ERRATA SHEET

The Following Corrections and Clarifications Apply to: Corrective Action Investigation Plan for Corrective Action Unit 99: Rainier Mesa/Shoshone Mountain, Nevada Test Site, Nevada

DOE Document Number: DOE/NV--1031

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Section A.1.2.2, p. A-19:

Replace the sentence reading, "This is inconsistent with the EPA approach (EPA, 1987, 1993, and 2000)." with the following: "This is not inconsistent with the EPA approach (EPA, 1987, 1993, and 2000)."

Nevada
Environmental
Restoration
Project

DOE/NV--1031

National Nuclear Security Administration

Corrective Action Investigation Plan for Corrective Action Unit 99: Rainier Mesa/Shoshone Mountain, Nevada Test Site, Nevada

Controlled Copy No.: ___
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December 2004

Environmental Restoration
Division

U.S. Department of Energy
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CORRECTIVE ACTION INVESTIGATION PLAN FOR CORRECTIVE ACTION UNIT 99: RAINIER MESA/SHOSHONE MOUNTAIN NEVADA TEST SITE, NEVADA

U.S. Department of Energy
National Nuclear Security Administration
Nevada Site Office
Las Vegas, Nevada

Controlled Copy No.: ___

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CORRECTIVE ACTION INVESTIGATION PLAN
FOR CORRECTIVE ACTION UNIT 99:
RAINIER MESA/SHOSHONE MOUNTAIN
NEVADA TEST SITE, NEVADA

Approved by: Signature Approved Date: 12/20/04

Bill Wilborn, Acting Project Manager
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Approved by: Signature Approved Date: 12/20/04

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Environmental Restoration Division

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List of Symbols for Elements and Compounds

Am	Americium
Ar	Argon
C	Carbon
Ca	Calcium
Cl	Chlorine
Co	Cobalt
CO_3^{2-}	Carbonate
Cs	Cesium
D	Deuterium
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
Eu	Europium
Fe	Iron
H	Hydrogen
HCO_3^-	Bicarbonate
He	Helium
I	Iodine
K	Potassium
Kr	Krypton
Mg	Magnesium
Na	Sodium
Nb	Niobium
Np	Neptunium
O	Oxygen
O_2	Oxygen Gas
Pb	Lead
Pu	Plutonium

List of Symbols for Elements and Compounds *(Continued)*

Ra	Radium
Ru	Ruthenium
Sb	Antimony
SO_4^{2-}	Sulfate
Sr	Strontium
Tc	Technetium
Th	Thorium
TNT	Trinitrotoluene
U	Uranium

List of Stratigraphic Unit Abbreviations and Symbols

AA	Alluvial Aquifer
BAQ	Basal Aquifer
BCU	Basal Confining Unit
BFCU	Bullfrog Confining Unit
BRA	Belted Range Aquifer
FCCM	Fortymile Canyon Composite Unit
LCCU	Lower Clastic Confining Unit
LCCU1	Lower Clastic Confining Unit of the Belted Range thrust fault
MGCU	Mesozoic Granite Confining Unit
PBRCM	Pre-Belted Range Confining Unit
PCM	Paintbrush Composite Unit
RMICU	Rainier Mesa Intrusive Confining Unit
SCVCU	Subcaldera Volcanic Confining Unit
SWNVF	Southwestern Nevada Volcanic Field
TCU	Tuff Confining Unit
TMA	Timber Mountain Aquifer
TMCM	Timber Mountain Confining Unit
TSDV	Tertiary Sedimentary Death Valley
UCCU	Upper Clastic Confining Unit
VA	Volcanic Aquifer
VCU	Volcanic Confining Unit
WTA	Welded Tuff Aquifer
YMCFCM	Yucca Mountain Crater Flat Composite Unit

List of Acronyms and Abbreviations

°C	Degrees celsius
δ	Delta
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
ALARA	As low as reasonably achievable
AMT	Audio Magnetotellurics
ASTM	American Society for Testing and Materials
BECAMP	Basic Environmental Compliance and Distribution Program
bgs	Below ground surface
BLM	U.S. Department of the Interior, Bureau of Land Management
BN	Bechtel Nevada
CADD	Corrective Action Decision Document
CAI	Corrective Action Investigation
CAIP	Corrective Action Investigation Plan
CAP	Corrective Action Plan
CAS	Corrective Action Site
CAU	Corrective Action Unit
CFC	Chlorofluorocarbon
CFR	*Code of Federal Regulations*
cm/yr	Centimeters per year
cm	Centimeter
cm^2/s	Square centimeters per second
CNTA	Central Nevada Test Area
DEM	Digital Elevation Model
DoD	U.S. Department of Defense

List of Acronyms and Abbreviations *(Continued)*

DOE/NV	U.S. Department of Energy, Nevada Operations Office
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DQO	Data Quality Objective
DRI	Desert Research Institute
DTRA	Defense Threat Reduction Agency
EPA	U.S. Environmental Protection Agency
ERP	Environmental Restoration Project
ET	Evapotranspiration
FAWP	Field Activity Work Package
FEHM	Finite Element Heat Mass Transfer Code
FFACO	*Federal Facility Agreement & Consent Order*
FMP	Fluid Management Plan
ft	Foot (feet)
ft/d	Foot (feet) per day
ft^2/s	Square foot (feet) per second
GSD	Gas seal door
GSP	Gas seal plug
FY	Fiscal year
HASP	Health and Safety Plan
HRMP	Hydrologic Resources Management Program
HSU	Hydrostratigraphic unit
IDW	Investigation-derived waste
in.	Inch(es)
in./yr	Inches per year
K	Hydraulic conductivity

List of Acronyms and Abbreviations *(Continued)*

K_d	Distribution coefficient
km	Kilometer
kt	Kiloton
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
LTHMP	Long-Term Hydrologic Monitoring Program
m	Meter
MCL	Maximum contaminant level
m/d	Meters per day
MDA	Minimum detectable activity
MDC	Minimum detectable concentration
mg/L	Milligrams per liter
: g/L	Micrograms per liter
mil	Parts per thousand
MPC	Maximum Permissible Concentration
mrem	Millirem
mrem/yr	Millirem per year
MWL	Meteoric water line
NDEP	Nevada Division of Environmental Protection
NEPA	*National Environmental Policy Act*
NNSA/NSO	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office
NTS	Nevada Test Site
OSHA	Occupational Safety and Health Administration
PAL	Preliminary action level
pCi/L	Picocuries per liter
PDF	Probability density function

List of Acronyms and Abbreviations *(Continued)*

PEST	Parameter Estimation
PPE	Personal protective equipment
QA	Quality assurance
QA/QC	Quality assurance and quality control
QAPP	Quality Assurance Project Plan
QC	Quality control
RadCon	Radiological Control
RCRA	Resource Conservation and Recovery Act
REECo	Reynolds Electrical & Engineering Co., Inc.
REOP	Real Estate/Operations Permit
RNM	Radionuclide Migration Project
RPP	Radiation Protection Program
RREMP	Routine Radiological Environmental Monitoring Plan
RTTF	Residence Time Transfer Project
RWP	Radiological Work Permit
SDWA	*Safe Drinking Water Act*
SMOW	Standard mean ocean water
SNJV	Stoller-Navarro Joint Venture
SPTR	Streamline Particle Tracking
SSHASP	Site-Specific Health and Safety Plan
STP	Special Technical Publication
TWG	Technical Working Group
UGTA	Underground Test Area
USGS	U.S. Geological Survey
UZ	Unsaturated Zone
VOIA	Value of Information Analysis

