alternatives posted in Group B represent the important alternatives that for full consideration would entail major modifications of both the HSU and numerical models. Associated calibrations would also become major efforts. A full calibration effort on all the alternatives would be hard to complete within the administration constraints associated with the efforts. The groundwater flow model grid for the base HSU geologic model will be designed to allow the modeling of the alternatives through variation of hydraulic properties.

Group C alternatives are important and can be implemented in the flow model without the need to update the HSU model. Group C alternatives will be simulated as part of the FEHM Frenchman Flat modeling effort.

A.2.0 Aqueous Geochemistry

This section contains a summary table of Frenchman Flat water chemistry data. The values in [Table A.2-1](#) are representative water chemistry values with the best major ion charge balance.

Table A.2-1
Frenchman Flat Groundwater Chemistry and Well Information

SITE_ID	UTM Easting (m) ^a	UTM Northing (m) ^a	Total Depth (m bgs) ^b	HSU ^c	Sample Collection Date	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Silicon dioxide (mg/L)	pH	Temperature (°C)	TDS Calculated (mg/L) ^d	Saturation Index (Calcite) ^e	Saturation Index (Dolomite) ^f	Data Source ^g
ER 5-3 #2	594,545	4,081,317	1732.2	LCA	5/17/2001	77	29	130	17	634.4	0	1.2	39	69	30.0	6.67 ^h	33.8 ^h	708	0.54	1.09	SNJV
ER 5-3 (Composite)	594,575	4,081,315	794.3	OAA (upper) TM-WTA (lower)	3/29/2001	13	3.4	58	4.7	170.8	0	2.8	15	41	51.4	8.25 ^h	30 ^h	272			SNJV
ER 5-3 upper	594,575	4,081,315	794.3	OAA	7/17/2001	1.1	0.1	130	5.9	134	60	5.4	14	36	55.6	9.29	26.9	340			SNJV
ER 5-4 #2	592,450	4,075,665	2113.6	LTCU	11/21/2002	0.6	0.15	310	7	366	22	61	52	120	70.6	8.7 ^h	38.1 ^h	754	-0.43	-1.02	SNJV
ER 5-4	592,450	4,075,696	1137.5	AA	7/5/2001	2	0.05	180	12	256	31.2	6.6	26	120	79.2	8.71 ^h	30.2 ^h	563			SNJV
RNM-1	592,132	4,075,693	396.8	AA	7/10/1974	15	4.5	61	7.9	171	0	0.6	17	33	72	8.2	26 ⁱ	296			USGS
RNM-2s	592,134	4,075,477	352.4	AA	10/11/1999	17	5.6	63	9.2	168	0	0.41 ^j	13.7	37	79.6 ^j	8.2	24.6	309			LLNL
TW-3	601,939	4,074,017	566.9	LCA	6/16/1990	49	19.7	79.6	9.18	343	0	1.5 ^k	23.2	66.8	17.4	7.4	34.5	436	0.22	0.48	DRI
TW-F	578,870	4,068,349	1036.3	LCA	3/12/1980	44	16	64	9.7	297	0	3	20	75	38	7.35	64	415			USGS
UE-11a	593,171	4,082,195	426.7	TM-WTA	8/26/1988	9.1	2.72	106	4.66	217	0		24.6	59.9	58	8.08		373			DRI
UE-5 PW-1	593,656	4,078,714	255.7	AA	5/26/1993	14.9	4.75	57	6	145	0	1.28	12	34.3	53.7	8.67	22.5	255			LLNL
UE-5 PW-2	593,670	4,080,138	280.4	AA	5/25/1993	19.2	4.9	56	6	173	0	1.13	15.2	26.6	31.2	8.52	23.3	246			LLNL
UE-5 PW-3	591,708	4,080,410	291.1	TM-WTA	8/9/2000	15.8	5.8	55.1	4.3	161	0	1.09	8.6	32.2	65.2	8.28	21.5 ^h	268	0.18	0.22	DRI
UE-5c WW	590,978	4,077,006	817.5	AA (upper) LTCU (lower)	8/8/2000	7	1.9	87.7	6.3	184	14.4	1.91	12.1	45.2	76.8	8.51	25.8 ^h	336			DRI
UE-5n	592,627	4,075,285	514.2	AA	4/19/2001	8.6	2	76	8	162	0	0.7	12.9	32	58.6	8.7	23	279			LLNL
WW-1	597,790	4,074,404	265.2	AA	4/21/1966	5.5	1.6	73	9	165	0	2.1	5.9	38	71	7.8	24.4	287			USGS
WW-4	586,962	4,084,576	450.8	TM-WTA	5/20/1993	23	5.9	48	5	148	0	0.87	15.21	41.66	58.6	7.39	25.3	271			LLNL
WW-4A	586,648	4,084,372	462.1	TM-WTA	8/8/2000	23.3	7.6	50.3	5.4	164	0	0.78	11.7	41.1	69.1	7.91	26.5 ^h	291			DRI
WW-5A	592,983	4,070,371	277.4	AA	8/14/2000	2	0.8	136	5.2	283	22.6	1.17	10.1	28.3	45.7	8.91	22.3 ^h	381			DRI
WW-5B	591,986	4,073,103	274.3	AA	8/7/2000	7.6	2.5	94.1	12	177	2.2	0.8	22.8	58.5	63.9	8.45	24.6 ^h	351			DRI
WW-5C	592,472	4,071,752	365.8	AA	8/7/2000	2.1	0.7	137	6.8	291	17.6	1.13	10.4	29.7	59.8	8.74	28.2 ^h	401			DRI
WW-C	588,208	4,086,130	518.5	LCA	9/11/1990	74.5	28.2	126	13.2	584	0	1.1	33.2	65	30.6	7.85		663	0.92	1.77	DRI
WW-C1	588,157	4,086,103	502.9	LCA	9/25/1996	73	27	120	14	580	0	1.2	33	66	60	6.7	37	683	-0.07	-0.11	USGS

^aUniversal Transverse Mercator Zone 11, North American Datum 1927 in meters; source is the UGTA Borehole Index Database.
^bTotal drilled depth in meters below ground surface (SNJV, 2004).
^cPrimary hydrostratigraphic units (SNJV, 2004).
^dCalculated Total Dissolved Solids - Calculated as total concentrations of Ca, Mg, Na, K, Cl, SO₄, SiO₂, and 1/2 HCO₃ + CO₃.
^eSaturation Index for Calcite.
^fSaturation Index for dolomite.
^gSource of major ion, fluoride, silicon dioxide, temperature, and pH data (unless otherwise noted).
^hField Results were reported by LLNL.
ⁱWater temperature for RNM-1 was measured by LLNL on 6/28/2003.
^jSample collected from RNM-2S by LLNL on 7/10/2003 for Si and F analysis.
^kSample collected from TW-3 by the USGS on 5/10/1962 for F analysis.

Note: Blank cells indicate no data are available.

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Appendix B

Data Transferability Methodology Overview

B.1.0 Data Transferability

The recommended approach for determining the relative emphasis that should be assigned to the data is to use a weight and multiplier system. This approach is also recommended for datasets obtained within a CAU of interest because, even though all such data will come from a relevant geologic setting, some CAU-specific datasets should rightfully be assigned greater emphasis than others due to differences in measurement methods, data quality, and documentation quality. The weight and multiplier system is quite subjective, which is not particularly appealing from a scientific perspective, but it is consistent with the subjective nature of the data transferability process. The system and process ultimately rely heavily on the documentation of the rationale for weights and multipliers, which essentially provides the rationale for the transfer of data.

In the weight and multiplier system, weights are determined for datasets based on the relevance of the geologic setting to the CAU, and multipliers (factors that the total weight score is multiplied by to obtain an overall score) are assigned based on the measurement method, the quality of data reduction and analyses, and documentation quality. The overall score for a given dataset is the sum of the weights multiplied by the product of the multipliers. Datasets with poor geologic setting relevance, while they may still be transferred, are assigned lower weights so they ultimately “count less” in determining the final parameter distribution used in CAU-scale modeling. Likewise, datasets associated with measurement methods having large uncertainties or inappropriate scales, or datasets of low-quality or having poor documentation are assigned lower multipliers so that they count less in the final CAU-scale application.

The rationale for using both weights and multipliers is that the geologic setting relevance and the data quality are two separate criteria that are largely independent. Weights are used for geologic setting relevance because this is an overriding consideration in most cases. Datasets obtained from the best possible measurement method and having high-quality analyses and documentation should nevertheless be rejected if the geologic setting is inappropriate. In a system based entirely on weights, such datasets could potentially still be assigned a relatively high weight score even though they are not appropriate for the CAU of interest. Multipliers are assigned after weights are determined so that appropriate credit can be taken for the measurement method and data/documentation quality. Although datasets will seldom be rejected outright at this stage, very low multipliers can be assigned because of a highly uncertain measurement method or very poor documentation. The weights and multipliers have relative scales rather than absolute scales. For instance, if there are only two datasets being considered, then multipliers of 1.0 and 0.5 for these sets will have the same effect as multipliers of 0.2 and 0.1, respectively (i.e., the first dataset has a multiplier twice that of the

second set in both cases). These relative scales make it imperative that the rationale for weights and multipliers be clearly documented so that if additional data are later considered for transfer, they can be scored in a manner consistent with the previously transferred data.