List of Acronyms and Abbreviations *(Continued)*

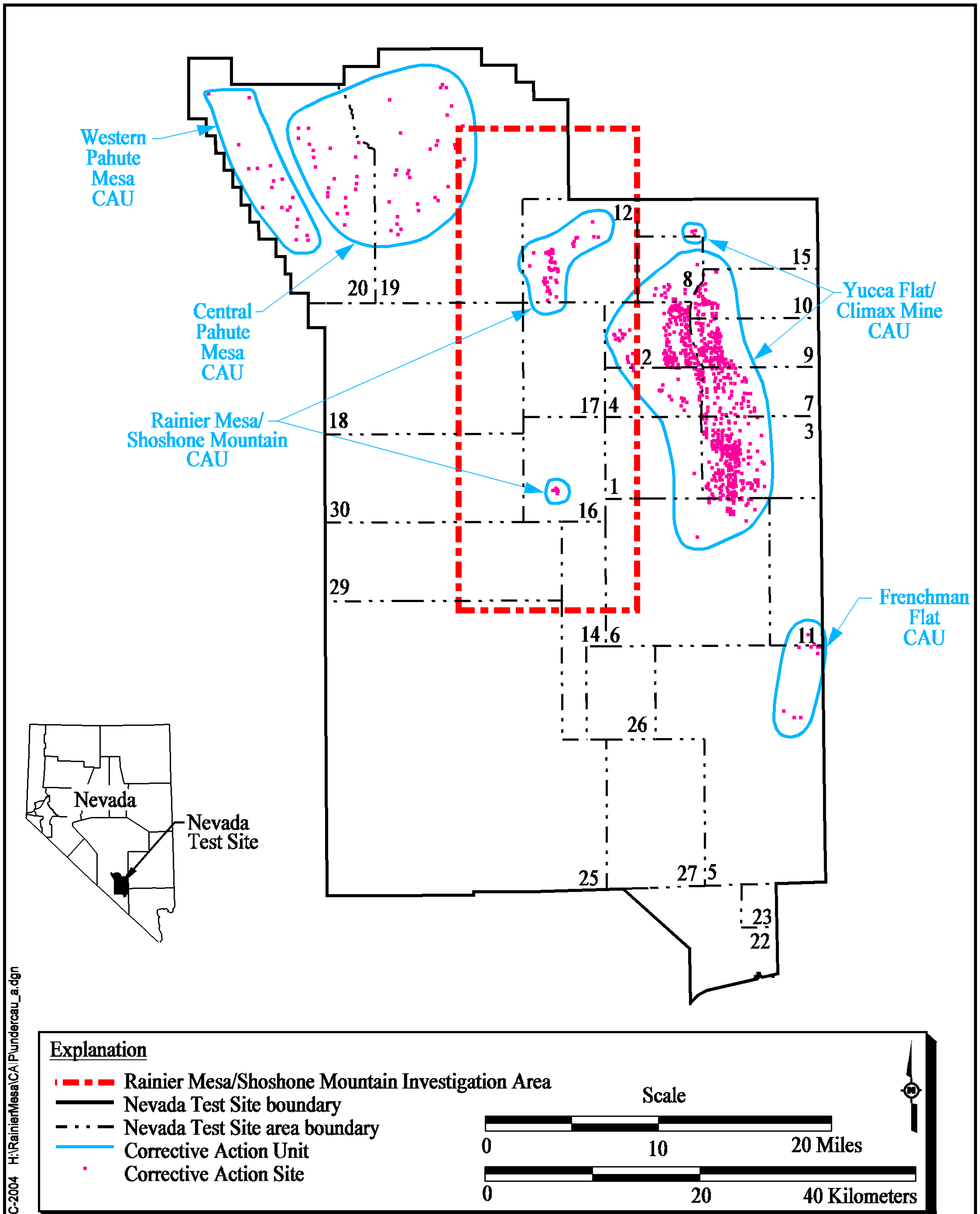
WMP	Waste Management Plan
WP	Working Point
WTA	Welded Tuff Aquifer
ybp	Years before present
YMP	Yucca Mountain Project

1.0 Introduction

This Corrective Action Investigation Plan (CAIP) was developed for Corrective Action Unit (CAU) 99, Rainier Mesa/Shoshone Mountain. The CAIP is a requirement of the *Federal Facility Agreement and Consent Order* (FFACO) agreed to by the State of Nevada, the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DoD) (FFACO, 1996). The FFACO addresses environmental restoration activities at U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office (NNSA/NSO) facilities and sites including the underground testing area(s) of the Nevada Test Site (NTS). This CAIP describes the investigation activities currently planned for the Rainier Mesa/Shoshone Mountain CAU. These activities are consistent with the current Underground Test Area (UGTA) Project strategy described in Section 3.0 of Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996) and summarized in Section 2.1.2 of this plan.

The Rainier Mesa/Shoshone Mountain CAU extends over several areas of the NTS (Figure 1-1) and includes former underground nuclear testing locations in Areas 12 and 16. The area referred to as "Rainier Mesa" includes the geographical area of Rainier Mesa proper and the contiguous Aqueduct Mesa. Figure 1-2 shows the locations of the tests (within tunnel complexes) conducted at Rainier Mesa. Shoshone Mountain is located approximately 20 kilometers (km) south of Rainier Mesa, but is included within the same CAU due to similarities in their geologic setting and in the nature and types of nuclear tests conducted. Figure 1-3 shows the locations of the tests conducted at Shoshone Mountain. The Rainier Mesa/Shoshone Mountain CAU falls within the larger-scale Rainier Mesa/Shoshone Mountain Investigation Area, which also includes the northwest section of the Yucca Flat CAU as shown in Figure 1-1.

Rainier Mesa and Shoshone Mountain lie adjacent to the Timber Mountain Caldera Complex and are composed of volcanic rocks that erupted from the caldera as well as from more distant sources. This has resulted in a layered volcanic stratigraphy composed of thick deposits of welded and nonwelded ash-flow tuff and lava flows. These deposits are proximal to the source caldera and are interstratified with the more distal facies of fallout tephra and bedded reworked tuff from more distant sources. In each area, a similar volcanic sequence was deposited upon Paleozoic carbonate and siliciclastic rocks that are disrupted by various thrust faults, normal faults, and strike-slip faults. In both Rainier Mesa



Source: Modified from Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996)

Figure 1-1
Location of the Rainier Mesa/Shoshone Mountain Corrective Action Unit and Corrective Action Sites at the Nevada Test Site

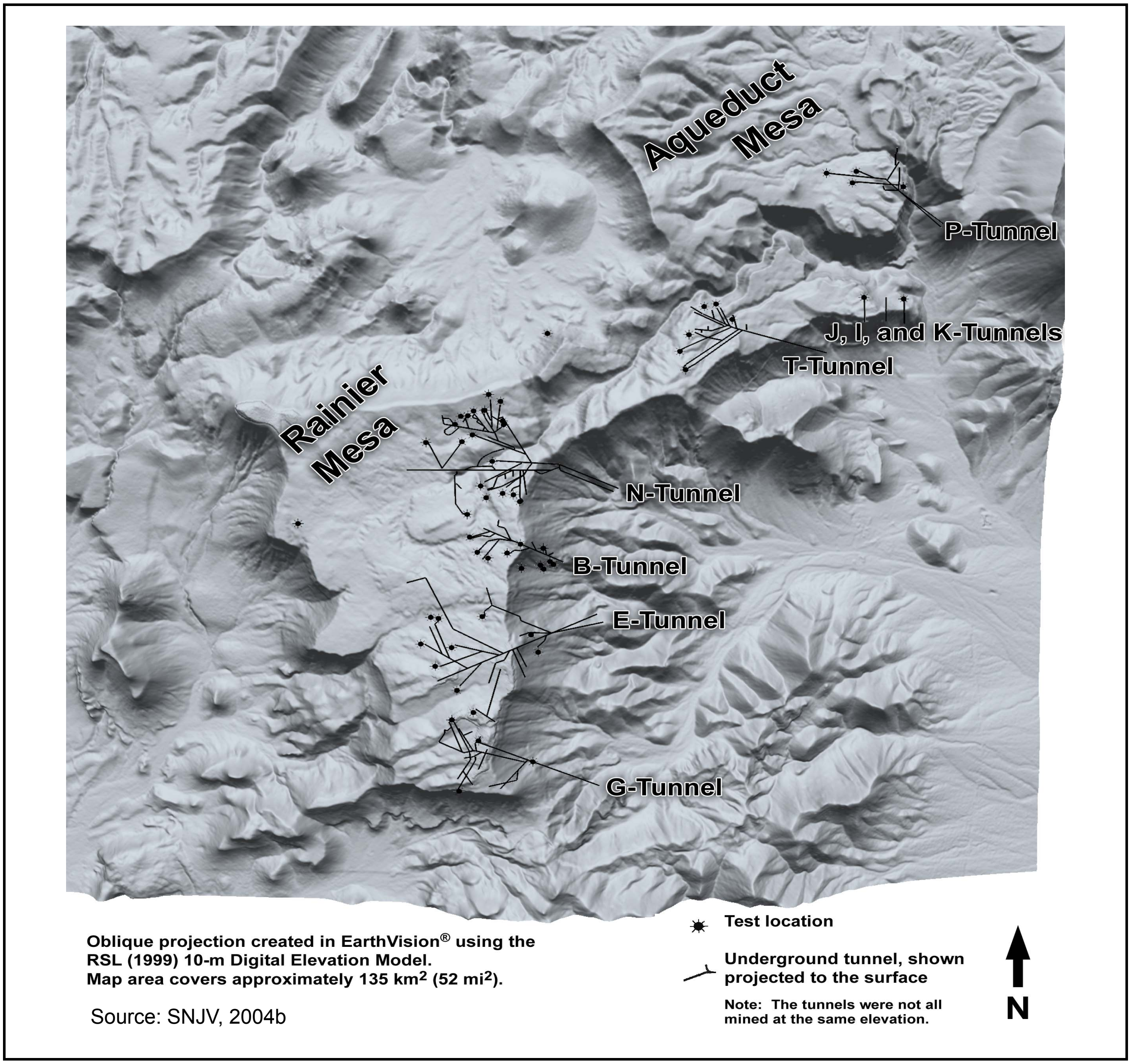
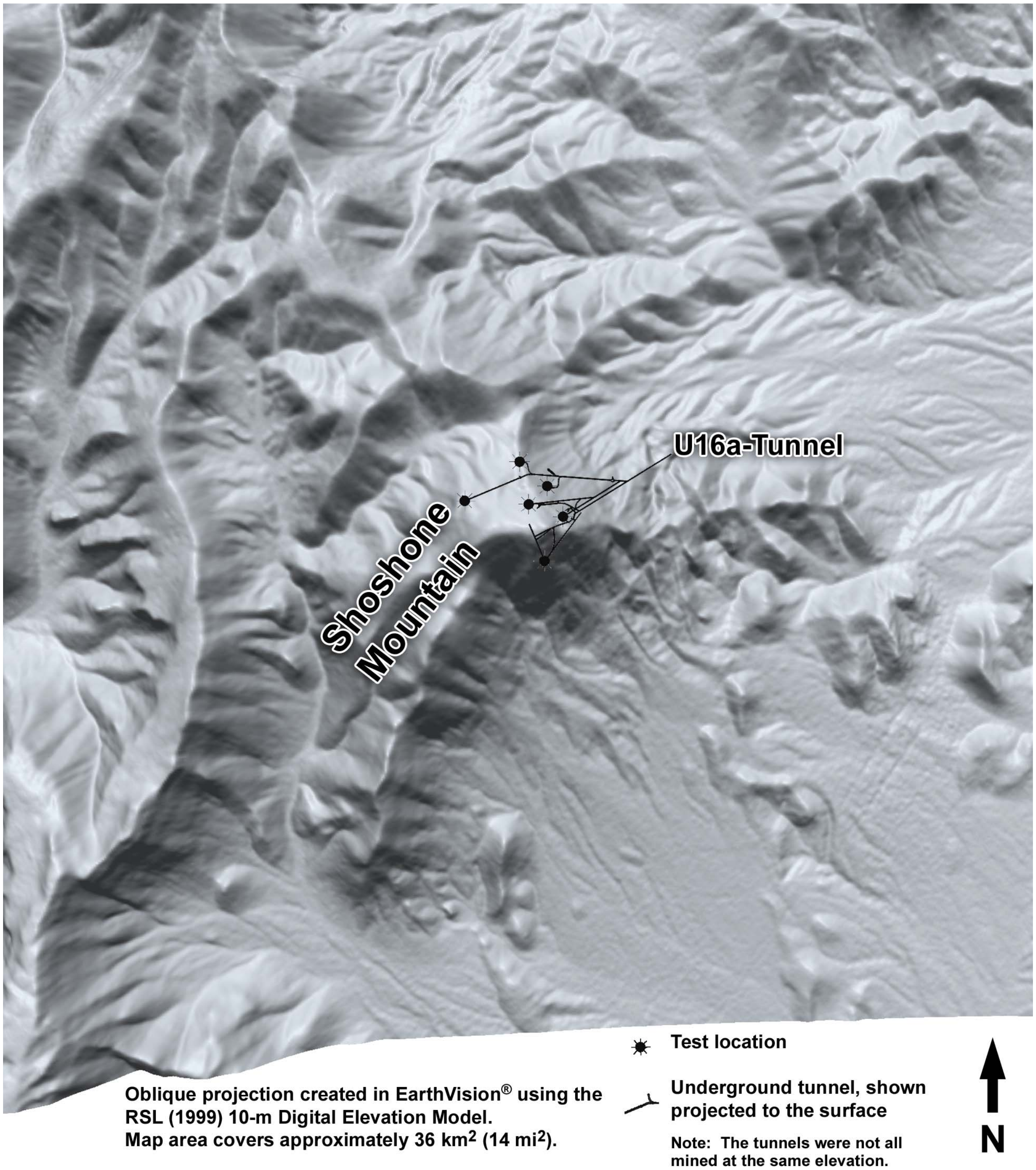


Figure 1-2
Rainier Mesa Tunnels and Testing Locations

and Shoshone Mountain, underground nuclear tests were conducted in tunnel complexes excavated above the regional groundwater table. Tunnel complexes in Rainier Mesa contain local perched groundwater near the elevation of the tests, as evidence by water in the drifts. There is evidence of groundwater contamination from the Rainier Mesa test tunnel complexes. There is no perched water evident in the vicinity of the Shoshone Mountain complex. The nearest springs, which are not likely to be hydraulically connected to the Shoshone tunnel complex, are Topopah Spring, 10 kilometers



Source: SNJV, 2004b

Figure 1-3
Shoshone Mountain Tunnels and Testing Locations

(km) to the southwest, and Tippipah Spring, 4 km to the north, and the tunnel complex is dry. Particle-tracking simulations performed during the value of information analysis (VOIA) (SNJV, 2004b) indicate that most of the regional groundwater that underlies the test locations at Rainier Mesa and Shoshone Mountain eventually follows similar and parallel paths and ultimately discharges in Death Valley and the Amargosa Desert. Particle-tracking simulations conducted for the regional groundwater flow and risk assessment indicated that contamination from Rainier Mesa and Shoshone Mountain were unlikely to leave the NTS during the 1,000-year period of interest (DOE/NV, 1997a). It is anticipated that CAU-scale modeling will modify these results somewhat, but it is not expected to radically alter the outcome of these previous particle-tracking simulations within the 1,000-year period of interest.

The Rainier Mesa/Shoshone Mountain CAIP describes the corrective action investigation (CAI) to be conducted at the Rainier Mesa/Shoshone Mountain CAU to evaluate the extent of contamination in groundwater due to the underground nuclear testing. The CAI will be conducted by the UGTA Project, which is part of the NNSA/NSO Environmental Restoration Project (ERP). The purpose and scope of the CAI are presented in this section, followed by a summary of the entire document.