This approach of “graded” transferability recognizes that most transfer decisions will not be a simple “yes or no,” but rather there will be varying degrees of relevance of datasets to a given CAU, as well as varying degrees of measurement and documentation quality. It also recognizes that, while the goal is to make objective decisions regarding data transferability, there are almost always subjective elements involved in these decisions.

[Section B.2.0](#) provides guidance for determining the relevance of geologic settings of datasets to NTS CAUs. [Section B.3.0](#) provides guidance for determining multipliers by ranking measurement methods, and evaluating data reduction and documentation quality. [Section B.4.0](#) addresses combining weights and multipliers to arrive at overall scores. [Section B.5.0](#) provides guidance for documenting the implementation of this process. [Section B.6.0](#) provides a discussion of the use of weights and multipliers in downstream analyses. Note that the guidance provided in these sections can be deviated from if there are justifiable reasons for doing so. However, such deviations should be documented in the rationale for the selection of weights and multipliers (see [Section B.5.0](#)).

B.2.0 Weights (Relevance of Geologic Setting)

Note that the overall weight for a dataset is the sum of the weights for each of the three criteria below.

1. Rock Type

If the rock type is significantly different from the type in the CAU, then the data should not be considered for transferability unless there is some unusual circumstance. That is, an overall weight score of zero should be assigned so that regardless of the measurement method or data quality, the dataset is rejected. If the rock type is the same, then the analyst should proceed to Step 2. However, the analyst may reject data at this point even if it is from the same rock type because of an obvious difference in geology. For instance, sandstone data should not be considered for limestone settings even though both rocks are nominally sedimentary. Also, glassy basalt data should not be considered for devitrified lava settings even though both rocks are volcanic lavas.

2. Deposition and Alteration History

Similarities and differences in deposition history and geochemical/hydrothermal alteration should be evaluated and weights assigned using a sliding scale of 0 to 0.7, with 0.7 indicating a very similar deposition and alteration history. Any score near zero should prompt the analyst to question whether the data should even be considered for transferability. This step represents a second point where data could potentially be rejected, with the examples above applying here as well. However, once data makes it past this step, it should no longer be rejected outright; instead, it should be assigned a low weight if it has questionable relevance to the CAU. Further guidance on how to assign sub-weights within the 0- to -0.7 sliding scale is not provided because of the multiplicity and complexity of considerations involved, as well as the desire to give the analyst(s) flexibility for a wide range of potential situations. However, the burden is on the analyst to document the rationale for the assigned weight.

3. Structural Setting and Mechanical Alteration

Similarities and differences in structural setting and mechanical alteration should be evaluated and weights assigned using a sliding scale of 0 to 0.3, with 0.3 indicating a very similar structural setting. In this case, a score near zero should not necessarily disqualify a dataset from consideration. Again, the analyst is encouraged to use the formal statistical methods of addressing similarity discussed in [Appendix A](#) to help determine and document a score.

Note: If CAU-scale models are developed that include domains of different rock types, deposition/alteration histories, and/or structural settings, individual datasets

can be considered for each model domain and weights can be assigned on a case-by-case basis for each domain. For instance, given the concept of multiple HSUs in flow and transport models, a particular dataset could be “transferred” to different HSUs, with a different weight assigned to each HUS. This same approach can be extended to situations where HSUs contain multiple rock types or multiple deposition/alteration histories; the data could be transferred with different weights assigned to different portions of the HUS. Also, if different structural features are distinguished in model domains (e.g., faulted and unfaulted regions), datasets could be weighted differently for these different regions.

B.3.0 Multipliers (Measurement Method and Quality of Analyses and Documentation)

Note that the overall multiplier for a dataset is the product of the multipliers for each of the three criteria listed below.

1. Measurement Method

Measurement method considerations include the quality and uncertainty of the method as well as the scale of the measurement. The approach taken for relative rankings of measurement methods should be documented by the analyst. Larger numbers should reflect what is considered to be a “better” measurement.

2. Data Reduction and Analysis Methods

Data reduction and analysis methods are evaluated independently of the type of measurement being evaluated. However, the analyst must be familiar with state-of-the-art methods in order to make an evaluation. The following multipliers apply (a sliding scale can be employed to allow for a continuum of scores):

- Current and widely-accepted data reduction and analysis method with reputable and traceable calibration information – 1.0
- Good method, but calibration information is suspect – 0.5
- Based on older or less widely-accepted methods, but calibration information is good – 0.5
- Both methods and calibration information are suspect – 0.2

Note: Score for any poorly-analyzed dataset can be raised if the raw data are available and are re-analyzed using state-of-the-art methods. However, it is not possible to raise a score above 0.5 for datasets with poor calibration information (unless other information can be used to effectively “recalibrate” the measurements).

3. Quality of Documentation

Documentation quality is also evaluated independently of the type of measurement being evaluated. The following multipliers apply (a sliding scale can be employed to allow for a continuum of scores):

- Good (thorough, easy to follow, traceable) – 1.0

- Appearing in a reputable journal or peer-reviewed report, but otherwise lacking in thoroughness – 0.6
- Poor – 0.3

Note: It is often the case that poor documentation results in the inability to evaluate the data reduction and analysis method (including the calibration information) for a given dataset. Thus, poorly-documented estimates can, in effect, be doubly penalized as a result of both poor documentation scores and poor data reduction and analysis scores.

B.4.0 Overall Scores

The overall score for a given dataset is taken to be the sum of the weights multiplied by the product of the multipliers. For example, if a dataset is assigned component weight scores of 0.5 and 0.2 (for categories 2 and 3, respectively, in [Section B.2.0](#)), the total weight score is 0.7. If this dataset is then assigned multipliers of 0.8, 1.0, and 0.6 (for the three respective categories in [Section B.3.0](#)), the total multiplier score is $0.8 \times 1.0 \times 0.6 = 0.48$. The overall score is then the product of the weight and multiplier scores, or $0.7 \times 0.48 = 0.336$.

B.5.0 **Documentation**

For each dataset that is considered for use in CAU-scale flow and transport modeling, the following information should be documented:

- For rejected data, rationale for rejection (i.e., rationale for assigning a total weight score of zero).
- For accepted data, a summary of the data.
- The scores for each weight and multiplier category listed in [Section B.2.0](#) and [Section B.3.0](#).
- The rationale for the scores for each weight and multiplier category listed in [Section B.2.0](#) and [Section B.3.0](#).
- The overall weight and multiplier score for the dataset.

A format for documenting this information is not specified, but each of the above elements should be addressed.

Documentation is very important because it is here that the weight and multiplier scores are justified. Assigning the weights and multipliers using the guidance and relative scales provided in [Section B.2.0](#) and [Section B.3.0](#) forces the analyst to consider the applicability and relative merits of each dataset. It is not so important that the analyst follow this guidance to the letter, but rather it is important that the analyst documents and justifies the assigned weights and multiplier scores. Documentation ensures that the analyst's decisions are traceable and easy to review. It also ensures that if additional data are later considered for transfer, these data are scored in a manner consistent with the scoring of previously transferred data.

B.6.0 Use of Weights and Multipliers in Downstream Analyses

The data that are transferred to a given CAU (as well as CAU-specific data) can be used in many different ways in CAU-scale modeling. It is not the purpose of this document to recommend or exhaustively consider all the possible uses of data or the ways in which the combined weight and multiplier scores should be incorporated into these uses. Rather, a specific and relatively common usage of data is considered, and the manner in which combined weight and multiplier scores are incorporated into other uses can be inferred from this discussion.

It is a common practice to compile CDFs of parameter values that are randomly sampled in Monte-Carlo fashion in large-scale models to simulate overall system performance. These CDFs are intended to capture the variability and uncertainty associated with parameter values within the model domain. The large-scale models are typically executed many times so that representative sampling of the component CDFs is accomplished. Finally, a CDF of the model output/predictions is constructed from the multiple model runs to allow an assessment of uncertainty in overall system performance.

The suggested method of incorporating the combined weight and multiplier scores into a CDF is best illustrated by example. We assume that there are 3 datasets from which a total of 10 values of a given parameter have been obtained to represent a given CAU (this may be from only a certain HSU within the CAU, rather than a bulk value representing the entire CAU). The three datasets are generically described as follows (the values associated with each separate measurement are listed in parentheses):

- A laboratory dataset with four separate measurements on samples taken directly from the CAU (2, 3, 7, 7).
- A field dataset consisting of three measurements taken outside the CAU but in what is considered a similar rock type (2, 8, 5).
- A field dataset consisting of three measurements taken from within the CAU (2, 6, 6).

Without going into the details of how and why, the combined weight and multiplier scores in [Table B.6-1](#) are assigned to the data. Note that the combined scores for the CAU-specific laboratory measurements are all assigned the same value because these measurements are assumed to be conducted as part of a single set of measurements (for this example) using the same analysis method. They are also assumed to be documented in a single report. Using the same combined score

for multiple measurements generated within a single study is an acceptable practice when CAU-specific measurements are made in the study. When multiple non-CAU measurements are made within a given study, the weight values may vary for the different measurements because the geologic setting of the measurements may have different relevance to the CAU of interest, but the multipliers should be the same (because the same methods and documentation presumably apply to all measurements). Similarly, when measurements on CAU-specific materials are obtained in different investigations and at different times, the weight scores should be the same, but different multipliers can apply because of differences in analytical methods or documentation. Finally, when measurements are obtained on non-CAU materials in different studies and at different times, both the weight scores and multipliers can be different.