1.1 Purpose

Based on the general definition of the CAI from Section IV.14 of the FFACO, the purpose of the CAI is "…to gather data sufficient to characterize the nature, extent, and rate of migration or potential rate of migration from releases or discharges of pollutants or contaminants and/or potential releases or discharges from corrective action units identified at the facilities…" (FFACO, 1996). For each UGTA CAU, a contaminant boundary delineating the portion of the groundwater system that may be unsafe for domestic and municipal use will be established (Appendix VI, Revision No. 1 [December 7, 2000] of the FFACO [1996]). According to the UGTA Corrective Action Strategy (Appendix VI, Revision No. 1 [December 7, 2000] of the FFACO [1996]), the CAI of a given CAU begins with the evaluation of existing data. New data collection activities are generally contingent upon the results of the CAU modeling, and may or may not be a part of the initial CAI. The term "CAU model," as used in this document, means the groundwater flow and contaminant transport model for the Rainier Mesa/Shoshone Mountain CAU. Any other types of models referred to in this document are explicitly stated. However, the Rainier Mesa/Shoshone Mountain CAI includes new data collection prior to initiation of the CAU modeling to fill relevant data gaps identified during the regional evaluation (DOE/NV, 1997a) and the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b).

Specific objectives of the CAI are as follows:

- Determine the characteristics of the groundwater flow system, the sources of contamination, and the transport processes to acceptable levels of uncertainty.
- Develop a credible numerical model of groundwater flow and contaminant transport for the Rainier Mesa/Shoshone Mountain CAU and down-gradient areas.
- Develop stochastic predictions of the contaminant boundary at an acceptable level of uncertainty.

1.2 Scope

This CAIP discusses the current scope of the Rainier Mesa/Shoshone Mountain CAI which includes the following activities:

- Three characterization activities to collect additional information
- Collection and evaluation of geophysical information
- The development and use of a three-dimensional (3-D), numerical, CAU-scale groundwater flow and transport model to predict the location of the contaminant boundary
- The development and use of several secondary models to support the CAU model

The characterization activities will be conducted before the initiation of model development to provide data for the CAU model. Characterization activities include field studies designed to reduce existing data uncertainties, and data analysis and modeling techniques to interpret the existing and newly acquired data. Field activities include well drilling and completion, and sampling and analysis of groundwater. Data analysis techniques and models used in support of field and laboratory data interpretation include mapping, geochemical modeling, geophysical and geologic modeling, local groundwater flow and transport modeling, and various other approaches described in Section 5.0 and Section 6.0. The field scope of work also includes support activities to fulfill health and safety, waste management, and quality control (QC) requirements.

The CAU-scale groundwater flow and contaminant transport model will be constructed for an area encompassing the Rainier Mesa/Shoshone Mountain CAU. The potential CAU model area encompasses the Rainier Mesa/Shoshone Mountain CAU, the western portion of Yucca Flat, a portion of the Timber Mountain Caldera Complex to the west, and the northern portion of Jackass Flats. These collective areas are referred to as the Shoshone Mountain/Rainier Mesa Investigation Area (Figure 1-1, Plate 1). The formal extent of the CAU model area will be finalized after the available geologic and hydrogeologic data are assessed. The final CAU model area will depend on the predicted extent of contamination. The area of investigation is the region where data will be collected and summarized for possible inclusion in the CAU model, and will be at a sufficient scale that all possible pathways for radionuclide migration from the Rainier Mesa/Shoshone Mountain CAU are considered.

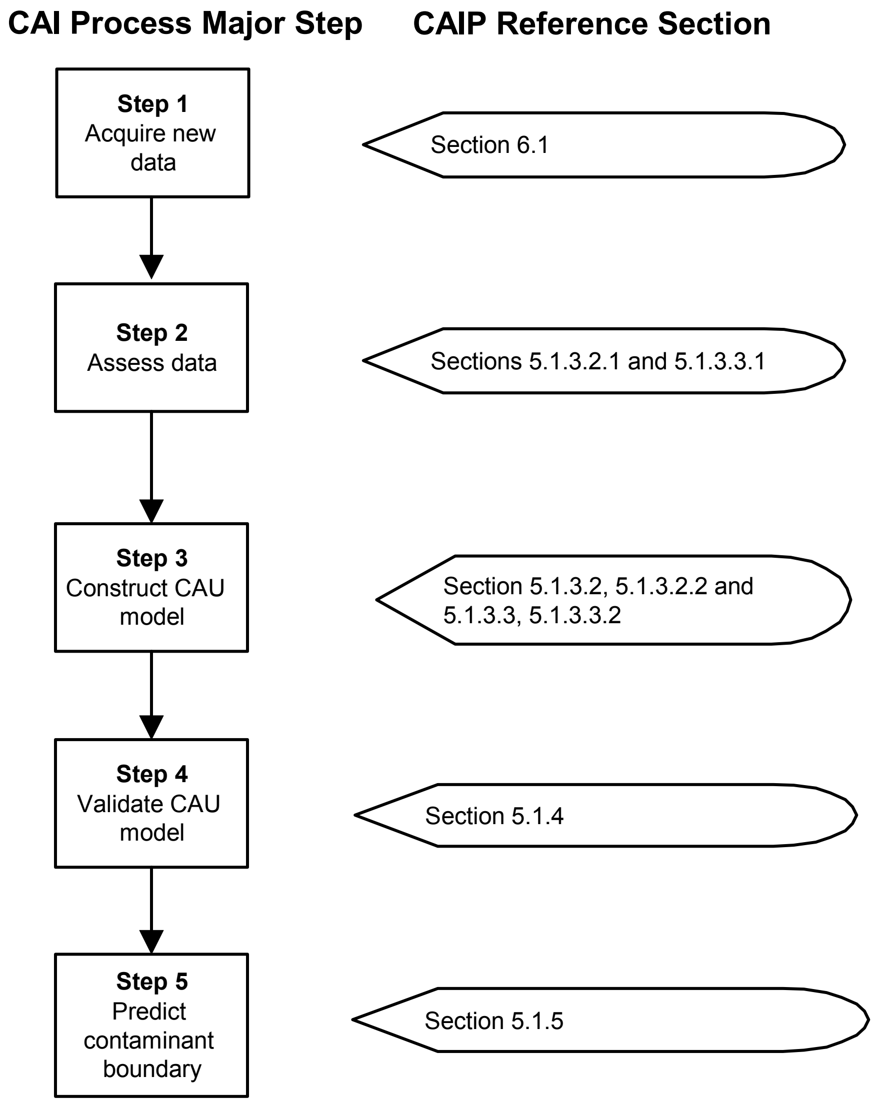
The CAU model will be developed and used to predict the location of the contaminant boundary. Modeling activities consist of code selection, compilation and evaluation of existing and newly acquired data, model development (including calibration and sensitivity analysis), uncertainty analysis, and contaminant boundary definition.

1.3 Summary of the CAIP

An overview of the technical elements of the CAIP is presented, followed by a summary description of the contents of the CAIP.

1.3.1 Overview of Technical Elements of the CAIP

The Rainier Mesa/Shoshone Mountain CAI will be conducted by NNSA/NSO with the involvement of the Nevada Division of Environmental Protection (NDEP) throughout the entire process. The CAI will progress in five sequential steps in accordance with the UGTA strategy described in Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996) and summarized in Section 2.1.2 of this document. Figure 1-4 summarizes the five steps and references the sections of the CAIP in which they are discussed. Documents generated to report the technical findings of the CAI are also described at the end of this section.



CAI: Corrective Action Investigation
CAIP: Corrective Action Investigation Plan
CAU: Corrective Action Unit

Source: Modified from SNJV, 2004b

Figure 1-4
Overview of Technical Elements of the Rainier Mesa/Shoshone Mountain CAIP

1.3.1.1 Characterization Activities

The proposed collection of new data is part of characterization activities designed to reduce existing uncertainties in the current conceptual model. The following activities were defined using the Data Quality Objectives (DQOs) process described in Section 4.0 and Appendix A:

- Two new drill holes at Rainier Mesa and one new drillhole at Shoshone Mountain
- Sampling at new and existing locations and laboratory analysis of samples
- Collection and evaluation of geophysical information for the Rainier Mesa and Shoshone Mountain region

These characterization activities will be conducted prior to the start of modeling. The plans for these activities are described in Section 6.0.