**Table B.6-1
Combined Weight and Multiplier Scores
for Hypothetical Parameter Data**

	Parameter Value	Combined Score
CAU Lab Measurements	2	0.5
	3	0.5
	7	0.5
	7	0.5
Non-CAU Field Data	2	0.3
	8	0.9
	5	0.6
CAU Field Data	3	1.0
	6	0.7
	6	1.2

In [Table B.6-1](#), the CAU field data were apparently obtained using different analysis methods or had different documentation quality because the scores are different. In the case of the non-CAU measurements, the scores are different either because of differences in the relevance of the geologic setting, differences in the analysis methods, differences in documentation quality, or any combination of these differences.

To construct a CDF from the data and combined scores of [Table B.6-1](#), it is necessary to sort the parameter values in ascending order and then add the scores in cumulative fashion for each successive value. The cumulative score for each value is then divided by the sum of the scores for all values to obtain an estimate of the cumulative probability for that parameter measurement. Thus, the probability of each parameter value is proportional to its combined score. The results of manipulating the data from [Table B.6-1](#) in the manner indicated above are shown in [Table B.6-2](#). [Figure B.6-1](#) shows the resulting CDF of parameter values.

For this example, the CDF does not appear to be heavily influenced by any single measurement or set of measurements. However, in some cases, a single “very

Table B.6-2
**Results of Manipulation of Data in [Table B.6-1](#) to Obtain
Cumulative Distribution Function of Parameter Values**

Sorted Parameter Value	Combined Score	Cumulative Score	Cumulative Probability
2	0.3	0.3	0.045
2	0.5	0.8	0.119
3	0.5	1.3	0.194
3	1.0	2.3	0.343
5	0.6	2.9	0.433
6	0.7	3.6	0.537
6	1.2	4.8	0.716
7	0.5	5.3	0.791
7	0.5	5.8	0.865
8	0.9	6.7	1

Figure B.6-1
Cumulative Distribution Function Associated With the Data of [Table B.6-1](#)

good” measurement may have a combined score equal to or greater than the sum of scores of all the other available data. In such cases, there will be a large jump in the CDF at the value corresponding to the “good” measurement.

This example also serves to illustrate the value of determining combined weight and multiplier scores for CAU-specific data in addition to non-CAU data. Even though the scores for CAU-specific data are not required to determine data transferability, they are essential for establishing a representative CDF.

If another method of data usage is employed in CAU-scale modeling, then the combined weight and multiplier scores should be used in some other manner to “weigh” the available datasets appropriately in the final analysis. The method(s) of translating combined scores into some measure of variability and/or uncertainty should be documented appropriately.

Finally, there are many considerations of variability and uncertainty in parameter values that are not effectively captured by the weight and multiplier system and that go beyond the scope of this document but should be addressed and documented by the analyst. For instance, because weights and multipliers are assigned using relative scales, a CDF generated with only a few data points, data of questionable relevance, and poor-quality measurement methods might look exactly the same as one with many data points, CAU-specific data, and high-quality measurements. However, even though these CDFs may look essentially the same, the uncertainty should be far greater and the confidence far less in the former distribution than the latter one. In general, uncertainty in distributions of parameter values should be considered greater for (1) less total data points, (2) less CAU-specific data, and (3) smaller values of the sum of combined scores divided by the total number of data points.

Appendix C

Description of BestFit Software

C.1.0 Introduction

A brief overview of the BestFit software is provided followed by detailed descriptions of the distributions used in this document. Detailed descriptions of the Bestfit software may be found in the user's manual (Palisade Corporation, 2002).

C.2.0 BestFit Software Overview

BestFit is a Windows program designed to find the distribution that best fits a given dataset. BestFit tests up to 28 different distribution types to find the best fit for the data. Results may be displayed as graphs or full statistical reports.

BestFit determines the optimal parameters for each distribution, performing three standard tests to determine the goodness of fit: Chi-squared, Anderson-Darling (A-D), and Kolmogorov-Smirnov (K-S). For a given dataset, the distribution fits are listed in order of goodness of fit.

BestFit fits to sample, density, or cumulative data. As many as 100,000 data points or pairs may be handled by BestFit. Outliers may be filtered out of the dataset. Parameter selection is performed using maximum-likelihood estimators and method of least squares.

The following distribution types are included in BestFit:

- BetaGeneral
- Binomial
- Chi-Square
- Error Function
- Erlang
- Exponential
- Extreme Value
- Gamma
- Geometric
- Hypergeometric
- Inverse Gaussian
- IntUniform
- Logistic
- Log-Logistic
- Lognormal
- Lognormal2

- Negative Binomial
- Normal
- Pareto
- Pareto2
- Pearson Type V
- Pearson Type VI
- Poisson
- Rayleigh
- Student's t
- Triangular
- Uniform
- Weibull

C.3.0 *Distribution Descriptions*

Detailed descriptions of the distributions used in this document are presented at the end of this section.

C.4.0 *References*

Palisade Corporation. 2002. "A Concise Summary of @Risk Probability Distribution Functions." Supplemental Document to *Guide to Using BestFit; Distribution Fitting for Windows*, Version 4.5 (included on the CD as part of the software package). Newfield, NY.

Description of Selected Probability Distribution Functions

This description of selected probability density distribution was extracted from the BestFit software user guide (Palisade, 2002).
The descriptions are provided verbatim.

Beta (Generalized)

RISKBetaGeneral($\alpha_1, \alpha_2, \min, \max$)

Parameters:

α_1	continuous shape parameter	$\alpha_1 > 0$
α_2	continuous shape parameter	$\alpha_2 > 0$
min	continuous boundary parameter	min < max
max	continuous boundary parameter	

Domain:

$\min \leq x \leq \max$	continuous
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Density and Cumulative Distribution Functions:

$$f(x) = \frac{(x - \min)^{\alpha_1 - 1} (\max - x)^{\alpha_2 - 1}}{B(\alpha_1, \alpha_2) (\max - \min)^{\alpha_1 + \alpha_2 - 1}}$$

$$F(x) = \frac{B_z(\alpha_1, \alpha_2)}{B(\alpha_1, \alpha_2)} \equiv I_z(\alpha_1, \alpha_2) \quad \text{with } z \equiv \frac{x - \min}{\max - \min}$$

where B is the *Beta Function* and B_z is the *Incomplete Beta Function*.

Mean:

$$\min + \frac{\alpha_1}{\alpha_1 + \alpha_2} (\max - \min)$$

Variance:

$$\frac{\alpha_1 \alpha_2}{(\alpha_1 + \alpha_2)^2 (\alpha_1 + \alpha_2 + 1)} (\max - \min)^2$$

Skewness:

$$2 \frac{\alpha_2 - \alpha_1}{\alpha_1 + \alpha_2 + 2} \sqrt{\frac{\alpha_1 + \alpha_2 + 1}{\alpha_1 \alpha_2}}$$

Kurtosis:

$$3 \frac{(\alpha_1 + \alpha_2 + 1)(2(\alpha_1 + \alpha_2)^2 + \alpha_1 \alpha_2(\alpha_1 + \alpha_2 - 6))}{\alpha_1 \alpha_2 (\alpha_1 + \alpha_2 + 2)(\alpha_1 + \alpha_2 + 3)}$$

Mode:

$$\min + \frac{\alpha_1 - 1}{\alpha_1 + \alpha_2 - 2} (\max - \min)$$

$$\alpha_1 > 1, \alpha_2 > 1$$

min

$$\alpha_1 < 1, \alpha_2 \geq 1 \text{ or } \alpha_1 = 1, \alpha_2 > 1$$

max

$$\alpha_1 \geq 1, \alpha_2 < 1 \text{ or } \alpha_1 > 1, \alpha_2 = 1$$

Chi-Squared

$RISKChiSq(v)$

Parameters:

v

discrete shape parameter

$v > 0$

Domain:

$0 \leq x \leq +\infty$

continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{2^{v/2} \Gamma(v/2)} e^{-x/2} x^{(v/2)-1}$$

$$F(x) = \frac{\Gamma_{x/2}(v/2)}{\Gamma(v/2)}$$

where Γ is the *Gamma Function*, and Γ_x is the *Incomplete Gamma Function*.

Mean:

v

Variance:

$2v$

Skewness:

$$\sqrt{\frac{8}{v}}$$

Kurtosis:

$$3 + \frac{12}{v}$$

Mode:

$$v-2$$

$$\text{if } v \geq 2$$

$$0$$

$$\text{if } v = 1$$

Erlang

RISKErlang(m,β)

Parameters:

m	integral shape parameter	$m > 0$
β	continuous scale parameter	$\beta > 0$

Domain:

$0 \leq x < +\infty$	continuous
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Density and Cumulative Functions:

$$f(x) = \frac{1}{\beta (m-1)!} \left(\frac{x}{\beta} \right)^{m-1} e^{-x/\beta}$$

$$F(x) = \frac{\Gamma_{x/\beta}(m)}{\Gamma(m)} = 1 - e^{-x/\beta} \sum_{i=0}^{m-1} \frac{(x/\beta)^i}{i!}$$

where Γ is the *Gamma Function* and Γ_x is the *Incomplete Gamma Function*.

Mean:

$$m\beta$$

Variance:

$$m\beta^2$$

Skewness:

$$\frac{2}{\sqrt{m}}$$

Kurtosis:

$$3 + \frac{6}{m}$$

Mode:

$$\beta(m-1)$$

Exponential

RISKExpon(β)

Parameters:

β

continuous scale parameter

$\beta > 0$

Domain:

$0 \leq x < +\infty$

continuous

Density and Cumulative Functions:

$$f(x) = \frac{e^{-x/\beta}}{\beta}$$

$$F(x) = 1 - e^{-x/\beta}$$

Mean:

β

Variance:

β^2

Skewness:

2

Kurtosis:

9

Mode:

0

Extreme Value

RISKExtValue(a, b)

Parameters:

a continuous location parameter

b continuous scale parameter $b > 0$

Domain:

$$-\infty \leq x \leq +\infty$$

continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{b} \left(\frac{1}{e^{z + \exp(-z)}} \right)$$

$$F(x) = \frac{1}{e^{\exp(-z)}}$$

$$\text{where } z \equiv \frac{(x - a)}{b}$$

Mean:

$$a - b\Gamma'(1) \approx a + .577b$$

where $\Gamma'(x)$ is the derivative of the *Gamma Function*.

Variance:

$$\frac{\pi^2 b^2}{6}$$

Skewness:

1.139547

Kurtosis:

5.4

Mode:

a

Gamma

RISKGamma(α, β)

Parameters:

α	continuous shape parameter	$\alpha > 0$
β	continuous scale parameter	$\beta > 0$

Domain:

$0 < x < +\infty$	continuous
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Density and Cumulative Functions:

$$f(x) = \frac{1}{\beta \Gamma(\alpha)} \left(\frac{x}{\beta} \right)^{\alpha-1} e^{-x/\beta}$$

$$F(x) = \frac{\Gamma_{x/\beta}(\alpha)}{\Gamma(\alpha)}$$

where Γ is the *Gamma Function* and Γ_x is the *Incomplete Gamma Function*.

Mean:

$$\beta \alpha$$

Variance:

$$\beta^2 \alpha$$

Skewness:

$$\frac{2}{\sqrt{\alpha}}$$

Kurtosis:

$$3 + \frac{6}{\alpha}$$

Mode:

$$\beta(\alpha - 1)$$

if $\alpha \geq 1$

Not Defined

if $\alpha < 1$

Logistic

RISKLogistic(α, β)

Parameters:

α	continuous location parameter	
β	continuous scale parameter	$\beta > 0$

Domain:

$-\infty \leq x \leq +\infty$	continuous
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Density and Cumulative Functions:

$$f(x) = \frac{\operatorname{sech}^2\left(\frac{1}{2}\left(\frac{x - \alpha}{\beta}\right)\right)}{4\beta}$$

$$F(x) = \frac{1 + \tanh\left(\frac{1}{2}\left(\frac{x - \alpha}{\beta}\right)\right)}{2}$$

where “tanh” is the *Hyperbolic Tangent Function*.

Mean:

$$\alpha$$

Variance:

$$\frac{\pi^2 \beta^2}{3}$$

Skewness:

0

Kurtosis:

4.2

Mode:

α

Log-Logistic

$RISKLogLogistic(\gamma, \beta, \alpha)$

Parameters:

γ	continuous location parameter	
β	continuous scale parameter	$\beta > 0$
α	continuous shape parameter	$\alpha > 0$

Definitions:

$$\theta \equiv \frac{\pi}{\alpha}$$

Domain:

$$\gamma \leq x \leq +\infty \qquad \text{continuous}$$

Density and Cumulative Functions:

$$f(x) = \frac{\alpha t^{\alpha-1}}{\beta \left(1 + t^\alpha\right)^2}$$

$$F(x) = \frac{1}{1 + \left(\frac{1}{t}\right)^\alpha}$$

$$\text{with } t \equiv \frac{x - \gamma}{\beta}$$

Mean:

$$\beta \theta \csc(\theta) + \gamma \qquad \text{for } \alpha > 1$$

Variance:

$$\beta^2 \theta \left[2 \csc(2\theta) - \theta \csc^2(\theta) \right] \quad \text{for } \alpha > 2$$

Skewness:

$$\frac{3 \csc(3\theta) - 6\theta \csc(2\theta) \csc(\theta) + 2\theta^2 \csc^3(\theta)}{\sqrt{\theta} \left[2 \csc(2\theta) - \theta \csc^2(\theta) \right]^{3/2}} \quad \text{for } \alpha > 3$$

Mode:

$$\gamma + \beta \left[\frac{\alpha - 1}{\alpha + 1} \right]^{1/\alpha} \quad \text{for } \alpha > 1$$

$$0 \quad \text{for } \alpha \leq 1$$

Lognormal (Format 1)

$$RISKLognorm(\mu, \sigma)$$

Parameters:

μ continuous parameter $\mu > 0$

σ continuous parameter $\sigma > 0$

Domain:

$0 \leq x \leq +\infty$ continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{x\sqrt{2\pi\sigma'}} e^{-\frac{1}{2}\left[\frac{\ln x - \mu'}{\sigma'}\right]^2}$$

$$F(x) = \Phi\left(\frac{\ln x - \mu'}{\sigma'}\right)$$

$$\text{with } \mu' \equiv \ln\left[\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right] \quad \text{and} \quad \sigma' \equiv \frac{1}{2} \ln\left[1 + \left(\frac{\sigma}{\mu}\right)^2\right]$$

where Φ is the *Error Function*.

Mean:

μ

Variance:

σ^2

Skewness:

$$\left(\frac{\sigma}{\mu}\right)^3 + 3\left(\frac{\sigma}{\mu}\right)$$

Kurtosis:

$$\omega^4 + 2\omega^3 + 3\omega^2 - 3$$

$$\text{with } \omega \equiv 1 + \left(\frac{\sigma}{\mu}\right)$$

Mode:

$$\frac{\mu^4}{(\sigma^2 + \mu^2)^{3/2}}$$

Lognormal (Format 2)

RISKLognorm2(μ , σ)

Parameters:

μ	continuous parameter	
σ	continuous parameter	$\sigma > 0$

Domain:

$0 \leq x \leq +\infty$	continuous
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Density and Cumulative Functions:

$$f(x) = \frac{1}{x\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left[\frac{\ln x - \mu}{\sigma}\right]^2}$$

$$F(x) = \Phi\left(\frac{\ln x - \mu}{\sigma}\right)$$

where Φ is the *Error Function*.

Mean:

$$e^{\mu + \frac{\sigma^2}{2}}$$

Variance:

$$e^{2\mu} \omega(\omega - 1) \quad \text{with } \omega \equiv e^{\sigma^2}$$

Skewness:

$$(\omega + 2)\sqrt{\omega - 1}$$

$$\text{with } \omega \equiv e^{\sigma^2}$$

Kurtosis:

$$\omega^4 + 2\omega^3 + 3\omega^2 - 3$$

$$\text{with } \omega \equiv e^{\sigma^2}$$

Mode:

$$e^{\mu - \sigma^2}$$

Normal

RISKNormal(μ, σ)

Parameters:

μ	continuous location parameter	
σ	continuous scale parameter	$\sigma > 0$

Domain:

$-\infty \leq x \leq +\infty$	continuous
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Density and Cumulative Functions:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

$$F(x) = \Phi\left(\frac{x-\mu}{\sigma}\right)$$

where Φ is the *Error Function*.

Mean:

$$\mu$$

Variance:

$$\sigma^2$$

Skewness:

0

Kurtosis:

3

Mode:

μ

Pareto (First Kind)

$$Pareto(\theta, a)$$

Parameters:

θ	continuous shape parameter	$\theta > 0$
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a	continuous scale parameter	$a > 0$
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Domain:

$a \leq x \leq +\infty$	continuous
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Density and Cumulative Functions:

$$f(x) = \frac{\theta a^\theta}{x^{\theta+1}}$$

$$F(x) = 1 - \left(\frac{a}{x}\right)^\theta$$

Mean:

$\frac{a\theta}{\theta-1}$	for $\theta > 1$
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Variance:

$\frac{\theta a^2}{(\theta-1)^2(\theta-2)}$	for $\theta > 2$
---	------------------

Skewness:

$$2 \frac{\theta+1}{\theta-3} \sqrt{\frac{\theta-2}{\theta}} \quad \text{for } \theta > 3$$

Kurtosis:

$$\frac{3(\theta-2)(3\theta^2 + \theta + 2)}{\theta(\theta-3)(\theta-4)} \quad \text{for } \theta > 4$$

Mode:

a

Pearson Type V

RISKPearson5(α , β)

Parameters:

α	continuous shape parameter	$\alpha > 0$
β	continuous scale parameter	$\beta > 0$

Domain:

$0 \leq x < +\infty$	continuous
----------------------	------------

Density and Cumulative Functions:

$$f(x) = \frac{1}{\beta \Gamma(\alpha)} \cdot \frac{e^{-\beta/x}}{(x/\beta)^{\alpha+1}}$$