1.3.1.2 Assessment of CAU-Related Data

Following completion of the characterization activities, the existing and newly acquired data will be assessed and used to refine the current conceptual groundwater flow and transport model. The existing data described in Section 3.0 will be supplemented with historical data acquired from public and private sources, and from data acquired from ongoing characterization and monitoring programs. All relevant published and unpublished existing data will be considered. Newly acquired data are those gathered from activities described in Section 6.0. The new data will be added to existing datasets prior to data assessment activities. The data assessment activities are described in Section 5.1.3.2.1 and Section 5.1.3.3.1. The results of the data assessment process will be reported in several data reports and documentation packages as described in Section 1.3.1.6

1.3.1.3 Development of Numerical Groundwater Flow and Transport Model

The refined conceptual model and all supporting data will be used to develop a 3-D groundwater flow and transport model at the CAU scale. Several other models of varying scales may also be used to support the CAU model.

The CAU model will simulate groundwater flow and contaminant transport under transient conditions. The scale of this model will be large, on the order of hundreds of square kilometers. The procedure for developing the CAU groundwater flow and contaminant transport model is detailed in Section 5.1.3.2, Section 5.1.3.2.2, Section 5.1.3.3, and Section 5.1.3.3.2. Other models used to support the CAU model may include:

- Hydrologic models at scales ranging from small (less than 1 km) to intermediate (about 5 km) to investigate specific hydrogeologic features at smaller scales than that of the CAU model.
- A near-field model (small-scale) to simulate the hydrologic source term.
- The NTS regional groundwater flow model to help estimate boundary conditions for the CAU model.

Brief descriptions of these models and their use in support of the CAU model are provided in Section 5.1.3.2.2.

1.3.1.4 Verification of Numerical Groundwater Flow and Contaminant Transport Model

When the CAU model is completed, it will be evaluated by NNSA/NSO, NDEP, and a peer review panel. If NNSA/NSO and NDEP do not provide written justification for rejecting the CAU model, a model verification plan will be prepared and submitted to NDEP as an addendum to this CAIP. Once the model verification plan is approved, it will be implemented. In the event that the CAU model is rejected, NNSA/NSO and NDEP will initiate discussions to identify the appropriate path forward. Activities relating to this step are detailed in Section 5.1.4.8.

1.3.1.5 Prediction of Contaminant Boundary

The CAU model will be used to simulate a contaminant boundary. The contaminant boundary is the starting point from which a compliance boundary is negotiated between NNSA/NSO and NDEP. A post-audit of the CAU model will be performed to verify the validity of the results during a five-year proof-of-concept period. This process is detailed in Section 5.1.5.

1.3.1.6 CAI Documentation

The Rainier Mesa/Shoshone Mountain CAI activities will be discussed in several reports. These include data reports, data documentation packages, model reports, and a Corrective Action Decision Document (CADD) as follows:

- Data reports will describe the results of the characterization activities.
- A geologic/hydrostratigraphic data documentation report will describe the assessment of geologic data and the resulting hydrostratigraphic model.
- A hydrologic data documentation report will describe the assessment of groundwater data, including geochemistry, areal recharge, surface discharge, lateral boundary flux, hydraulic properties, and hydraulic heads.
- A transport data documentation report will describe the contaminant transport data relating to porosity, dispersivity, matrix diffusion, matrix and fracture sorption, and colloid-facilitated transport.
- A source term data documentation report will describe the likely contaminant inventory, test phenomenology as it relates to the mobilization of contaminants, and upscaling from near field models of contaminant distribution to the scale of the CAU.
- The CAU model report will summarize the CAU modeling effort and its results.
- The CADD will discuss the findings of all CAI activities, including the CAU model, its verification, and contaminant boundary predictions. In addition, the CADD will describe the corrective action alternatives considered and the recommended alternative.

If additional models are created to support the CAU modeling, they will be documented in the CAU model report or in separate model documents, as appropriate.

1.3.2 Document Organization

As required by the FFACO, this CAIP provides or references all specific information used for planning the investigation activities associated with the Rainier Mesa/Shoshone Mountain CAU. Specific information required by the FFACO, and provided or referenced in this CAIP, include administrative and technical aspects, quality assurance (QA), health and safety, public involvement, field sampling, and waste management (FFACO, 1996). The organization and contents of this document are based on an annotated outline agreed to by the U.S. Department of Energy, Nevada

Operations Office (DOE/NV) and NDEP (Liebendorfer, 1998). This document consists of nine sections and one appendix, summarized as follows:

- Section 1.0 describes the purpose and scope of the Rainier Mesa/Shoshone Mountain CAI and provides a summary of the CAIP.
- Section 2.0 describes how the proposed CAI will be planned and conducted in accordance with the requirements of the FFACO.
- Section 3.0 provides a description of the Rainier Mesa/Shoshone Mountain CAU to define the problem at hand. The section includes descriptions of the investigative background of the CAU, its operational history, the Corrective Action Sites (CASs), the physical setting based on available information, the potential contaminants, the conceptual model of the CAU, and the preliminary corrective action levels for the potential contaminants.
- Section 4.0 discusses the results of the DQO process and relates the proposed conceptual model and the migration scenarios identified to these results.
- Section 5.0 describes the planned CAU-scale groundwater flow and contaminant transport modeling activities to be conducted during the CAI, including the assessment of the existing and the newly acquired data described in Section 6.0.
- Section 6.0 provides descriptions of the characterization activities to acquire new information that are planned for the Rainier Mesa/Shoshone Mountain CAU. Supporting activities such as waste management, health and safety, and field sampling and analysis are summarized in this section. References are made to the appropriate plans.
- Section 7.0 includes summary descriptions of the field and laboratory QA/QC procedures. References are made to the appropriate plans.
- Section 8.0 contains a description of the project schedule and records availability information.
- Section 9.0 provides a list of references used to prepare the CAIP.
- Appendix A contains a detailed discussion of the DQO process. The DQO approach used for the Rainier Mesa/Shoshone Mountain CAU and the DQO process results are presented.

The administrative aspects of this project are discussed in the *Nevada Environmental Restoration Project Data Management Plan*, Rev. 0 (DOE/NV, 1994). No CAU-specific public involvement activities are planned at this time; however, an overview of public involvement is documented in the Public Involvement Plan in Appendix V of the FFACO (1996).

2.0 Legal/Regulatory Requirements

The State of Nevada, DOE, and DoD negotiated the FFACO to address environmental restoration activities for release from historic testing activities at the NTS, Tonopah Test Range, parts of the Nellis Air Force Range (now known as the Nevada Test and Training Range), Central Nevada Test Area (CNTA), and Project Shoal Area. The FFACO (1996) is the primary regulatory driver for DOE environmental restoration activities in Nevada. Part III of the FFACO (1996) identifies the legal authorities under which the DOE and NDEP entered into the agreement. The FFACO (1996) and other regulatory requirements that may be applicable to the Rainier Mesa/Shoshone Mountain CAI are discussed in this section. The most relevant of these drivers is Section 3.0 of Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996). This appendix provides the negotiated framework for planning, implementing, and completing corrective action activities for projects covered by the FFACO, including UGTA.

2.1 Federal Facility Agreement and Consent Order

This section includes a summary of the FFACO requirements and the UGTA corrective action strategy as described in the FFACO (1996). It presents the application of the strategy to the Rainier Mesa/Shoshone Mountain CAU, as detailed in Section 3.0 of Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996).

2.1.1 FFACO Requirements

The FFACO requirements that are applicable to the Rainier Mesa/Shoshone Mountain CAU are discussed in this section.

2.1.1.1 General Requirements

The FFACO (1996) sets the framework and contains the requirements for prioritizing and enforcing the environmental restoration activities of contaminated NNSA/NSO facilities and sites. Technical strategies for these activities are also provided in Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996). NNSA/NSO, through the UGTA Project, is responsible for completing corrective actions for five CAUs associated with historical underground nuclear testing on the NTS.