F(x) Has No Closed Form

Mean:

$$\frac{\beta}{\alpha - 1} \quad \text{for } \alpha > 1$$

Variance:

$$\frac{\beta^2}{(\alpha - 1)^2 (\alpha - 2)} \quad \text{for } \alpha > 2$$

Skewness:

$$\frac{4\sqrt{\alpha-2}}{\alpha-3}$$

for $\alpha > 3$

Kurtosis:

$$\frac{3(\alpha+5)(\alpha-2)}{(\alpha-3)(\alpha-4)}$$

for $\alpha > 4$

Mode:

$$\frac{\beta}{\alpha+1}$$

Rayleigh

RISKRayleigh(b)

Parameters:

b	continuous scale parameter	b > 0
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Domain:

$0 \leq x < +\infty$	continuous
----------------------	------------

Density and Cumulative Functions:

$$f(x) = \frac{x}{b^2} e^{-\frac{1}{2}\left(\frac{x}{b}\right)^2}$$

$$F(x) = 1 - e^{-\frac{1}{2}\left(\frac{x}{b}\right)^2}$$

Mean:

$$b\sqrt{\frac{\pi}{2}}$$

Variance:

$$b^2\left(2 - \frac{\pi}{2}\right)$$

Skewness:

$$\frac{2(\pi - 3)\sqrt{\pi}}{(4 - \pi)^{3/2}} \approx 0.6311$$

Kurtosis:

$$\frac{32 - 3\pi^2}{(4 - \pi)^2} \approx 3.2451$$

Mode:

b

Triangular

RISKTriang(min, m.likely, max)

Parameters:

min	continuous boundary parameter	$\min < \max$
m.likely	continuous mode parameter	$\min \leq \text{m.likely} \leq \max$
max	continuous boundary parameter	

Domain:

$\min \leq x \leq \max$	continuous
-------------------------	------------

Density and Cumulative Functions:

$$f(x) = \frac{2(x - \min)}{(m.\text{likely} - \min)(\max - \min)} \quad \min \leq x \leq m.\text{likely}$$

$$f(x) = \frac{2(\max - x)}{(\max - m.\text{likely})(\max - \min)} \quad m.\text{likely} \leq x \leq \max$$

$$F(x) = \frac{(x - \min)^2}{(m.\text{likely} - \min)(\max - \min)} \quad \min \leq x \leq m.\text{likely}$$

$$F(x) = 1 - \frac{(\max - x)^2}{(\max - m.\text{likely})(\max - \min)} \quad m.\text{likely} \leq x \leq \max$$

Mean:

$$\frac{\min + m.\text{likely} + \max}{3}$$

Variance:

$$\frac{\max^2 + \text{m.likely}^2 + \min^2 - (\max)(\text{m.likely}) - (\text{m.likely})(\min) - (\max)(\min)}{18}$$

Skewness:

$$\frac{2\sqrt{2}}{5} \frac{f(f^2 - 9)}{(f^2 + 3)^{3/2}}$$

$$\text{where } f \equiv \frac{2(\text{m.likely} - \min)}{\max - \min} - 1$$

Kurtosis:

2.4

Mode:

m.likely

Uniform

RISKUniform(min, max)

Parameters:

min continuous boundary parameter min < max

max continuous boundary parameter

Domain:

$\min \leq x \leq \max$

continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{\max - \min}$$

$$F(x) = \frac{x - \min}{\max - \min}$$

Mean:

$$\frac{\max - \min}{2}$$

Variance:

$$\frac{(\max - \min)^2}{12}$$

Skewness:

0

Kurtosis:

1.8

Mode:

Not uniquely defined

Weibull

RISKWeibull(α, β)

Parameters:

α	continuous shape parameter	$\alpha > 0$
β	continuous scale parameter	$\beta > 0$

Domain:

$0 \leq x < +\infty$	continuous
----------------------	------------

Density and Cumulative Functions:

$$f(x) = \frac{\alpha x^{\alpha-1}}{\beta^\alpha} e^{-(x/\beta)^\alpha}$$

$$F(x) = 1 - e^{-(x/\beta)^\alpha}$$

Mean:

$$\beta \Gamma\left(1 + \frac{1}{\alpha}\right)$$

where Γ is the *Gamma Function*.

Variance:

$$\beta^2 \left[\Gamma\left(1 + \frac{2}{\alpha}\right) - \Gamma^2\left(1 + \frac{1}{\alpha}\right) \right]$$

where Γ is the *Gamma Function*.

Skewness:

$$\frac{\Gamma\left(1+\frac{3}{\alpha}\right)+3\Gamma\left(1+\frac{2}{\alpha}\right)\Gamma\left(1+\frac{1}{\alpha}\right)+2\Gamma^3\left(1+\frac{1}{\alpha}\right)}{\left[\Gamma\left(1+\frac{2}{\alpha}\right)-\Gamma^2\left(1+\frac{1}{\alpha}\right)\right]^{3/2}}$$

where Γ is the *Gamma Function*.

Mode:

$$\begin{aligned} &\beta\left(1-\frac{1}{\alpha}\right)^{1/\alpha} && \text{for } \alpha > 1 \\ &0 && \text{for } \alpha \leq 1 \end{aligned}$$

Inverse Gaussian

$RISKInvGauss(\mu, \lambda)$

Parameters:

μ	continuous parameter	$\mu > 0$
λ	continuous parameter	$\lambda > 0$

Domain:

$x > 0$	continuous
---------	------------

Density and Cumulative Functions:

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} e^{-\left[\frac{\lambda(x-\mu)^2}{2\mu^2 x}\right]}$$

$$F(x) = \Phi\left[\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} - 1\right)\right] + e^{2\lambda/\mu} \Phi\left[-\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} + 1\right)\right]$$

where Φ is the *Error Function*.

Mean:

$$\mu$$

Variance:

$$\frac{\mu^3}{\lambda}$$

Skewness:

$$3\sqrt{\frac{\mu}{\lambda}}$$

Kurtosis:

$$3 + 15\frac{\mu}{\lambda}$$

Mode:

$$\mu \left[\left(1 + \frac{9\mu^2}{4\lambda^2} \right) - \frac{3\mu}{2\lambda} \right]$$

Appendix D

Description of Porosity Data

D.1.0 Introduction

Matrix porosity data are derived from laboratory measurements of borehole core samples and from the interpretation of borehole geophysical logs. [Section D.2.0](#) through [Section D.7.0](#) describe and present the matrix porosity dataset and include the following items:

- A summary of the contents of the dataset
- The structure and fields description of the table containing the dataset
- Directions on how to access the full dataset

[Section D.5.0](#) presents matrix porosity depth profiles per HSU.

[Section D.6.0](#) presents in tabular format the probability distribution-specific parameters that define the matrix porosity probability models for each HSU ([Table 5-4](#)).

D.2.0 Datasets Summary

Two datasets are presented. The first contains matrix porosities measured from within Frenchman Flat. A description for each of the field entries for this table is presented in [Section D.3.0](#). The second dataset presents matrix porosities transferred from Pahute Mesa. As reported in [Section 5.2.2](#), these data were compiled and published in FY 2003 for the UGTA Project (Shaw, 2003); therefore, the description for each of the table field entries is presented in Appendix D of Shaw (2003). Field entries pertaining to the scoring system ([Section 5.3](#)) for the Pahute Mesa data were added to this table and are described below in [Section D.3.0](#).

Each record of the matrix porosity dataset contains information about a porosity measurement that corresponds to either an exact depth or to a depth interval. The combined datasets contain approximately 59,000 records for roughly 71 different locations. The number of records per HSU is presented in [Table 5-4](#). In general, the datasets contain information pertaining to the borehole, the measurement depth, the measurement method, the score assigned to each datum, and the source of each datum. A list of references, as referred to in the two datasets, is attached.

D.3.0 Table Structure

The Frenchman Flat matrix porosity table contains the following fields:

- ID - Sorted ascending number of table entry.
- Well Name - Name of the borehole/well if available.
- Sample Depth (m) - The exact sample depth or depth interval of the measurement sample in units of meters below ground surface.
- n(calc) - Porosity derived from a core sample(s). Usually the core is oven dried to determine dry bulk density. Particle density is determined from subsamples of the core. In a few rare instances, injection of other fluids into the core is used to determine porosity.
- n(D) - Porosity derived from gamma-gamma logs, which measure rock bulk density. A relationship is developed that produces porosity from the log density when a particle density is assumed or measured. The measurement represents the sample total porosity.
- n(R, D, N) - Porosity derived respectively from (electrical) resistivity logs, gamma-gamma logs, and neutron logs. See n(N) for a brief description of neutron logs. The porosity reported is an arithmetic average of the three measurement types.
- n(G) - Porosity derived from borehole gravimetry logs. The measurement represents the sample total porosity.
- n(N) - Porosity derived from neutron logs. The relationship yields the total porosity (if the sample is saturated) based on the indirect neutron log measurement of the sample water content.
- n(N, D) - Porosity derived from neutron and density logs, respectively.
- n(R) - Porosity derived from (electrical) resistivity logs. Based on Archie's equation, a relationship is developed that yields interconnected porosity from the formation resistivity.
- n(V) - Porosity derived from velocity logs. The method uses a form of Wyllie's equation to calculate total porosity from the sonic transit time, given per meter. In this manner, the transit time is the inverse of the sonic velocity.
- Average Sample Depth (m) - Either the exact or average sample depth (sample interval midpoint) of the measurement sample in meters below ground surface.

- Method - A list of the total number of measurement methods used for each sample.
- Source - A reference number that corresponds to the source of each matrix porosity datum. The list of reference numbers and the corresponding sources is presented in [Section D.7.0](#).
- Source Table - The table, corresponding to the source in the prior field, in which the matrix porosity datum is presented.
- Sample Depth (m) - Sample depth in meters below ground surface if the measurement sample is from an exact depth and if the datum source is reported in units of meters; otherwise not applicable.
- Sample Top (m) - Sample top in meters below ground surface if the measurement sample extends over a depth interval and if the datum source is reported in units of meters; otherwise not applicable.
- Sample Bottom (m) - Sample bottom in meters below ground surface if the measurement sample extends over a depth interval and if the datum source is reported in units of meters; otherwise not applicable.
- Sample Depth (ft) - Sample depth in feet below ground surface if the measurement sample is from an exact depth and if the datum source is reported in units of feet; otherwise not applicable.
- Sample Top (ft) - Sample top in feet below ground surface if the measurement sample extends over a depth interval and if the datum source is reported in units of feet; otherwise not applicable.
- Sample Bottom (ft) - Sample bottom in feet below ground surface if the measurement sample extends over a depth interval and if the datum source is reported in units of feet; otherwise not applicable.
- Frenchman Flat HSU - The HSU corresponding to the measurement sample
- Weights: 1. Rock Type * - Weight assigned for the sample rock type relative to that of the HSU of interest. If the sample rock type is different from the HSU, an overall (composite) weight of zero should be assigned to the datum. If the same, then the analyst should proceed to Weight 2.
- Weights: 2. Dep. and Alt. History * - Similarities and differences in deposition history and geochemical/hydrothermal alteration between the sample and CAU HSU should be accounted for by assigning a weight between 0.0 and 0.7, with 0.7 indicating a very similar deposition and alteration history.
- Weights: 3. Structure and Mechanical * - Similarities and differences in structural setting and mechanical alteration between the sample and CAU

HSU should be accounted for by assigning a weight between 0.0 and 0.3, with 0.3 indicating a very similar structural setting.

- Multipliers: 1. Measurement Method * - The measurement method multiplier should consider both the quality and uncertainty of the method and the scale of the measurement. Exact multiplier values are provided in Attachment 4.2 of SNJV (2004).
- Multipliers: 2. Reduction and Analysis Methods * - This multiplier considers the methods of data reduction and the data analysis methods independent of the type of porosity measurement being evaluated. Exact multiplier values are provided in Attachment 4.2 of SNJV (2004).
- Multipliers: 3. Documentation Quality * - This multiplier considers the datum source documentation quality and is independent of the type of porosity measurement being evaluated. Exact multiplier values are provided in Attachment 4.2 of SNJV (2004).
- Reduction and Analysis Methods and Documentation Quality Comments * - A general comments field for analysis methods and documentation quality assurance.

* These fields are included with the transferred Pahute Mesa dataset

D.4.0 Access to Dataset

The Frenchman Flat and (transferred) Pahute Mesa datasets are listed below. They are provided in pdf format.

ADOBE ACROBAT:

- FF_matrix_porosity.pdf
- PM_matrix_porosity.pdf

D.5.0 Matrix Porosity Depth Profiles per HSU

Figure D.5-1
PCU Matrix Porosity Depth Profile

Figure D.5-2
BLFA Matrix Porosity Depth Profile

Figure D.5-3
TMWTA Matrix Porosity Depth Profile

Figure D.5-4
TMLVTA Matrix Porosity Depth Profile

Figure D.5-5
TSA Matrix Porosity Depth Profile

Figure D.5-6
U/LTCU Matrix Porosity Depth Profiles

Figure D.5-7
LCA Matrix Porosity Depth Profile

D.6.0 (BestFit) Probability Distribution Parameters

**Table D.6-1
HSU-Specific Matrix Porosity Probability Distribution Parameters**

HSU:	AA	OAA	PCU	BLFA	TMWTA	TMLVTA	TSA	U/LTCU	LCA
Distribution:	Logistic	Inverse Gaussian	Inverse Gaussian	Inverse Gaussian	Triangular	Gaussian	Beta General	Logistic	Log Logistic
shift		-146.04	30.57	-0.41					
min					2.58		4.30		
max					46.56		50.36		
mu (μ)		179.37	7.35	18.35		35.70			
sigma (σ)						6.07			
lambda (λ)		62,990.19	14.73	43.47					
most likely					37.12				
alpha (α)	39.16							28.25	1.83
alpha 1 (α_1)							0.97		
alpha 2 (α_2)							1.28		
beta (β)	3.93							2.95	4.18
gamma (γ)									0.24

D.7.0 References

Shaw, see Shaw Environmental, Inc.

Shaw Environmental, Inc. 2003. *Contaminant Transport Parameters for the Groundwater Flow and Transport Model of Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nye County, Nevada*, Shaw/13052--201-CD Rev. 0, August 2003. Las Vegas, NV.

SNJV, see Stoller-Navarro Joint Venture.

Stoller-Navarro Joint Venture. 2004. *Assessment of Radionuclide Migration from Underground Nuclear Tests in Northern Frenchman Flat, Nevada Test Site*, Rev 0. S-N/99205-032. Las Vegas, NV.

Appendix E

Description of Matrix Diffusion Dataset

E.1.0 Introduction

Data relating to matrix diffusion include diffusion values that were obtained from diffusion cell experiments and fracture transport experiments.

This description of the matrix diffusion datasets includes the following items:

- A summary of the contents of the dataset
- The structure of the tables containing the dataset
- Directions on how to access the full dataset
- Fitting parameters used in the statistical analysis of matrix diffusion data

E.2.0 Dataset Summary

Each record of the dataset for the diffusion cell experiments contains information about a given measurement for a porous media sample. Of the 258 matrix diffusion measurements in the dataset, 139 measurements are for samples with a Frenchman Flat equivalent HSU and 119 measurements are for YMP or Pahute Mesa HSUs not present at Frenchman Flat - indicated by a “NP” in the equivalent FF HSU column (the fourth column). The first column in the dataset is a sample number which typically includes the well name and depth. The matrix diffusion dataset includes information on the interval tested for each site, the porosity in the tested interval, the various diffusion parameter values and weight and multiplier factors that indicate each measurement's quality and transferability to Frenchman Flat HSUs, comments on the experimental techniques and quality, and information on geology and mineralogy of the samples.

E.3.0 Table Structure

The matrix diffusion table from the diffusion cell experiments contain the following fields:

- Sample_number - contains the name of the well, unique sample numbers, and, typically, the depth in feet.
- Location - Frenchman Flat (FF), Yucca Mountain (YM), for PM (Pahute Mesa)

- HSU - HydroStratigraphic Unit for this sample
- Equiv FF HSU - equivalent Frenchman Flat HSU for this sample (NP indicates there is no FF equivalent HSU for this sample)
- Depth (m)
- Diffusion_test_date
- Porosity
- Diffusion coefficient - experimentally derived diffusion coefficient, in m^2/s
- Chemical species - tracer chemical used in the diffusion cell experiment
- Species adj. diffusion coefficient -- experimentally derived diffusion coefficient, in m^2/s , adjusted from the actual tracer species used in the measurement to a tritiated water basis, to achieve a consistent tracer basis for the entire dataset of measurements (see [Section 8.2.4](#))
- Original_source - Reference source reporting the diffusion coefficient measurement
- Source page # Table # -- page and table number, where available, from original source reporting diffusion coefficient measurement and other raw data
- W1 perm. simil -- weight factor for permeability similarity (between measurement and FF equivalent HSU)
- EquivHSU_poros - mean porosity of the FF equivalent. HSU
- Percent diff in poros. - difference between the porosity of the sample and the mean porosity for the FF equivalent HSU
- W2 poros simil. - Weight factor for porosity similarity (see [Table 8-3](#))
- W Total Weight (W1xW2) - The total weight factor (for data transferability) is the product of the W1 weight factor and W2 weight factor
- Diffus_measur_method - measurement method, such as diffusion cell experiment (DCE) or non-DCE methods such as x-ray or neutron imaging, electrical conductivity, batch experiments using pulverized particles, etc.
- Frac in sample? - indicates if sample includes a natural fracture surface, which have mineral coatings that affect diffusion, and are of great interest in modeling naturally fractured system

- Sample thickness, cm - sample thickness across which the diffusion is measured
- M1a meas. method factor - diffusion cell experiments are considered of higher quality and have a higher multiplier factor than other diffusion measurement methods
- M1b frac. meas. factor - if natural fracture surface is present, would give useful information and diffusion in fractured systems present at Frenchman Flat; therefore, these data are given a higher multiplier factor
- M1c sample thick. factor - thicker samples have a higher multiplier factor, as they are more representative of field conditions
- M1 meas. meth. - measurement method multiplier, product of M1a, M1b, and M1c
- M2a test series meth.- quality of test series experimental method and calibration
- M2b indiv. meas. meth.-quality of an individual measurement, fit of the data to the experimental model, etc.
- M2 data anal. meth.-data analysis method multiplier, product of M2a and M2b
- M3 doc. qual.- factor representing the quality of the documentation for the diffusion measurements test series
- M Total Multiplier - factor representing data quality; product of M1, M2, and M3
- Total Score WxM - factor representing both data transferability and data quality, product of Total Weight (W) and Total Multiplier (M)
- Multiplier_comments -contains author's comments on individual measurement quality, experimental difficulties and ambiguous results, comments relating to how multiplier factors were determined, etc.
- Temp. oC - temperature at which matrix diffusion was measured (rarely reported)
- Major_minerals (%) - mineral content of the sample
- Comments -comments related to sample or matrix diffusion measurement
- Geologic description - geologic description of sample HSU

E.4.0 Access to Dataset

The matrix diffusion dataset for this analysis can be found in the following file:

- Matrix_Diffusion_Dataset.pdf

To access the data use the CD included with the document.