The UGTA CAUs are Frenchman Flat, Western Pahute Mesa, Central Pahute Mesa, Yucca Flat/Climax Mine, and Rainier Mesa/Shoshone Mountain (Figure 1-1). The CAUs were defined based on geography and hydrogeologic characteristics.

Several plans and reports are required to document the corrective action process. These documents provide details about the activities needed to ensure the completion of the corrective action. Documents that are applicable to each of the UGTA CAUs are listed and described below.

Corrective Action Investigation Plan

This FFACO-required document provides or references all specific information for planning investigation activities associated with CAUs.

Corrective Action Decision Document

This FFACO-required report documents the CAI. It describes the results of the CAI, the recommended corrective action, and the rationale for its selection.

Corrective Action Plan

This is the FFACO-required plan for implementing approved corrective actions.

Closure Report

This FFACO-required report documents corrective action implementation and verifies that the corrective action was conducted in accordance with the approved Corrective Action Plan (CAP). The Closure Report also provides information on post-closure monitoring, if needed.

2.1.1.2 Specific Requirements

The Rainier Mesa/Shoshone Mountain CAI is planned and will be conducted in accordance with the appropriate investigation purposes of the FFACO, as outlined in Subparts II.1.b.ii and II.1.c, as well as the requirements of Subparts IV.14 and IV.15 and Appendix VI (Revision No. 1 [December 7, 2000]) (FFACO, 1996). Each of these specific subparts of the FFACO is quoted below, followed by a description of how their requirements are being fulfilled during the CAI.

> II.1.b.ii. Determine whether releases of pollutants and/or hazardous wastes or potential releases of pollutants and/or hazardous wastes are migrating or potentially could migrate, and if so, identify the constituents, their concentration(s), and the nature and extent of that migration;…

In accordance with FFACO Section II.1.b.ii., characterization and modeling activities designed to determine whether releases are migrating or could potentially migrate are planned in the CAI as described in Section 5.0 and Section 6.0. Also, in accordance with this subpart, a preliminary list of the constituents and their concentrations is provided in Section 3.5. A description of the nature and extent of the contaminant migration based on the current information is presented in Section 3.4 through Section 3.6 of this report.

> II.1.c. Providing all parties with sufficient information to enable adequate evaluation of appropriate remedies by specifying the radioactive and hazardous constituents for each corrective action unit.

As required by FFACO Subpart II.1.c., a preliminary list of radioactive and hazardous constituents for the Rainier Mesa/Shoshone Mountain CAU is provided in Section 3.5 of this report. This list provides all parties with sufficient information to enable adequate evaluation of appropriate remedies and will be updated based on the findings made during the CAI.

> IV.14. "Corrective action investigation" (CAI) shall mean an investigation conducted by the DOE and/or DoD to gather data sufficient to characterize the nature, extent, and rate of migration or potential rate of migration from releases or discharges of pollutants or contaminants and/or potential releases or discharges from corrective action units identified at the facilities.

In accordance with FFACO Subpart IV.14., the Rainier Mesa/Shoshone Mountain CAI will be conducted by NNSA/NSO to gather sufficient data to characterize the nature, extent, and rate of migration or potential rate of migration from releases or potential releases of contaminants from the Rainier Mesa/Shoshone Mountain CAU. This CAIP describes the planned investigation activities which include field data gathering (Section 6.0) and groundwater flow and transport modeling at the CAU scale (Section 5.0).

> IV.15. "Corrective action investigation plan" (CAIP) shall mean a document that provides or references all of the specific information for planning investigation activities associated with corrective action units of corrective action sites. A CAIP may reference information in the optional CAU work plan or other applicable documents. If a CAU work plan is not developed, then the CAIP must include or reference all of the management, technical, quality assurance,

health and safety, public involvement, field sampling, and waste management information needed to conduct the investigations in compliance with established procedures and protocols.

In accordance with FFACO Subpart IV.15., this CAIP provides or references all of the specific information for planning investigation activities associated with the Rainier Mesa/Shoshone Mountain CAU. The CAIP includes or references all management, technical, QA, health and safety, public involvement, field sampling, and waste management information needed to conduct the investigation in compliance with established procedures and protocols as described in Section 1.0.

All information provided in this CAIP is based on the current state of knowledge and will be updated following completion of the CAI. The results of this CAI will ultimately be reported in the CADD.

2.1.2 Corrective Action Strategy

The NNSA/NSO and NDEP will work together throughout the implementation of the strategy for each of the UGTA CAUs, including the Rainier Mesa/Shoshone Mountain CAU, as negotiated by DOE and NDEP for UGTA (Appendix VI, Revision No. 1 [December 7, 2000] of the FFACO [1996]). Upon approval of the CAIP and at the beginning of each fiscal year in which the CAI is conducted, NNSA/NSO will inform NDEP of the planned activities for the CAI. NNSA/NSO will facilitate any visits or meetings requested by NDEP to evaluate the CAI process presented in Section 5.0. The NNSA/NSO will also identify when various work products will be available for transmittal to NDEP. The details of the implementation of the UGTA strategy are described in the following section.

2.1.2.1 Description of Corrective Action Strategy

The objective of the UGTA Corrective Action strategy is to analyze and evaluate each UGTA CAU through a combination of data and information collection and evaluation, and modeling of groundwater flow and contaminant transport. The corrective action strategy for UGTA is based on the complex corrective action process (Appendix VI, Revision No. 1 [December 7, 2000] of the FFACO [1996]).

2.1.2.1.1 General Definition of Contaminant Boundary

The UGTA Corrective Action Strategy was developed to address the contamination created by the underground testing of nuclear devices in shafts and tunnels at the NTS. This analysis will estimate the vertical and horizontal extent of contaminant migration for each CAU in order to predict contaminant boundaries. The definition of contaminant boundary has been described in Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996) as follows:

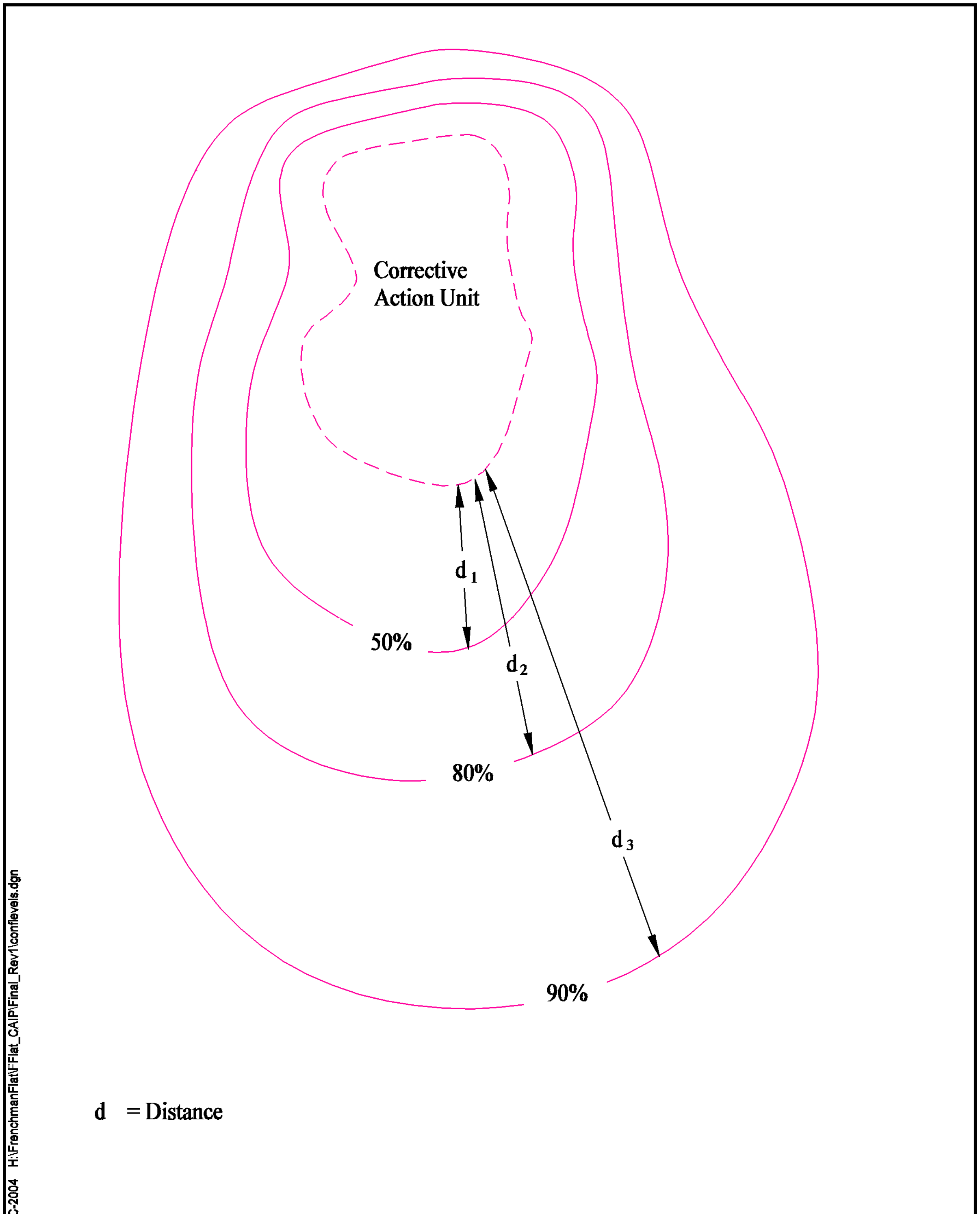
> "A contaminant boundary is the model-predicted perimeter which defines the extent of radionuclide-contaminated groundwater from underground testing above background conditions exceeding the *Safe Drinking Water Act* (SDWA) standards. The contaminant boundary will be composed of both a perimeter boundary and a lower hydrostratigraphic unit boundary. The computer model predicts the location of this boundary within 1,000 years and must do so at a 95 percent level of confidence. Additional results showing contaminant concentrations and the location of the contaminant boundary at selected times will also be presented. These times may include the verification period, the end of the five-year proof of concept period, as well as other times that are of specific interest."