E.5.0 Statistical Model Parameters

Four of the ten Frenchman Flat HSUs have experimentally-derived data or experimentally-derived data from YMP or Pahute Mesa HSUs that correspond to those FF HSUs. For these four HSUs, the most appropriate statistical model of the data was determined using BestFit, a statistical analysis package that determines the “goodness of fit” of 28 different statistical models to a given dataset and ranks the models in order of best fit. Palisade (2002) and Appendix C of Shaw (2003a) contain additional information on BestFit, including descriptions of these 28 different statistical models.

The table below lists the statistical model chosen as most appropriate for each of the matrix diffusion datasets for the four FF HSUs, along with the fitting or shape parameters for that statistical model, the number of measurements, and RMS error, a measure of the quality of this fit.

Table E.5-1
CDF Shape Parameters and Fit Statistics for FF HSUs

HSU	TM-WTA	TM-LVTA	U/L TCU	TSA
Best statistical model	Uniform	Triangular	Exponential	Log Normal
Fitting Parameters, x 10^{-10} m ² /sec	Min = 0.105 Max = 1.43	Min = 0 Most Likely = 0.00005 Max = 3.65	β = 2.97 Shift = 0.00343	μ = 1.80 σ = 1.95 Shift = 0.0246
Number of measurements	6	9	72	52
RMS error	0.0037	0.0050	0.0022	0.0004

Appendix F

Description of Dispersivity Dataset

F.1.0 Introduction

This section contains the data required to reproduce the probabilistic uncertainty model of longitudinal dispersivity as a function scale and the original data sets compiled from tracer test sites worldwide.

Data relating to dispersivity include measurements obtained from four transport experiments that have been performed at or near the NTS plus additional dispersivity data compiled from various literature sources.

This description of the dispersivity dataset includes the following items:

- A summary of the contents of the dataset
- The structure of the table containing the dataset
- Directions on how to access the dataset

F.2.0 Probabilistic Model Data

[Table F.3-1](#) provides the log-logistic CDF data used to develop the probabilistic model used to describe the uncertainty in longitudinal dispersivity as a function of transport scale.

F.3.0 Dataset Summary

Each record of the dispersivity dataset contains information about a given tracer test and the results of the data analysis following a specific method of analysis. The dataset is, therefore, organized primarily by the tracer test location and secondarily by the data analysis method. The dispersivity dataset contains data from different sites throughout the world. The dataset contains information about the specific tracer test, the method of analysis, the various dispersivity types, and an indication of the quality of the data.

Table F.3-1
Log-Logistic Parameters Describing Probabilistic Model of Binned Dispersivity Values

Bin Number	1		2		3		4		5		6		7	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Scale (m)	0.75	10.7	5	29.3	14	80	35	200	79.2	600	250	5000	800	50000
Distribution Fit	Log Logistic		Log Logistic		Log Logistic		Log Logistic		Log Logistic		Log Logistic		Log Logistic	
gamma	0		0		0		0		0		0		0	
beta	0.28		1.12		1.21		0.68		0.96		6.00		28.74	
alpha	1.71		2.01		1.49		1.31		1.22		5.48		2.45	

F.4.0 Table Structure

The dispersivity dataset contains the following fields:

- `site_name` - Name of test, if any, and generalized location of the test
- `aquifer_material` - Geologic material the test was conducted in
- `min_avg_aquifer_thickness (m)` - The minimum average aquifer thickness in meters; if only one thickness is given, it is placed in this field
- `max_avg_aquifer_thickness (m)` - The maximum average aquifer thickness in meters
- `min_hydraulic_conductivity (m/s)` - The minimum hydraulic conductivity in meters per second for the given test material; if only one conductivity is given, it is placed in this field
- `max_hydraulic_conductivity (m/s)` - The maximum hydraulic conductivity in meters per second for the given test material
- `min_transmissivity (m2/s)` - The minimum transmissivity in square meters per second for the given test material; if only one transmissivity is given, it is placed in this field
- `max_transmissivity (m2/s)` - The maximum transmissivity in square meters per second for the given test material
- `min_eff_porosity (%)` - The minimum effective porosity in percent for the given test material; if only one porosity is given, it is placed in this field
- `max_eff_porosity (%)` - The maximum effective porosity in percent for the given test material
- `min_velocity (m/d)` - The minimum velocity in meters per day for the given test material; if only one velocity is given, it is placed in this field
- `max_velocity (m/d)` - The maximum velocity in meters per day for the given test material
- `flow_configuration` - The flow configuration for the test
- `monitoring` - The type of monitoring involved with the test
- `tracer_and_input` - The tracer used and input method for the test
- `method_of_data_interpretation` - The method of data interpretation used for the test

- min_scale_of_test (m) - The minimum distance of the test in meters; if only one distance is given, it is placed in this field
- max_scale_of_test (m) - The maximum distance of the test in meters
- dispersivity_longitudinal_min - The minimum longitudinal dispersivity in meters for the given test material; if only one value is given, it is placed in this field
- dispersivity_longitudinal_max - The maximum longitudinal dispersivity in meters for the given test material
- dispersivity_transverse_min - The minimum transverse dispersivity in meters for the given test material; if only one value is given, it is placed in this field
- dispersivity_transverse_max - The maximum transverse dispersivity in meters for the given test material
- dispersivity_vertical_min - The minimum vertical dispersivity in meters for the given test material; if only one value is given, it is placed in this field
- dispersivity_vertical_max - The maximum vertical dispersivity in meters for the given test material
- DQE_F - The reporting author's (see ref_id) reliability assessment of the data
- DDE_F - Data documentation flag
- data_source - The original source of the data
- ref_id - Reference for the record
- remarks - Contains additional information for a given record

F.5.0 Access to Dataset

The full dispersivity dataset is provided in a PDF format. To access the dataset, use the CD.

Appendix G

Description of Matrix Sorption Parameter Dataset

G.1.0 ***Introduction***

Data relating to matrix sorption parameters include calculated matrix sorption parameters from laboratory studies for nineteen different elements. The laboratory studies were performed at a variety of experimental conditions including different lithologies, groundwater types, temperature, pH, and atmospheric conditions.

This description of the matrix sorption parameter data includes the following items:

- A summary of the contents of each of the datasets
- The structure of the tables containing the datasets

G.2.0 ***Dataset Summary***

The matrix sorption parameter dataset is provided as one table containing the experimental results for every rock type and species. There are 7,211 records in the dataset including 380 records for alluvial samples; 1,070 records for vitric tuffs; 1,936 records for devitrified tuffs; 1,667 records for zeolitic tuffs; and 2,158 records for other tuffs and pure mineral samples.

The sorption data for alluvial, vitric tuff, devitrified tuffs, and zeolitic tuffs were used to develop the sorption coefficient distributions. The remaining data were included in the source and are listed here for the sake of completeness.

The dataset is included in a PDF file on the CD attached to this document. The data are sorted first on the basis of whether the experiment is a sorption or desorption experiment, then by the rock type, and finally by the ionic species for which the sorption coefficient was measured.