Figure 2-1 illustrates how modeling uncertainty can be expressed as confidence levels. Each contour reflects an increased level of confidence that no contaminants exceeding a given regulatory concentration will ever cross that boundary. As confidence increases, the distance from the CAU increases. The confidence levels could lead to the development of different contaminant boundaries, depending on the degree of certainty decision makers need to select appropriate controls (FFACO, 1996).

2.1.2.1.2 Process Description

The process used to achieve the strategy is defined in the flow diagram on page VI-3-6 of Appendix VI, Revision No. 1, December 7, 2000, of the FFACO, 1996 (Figure 2-2). The objective of the CAI process is to define boundaries around each UGTA CAU to establish areas that contain water that may be unsafe for domestic and municipal use (FFACO, 1996).

Once the CAIP is approved, the CAI will be implemented. The CAI includes collecting new data and evaluating the existing and new geologic, hydrologic, geochemical, isotopic, and radionuclide information available for the CAU. The first major decision point is the determination of whether the data are adequate. If the data are adequate, the CAU flow and contaminant transport model will be



Source: Modified from Appendix VI, Revision No. 1 (December 7, 2000) of the FFACO (1996).

Figure 2-1
Example of Contaminant Boundary Confidence Levels

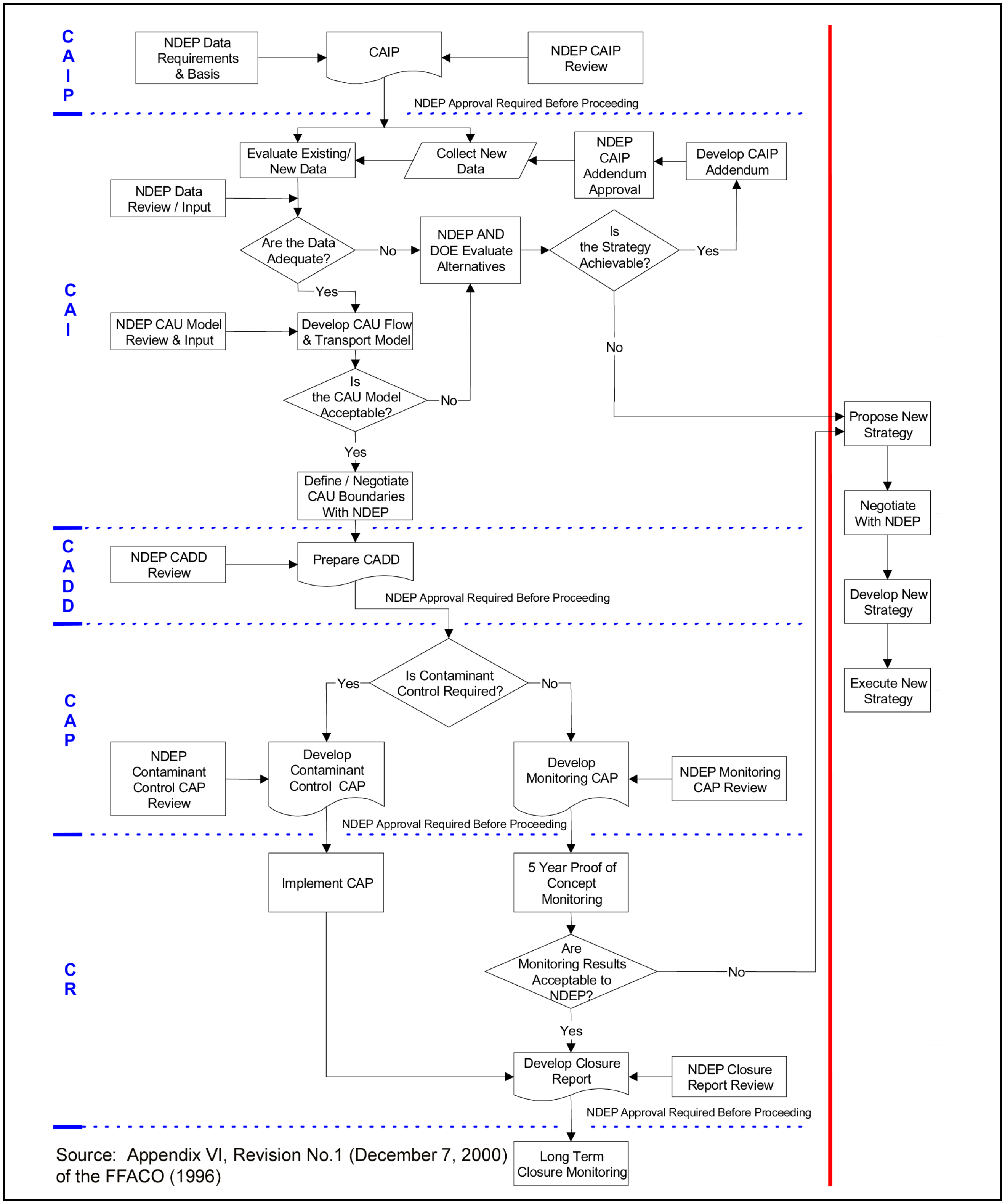


Figure 2-2
Decision Diagram for the Underground Test Area

developed. If the data are not adequate, alternatives will be evaluated, and the second major decision point, a decision on whether the UGTA strategy can be achieved, will be reached. If the strategy can be achieved, an addendum to the CAIP will be developed, approved, and implemented. If the strategy cannot be achieved, a new strategy will be proposed (FFACO, 1996).

After the CAU flow and transport model is developed, the third major decision point reached is the determination of whether the CAU groundwater flow and contaminant transport model is acceptable. If it is, the CAU boundaries will be defined and negotiated with NDEP. If not, the alternatives will be evaluated, and a determination will be made regarding whether the strategy can be achieved. If the strategy can be achieved, an addendum to the CAIP will be developed and implemented. If the strategy cannot be achieved, a new strategy will be proposed. Once the contaminant boundary is accepted, the final step of the CAI process is that NNSA/NSO and NDEP will negotiate the compliance boundary (FFACO, 1996).