G.3.0 ***Table Structure***

The matrix sorption parameter table contains the following fields:

- Chemical_Species - This is the ionic species for which the distribution coefficient was determined
- Site_Location - General location rock sample acquired

- Sample well - Name of the well from which the rock sample was taken
- Sample Depth - Depth below ground surface in meters from which the sample was taken
- Rock_type - General rock type of the sample. Includes alluvium, vitric tuff, devitrified tuff, zeolitic tuff, and various mineral names (for experiments using pure mineral phases)
- Lithostratigraphic Unit - Stratigraphic unit from which rock sample was taken
- Mass % Calcite - Weight percent calcite of rock sample, generally from XRD analysis
- Mass % zeolite - Weight percent zeolite of rock sample, generally from XRD analysis
- Mass % smectite - Weight percent smectite of rock sample, generally from XRD analysis
- Mass % hematite - Weight percent hematite of rock sample, generally from XRD analysis
- Mass % mica - Weight percent mica of rock sample, generally from XRD analysis
- Sorption/Desorption - Denotes whether the K_d is a sorption or desorption coefficient
- K_d or R_d (mL/g) - Experimentally determined sorption/desorption coefficient for the ionic species
- Recommended sorption coefficient - Alternate sorption coefficient recommended in source to account for experimental limitations
- stnd_dev (+/-) - Standard deviation of the sorption/desorption coefficient
- Water_type - Type of water used in sorption experiment
- Water - Water sample ID of water used by lab in sorption experiment
- Initial pH - pH of water before equilibration
- Final pH - pH of water after equilibration (if available)
- Eh (mV) - The final Eh of the water in millivolts
- Temp (deg C) - The temperature at which the sorption experiment was performed

- aq Cl⁻ (mg/L) - Concentration of Cl⁻ in the water used for the experiment
- aq NO₃⁻ (mg/L) - Concentration of NO₃⁻ in the water used for the experiment
- aq SO₄²⁻ (mg/L) - Concentration of SO₄²⁻ in the water used for the experiment
- aq Na⁺ (mg/L) - Concentration of Na⁺ in the water used for the experiment
- aq Mg²⁺ (mg/L) - Concentration of Mg²⁺ in the water used for the experiment
- aq K⁺ (mg/L) - Concentration of K⁺ in the water used for the experiment
- aq Ca²⁺ (mg/L) - Concentration of Ca²⁺ in the water used for the experiment
- aq F⁻ (mg/L) - Concentration of F⁻ in the water used for the experiment
- aq Sr²⁺ (mg/L) - Concentration of Sr²⁺ in the water used for the experiment
- Test_Duration (days) - Length of time in days that the ionic solution was left in contact with the rock sample
- Atmosphere - Type of atmosphere in which the sorption experiment was conducted
- Sample_number - Sample number of the rock on which experiment was performed
- Sample_description - Lab designated description of the rock sample. Generally includes water type for experiment, well name and depth of rock sample, and some temperature designation
- Experiment - Designator for the experiment
- Initial Species Concentration - Concentration of the sorbed ionic species at the beginning of the experiment
- Initial Species Concentration Units - Units of the initial species concentration measurement
- Multiplier_MM - Measurement method multiplier; assigned on a scale of 0 to 2 based on quality of the experimental method used to determine sorption coefficient

- Multiplier_RAM - Reduction and analysis method multiplier; assigned from a scale of 0 to 1 based on the quality of data reduction
- Multiplier_DQ - Quality of documentation multiplier; assigned from a scale of 0 to 1 based on the quality of documentation for an experiment
- Rock Type (weight) - Data transferability weight. Ranked on a scale of 0 to 1 based on similarity of rock chemistry to Frenchman Flat
- Deposition History (weight) - Data transferability weight; ranked on a scale of 0 to 1 based on similarity of deposition and alteration history of the sample to Frenchman Flat
- Water Chem (weight) - Data transferability weight; ranked on a scale of 0 to 1 based on the similarity of the water type used in the experiment to Frenchman Flat
- Remarks - Any other pertinent information relating to the experiment or the measurement.
- ref_id - Reference number for the source of measurements in the UGTA library.
- Source - Reference number of source used by originator of the data
- YMP_ID - Yucca Mountain Data Tracking number containing data

Appendix H

Description of Colloid Parameter Datasets

H.1.0 Introduction

Colloid-facilitated transport parameter data can be found in five different datasets. These datasets include measured colloid concentrations and size distributions for groundwater samples, calculated colloid distribution coefficients from sorption and desorption experiments, calculated rate constants from actinide sorption and desorption experiments, and colloid filtration and retardation data obtained from both laboratory and field tracer responses.

This description of the colloid-facilitated transport parameter datasets includes the following items:

- A summary of the contents of each dataset
- The structure of the table containing each dataset
- Directions on how to access the each dataset

H.2.0 Dataset Summary

Each record in the colloid concentrations and size distribution dataset contains information about a given measurement of colloid concentrations for a given borehole. The dataset is, therefore, organized primarily by the borehole name. The dataset contains 84 colloid concentrations and size measurements for 47 different boreholes. The dataset contains information about the well name, colloid size ranges, and sources of the data.

Each record in the colloid distribution coefficients table contains distribution coefficient data for a specific actinide and colloid combination. As a result, the table is organized primarily by the sorbing actinide and secondarily by the composition of the colloid. The dataset contains 13 distribution coefficient ranges for 4 different actinides. The dataset contains information about the colloid type, the distribution coefficient range, and the source of the data.

Each record in the actinide sorption and desorption rate constants table contains forward- and reverse-rate constants for a given colloid and actinide combination. As a result, the table is organized primarily by the colloid type and secondarily by the sorbing actinide. The dataset contains 20 records of information that document rate constant ranges for both sorption and desorption of actinides onto various colloid types.

The colloid filtration and retardation datasets contain information about filtration rate constants for various wells. The data were split into two tables. The first table

contained data for laboratory tracer responses, and the second table contained data for field tracer responses. Both datasets are organized primarily by well name. The two datasets contain over 50 records for approximately 9 different locations. The datasets contain specific information on rate constants, retardation factors, and residence times.

H.3.0 Data Table Structure

The colloid concentration and size distribution table contains the following fields:

- well_name - Name of the well sampled
- Diam_50 (nm) - Number of colloids in the 50 nm size bin
- Diam_60 (nm) - Number of colloids in the 60 nm size bin
- Diam_70 (nm) - Number of colloids in the 70 nm size bin
- Diam_80 (nm) - Number of colloids in the 80 nm size bin
- Diam_90 (nm) - Number of colloids in the 90 nm size bin
- Diam_100 (nm) - Number of colloids in the 100 nm size bin
- Diam_110 (nm) - Number of colloids in the 110 nm size bin
- Diam_120 (nm) - Number of colloids in the 120 nm size bin
- Diam_130 (nm) - Number of colloids in the 130 nm size bin
- Diam_140 (nm) - Number of colloids in the 140 nm size bin
- Diam_150 (nm) - Number of colloids in the 150 nm size bin
- Diam_160 (nm) - Number of colloids in the 160 nm size bin
- Diam_170 (nm) - Number of colloids in the 170 nm size bin
- Diam_180 (nm) - Number of colloids in the 180 nm size bin
- Diam_190 (nm) - Number of colloids in the 190 nm size bin
- Diam_200 (nm) - Number of colloids in the 200 nm size bin
- Diam_220 (nm) - Number of colloids in the 220 nm size bin
- Diam_240 (nm) - Number of colloids in the 240 nm size bin
- Diam_260 (nm) - Number of colloids in the 260 nm size bin
- Diam_280 (nm) - Number of colloids in the 280 nm size bin
- Diam_300 (nm) - Number of colloids in the 300 nm size bin
- Diam_400 (nm) - Number of colloids in the 400 nm size bin
- Diam_500 (nm) - Number of colloids in the 500 nm size bin
- Diam_600 (nm) - Number of colloids in the 600 nm size bin
- Diam_800 (nm) - Number of colloids in the 800 nm size bin
- Diam_1000 (nm) - Number of colloids in the 1,000 nm size bin
- Concentration - Number of colloids in one mL of solution.
- ref_id - Reference for the record

The colloid distribution coefficients table contains the following fields:

- actinide - Actinide
- colloid_type - Type of colloid
- lower_K_d_bound (mL/g) - Lower K_d bound in milliliters per gram

- upper_K_d_bound (mL/g) - Upper K_d bound in milliliters per gram
- UGTA_extension (mL/g) - Extensions to the bounds determined from U-20WW experiments
- comments - Comments on the record
- source - Source of the information
- ref_id - Reference for the record

The actinide sorption and desorption rate constants table contains the following fields:

- Colloids/Actinides - Colloid and actinide combination
- batch_kf (hr-1) - Batch sorption rate constant per hour
- batch_kb (hr-1) - Batch desorption rate constant per hour
- fracture_kf (hr-1) - Fracture sorption rate constant per hour
- fracture_kb (hr-1) - Fracture desorption rate constant per hour
- comments - Comments regarding the values
- source - Source of the information
- ref_id - Reference for the record

The colloid filtration and retardation data obtained from laboratory tracer responses contain the following fields:

- Well_name_depth (ft) - Combination of the well name and depth of the sample in feet
- Mean_res_time (hr) - Mean residence time in hours
- Filt_rate_constant (1/hr) - Filtration rate constant per hour
- Detach_rate_constant (1/hr) - Detachment rate constant per hour
- Retardation_factor - Retardation factor
- Colloid_type - Type of colloid used in the experiment
- Comments - Comments regarding the experiment
- Source - Source of the information
- Ref_id - Reference for the record

The colloid filtration rate and retardation data obtained from field tracer responses contain the following fields:

- site_name - Site name for the record
- distance (m) - Distance for the field test in meters

- mean_res_time (hr) - Mean residence time in hours
- fill_rate_constant (1/hr) - Filtration rate constant per hour
- ret_factor - Retardation factor
- probability - Probability
- comments - Additional comments regarding the record
- source - Source of the data
- ref_id - Reference for the record

H.4.0 Access to Dataset

The colloid size concentrations, distribution coefficients, actinide sorption and desorption rate constants, and colloid filtration rate and retardation data are provided in PDF format in the following files:

- Colloid_size_concentration.pdf
- Colloid_Kd_Ranges.pdf
- Colloid_sorption_desorption.pdf
- Colloid_lab_fracture.pdf
- Field_microsphere_exp.pdf

To access the data, use the CD provided with the document.

Plates

Distribution

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