After the compliance boundary is defined and accepted, NNSA/NSO will evaluate various remedial alternatives and propose a corrective action. The CAU data analysis and model results, contaminant boundary, and proposed corrective action will be documented in the CADD and submitted to NDEP for approval. After approval of the CADD, a CAP will be developed to implement the approved corrective action. An initial assumption is that contaminant control will not be required. If the corrective action is long-term monitoring, a five-year proof-of-concept period will be initiated using groundwater wells in a monitoring network to determine if the monitoring network design will provide adequate CAU surveillance. If the monitoring network is found acceptable, a closure report will be developed, followed by implementation of a long-term closure monitoring program. Monitoring compliance with the CAU boundary will be accomplished through measurement of appropriate physical and chemical parameters in wells within the modeled region. Appropriate physical and chemical parameters remaining within the range of measurements used in the flow model will be an indication that the conditions have not significantly changed. Sensitivity analysis of parameters relevant to the groundwater will indicate the extent that appropriate physical and chemical parameters can vary before the acceptable confidence limit for the model is exceeded. If the results are not acceptable, NNSA/NSO and NDEP will determine whether the strategy is still achievable (FFACO, 1996). If not, new strategies will be considered.

The long-term closure monitoring program will address any contamination left in place in a closed CAU. This program consists of all activities necessary to ensure protection of human health and the environment following the completion of corrective actions at a CAU. These activities will include periodic analysis of monitoring results, determining optimum performance indicators, evaluation of monitoring performance criteria, locating new monitoring wells, and replacing existing monitoring wells to support performance criteria evaluation at timed intervals of interest within the 1,000-year time period (FFACO, 1996).

2.1.2.2 Implementation of Corrective Action Strategy

The NNSA/NSO's approach for implementing the FFACO strategy for the UGTA CAUs is described in this section. The approach is described in terms of the specific definition of the contaminant boundary, CAI, corrective action implementation, and CAU closure.

2.1.2.2.1 Specific Definition of the Contaminant Boundary

For the Rainier Mesa/Shoshone Mountain CAU, where unsaturated groundwater conditions prevail, saturated zone flow and transport modeling results, based on field data, will be evaluated to determine if the saturated zone was impacted. If the saturated zone was impacted, then the need for further examination of the unsaturated zone will be evaluated (FFACO, 1996).

The CAU model will use tritium as the source term to establish the contaminant boundary. The boundary will be composed of a perimeter boundary and a lower hydrostratigraphic unit boundary. The perimeter boundary will define the aggregate maximum extent of contamination transport at or above the concentration of concern for the CAU. The lower hydrostratigraphic unit boundary will define the lowest aquifer unit affected by the contamination. In addition to tritium, long-lived radionuclides will be included to evaluate the relative extent of migration of different radionuclides in the future. If it is predicted that another radionuclide will migrate farther than tritium at concentrations of concern, the contaminant boundary will include that prediction.

2.1.2.2.2 Corrective Action Investigation

The CAI is led by the NNSA/NSO UGTA Project Manager. A Technical Working Group (TWG) was formed to assist the NNSA/NSO UGTA Project Manager with technical issues. The TWG consists of representatives from the participating organizations, and currently includes Bechtel Nevada (BN), Desert Research Institute (DRI), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Stoller-Navarro Joint Venture (SNJV), and the U.S. Geological Survey (USGS). The TWG serves as a technical advisory group to the NNSA/NSO UGTA Project Manager. Tasks assigned to the TWG committee include providing technical recommendations to NNSA/NSO, providing expert technical support in specific UGTA tasks by way of subcommittees, and serving as internal peer reviewers of UGTA products.

The CAI process consists of two major stages: collection and evaluation of data, and development of the CAU groundwater flow and contaminant transport model. These stages both rely on the use of the regional groundwater flow and transport model (DOE/NV, 1997a), which is a model of regional flow encompassing the NTS and the groundwater flow systems extending to downgradient discharge points. Regional modeling is a cross-cutting activity that supports the entire UGTA program. It provides the initial basis for assessing flowpaths from CAUs, determining potential receptors, evaluating isolation or interaction of CAUs, and creating a consistent hydrogeologic framework across all the CAUs. Regional transport modeling provides the initial basis for determining the magnitude of risk from the source to potential receptors and for scaling individual CAU work (FFACO, 1996).

Collection and Evaluation of Data

In the first stage, NNSA/NSO will collect new data to address deficiencies in existing data, or to improve the assimilation and utilization of existing data. The data collection activities undertaken will be those specific tasks detailed in the CAIP or an addendum to the CAIP. Next, NNSA/NSO will evaluate new and existing data to determine if this current data set will allow for the development of an acceptable flow and contaminant transport model, and provide the data evaluation results to NDEP. NDEP will review work products and supplemental materials, attend presentations on the status of the investigation, and provide comments to NNSA/NSO specifically aimed at data adequacy issues and the data evaluation process (FFACO, 1996).

After NNSA/NSO completes its evaluation of existing and new data, the results will be published in a series of data documentation packages and delivered to NDEP for review. These data documentation packages document the hydrostratigraphic framework model, the hydrologic data, the contaminant transport data, and the source term. If either party determines that the data are not adequate to develop a flow and contaminant transport model to meet the conditions of the strategy, or that the flow and contaminant transport model has not produced acceptable results, then NDEP and NNSA/NSO will conduct an evaluation of the alternatives. If it is determined that the strategy is achievable, then NNSA/NSO will develop and prepare an addendum to the CAIP. The CAIP Addendum will address the identified needs, how these needs are translated to requirements, and what additional work activities will be conducted to address and/or satisfy these requirements. The CAIP Addendum will be structured as mutually agreed to by NNSA/NSO and NDEP prior to document preparation. During the development and preparation of the CAIP Addendum, NNSA/NSO will keep NDEP informed and updated in order to expedite NDEP's review and approval. If an addendum is required, CAI-related activities will not be initiated until NDEP has approved the CAIP Addendum.

Development of the CAU Groundwater Flow and Contaminant Transport Model

Once DOE and NDEP agree that the data are correct the flow and transport model will be developed. The CAU-scale groundwater flow and contaminant transport model will be a 3-D, mathematical representation of the important physical and chemical features of the flow system, and will simulate the movement of a variety of radiological contaminants through the water-bearing units. For the Rainier Mesa/Shoshone Mountain CAU, the Finite Element Heat and Mass (FEHM) transfer code developed by LANL is proposed. Evaluation of the scale of the CAU and distance between parts of the flow system may result in the construction of two sets of CAU models to model groundwater flow and contaminant transport separately for Rainier Mesa and Shoshone Mountain.

First, a hydrostratigraphic model will be constructed from surface and subsurface geologic and geophysical data. Alternative interpretations of the hydrostratigraphy will be developed to account for different interpretations of the geology that are still consistent with the data. The alternatives will be used to create alternative flow models. The hydrostratigraphic models will then be used in conjunction with boundary fluxes, recharge and discharge data, hydraulic head data, and hydraulic conductivity data to develop flow models. After completion of the flow models, a contaminant transport model will be developed from each flow model that is plausible. The contaminant transport models will estimate the extent to which the migration of radionuclides exceed the SDWA standards above background within 1,000 years, which will comprise the contaminant boundary. These alternative models together comprise the CAU model.

The CAU model will be reviewed by NNSA/NSO and presented to NDEP for review and evaluation. Both NNSA/NSO and NDEP will evaluate the flow and contaminant transport model to determine if it is acceptable for defining the contaminant boundary (FFACO, 1996). The model will also be reviewed by an external peer review panel.

Calibration and verification are steps in the model validation process. Calibration refers to the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulation and observations of the groundwater flow system. Verification uses the set of parameter values and boundary conditions from a calibrated model to approximate a second set of data measured under similar hydrologic conditions. If both NNSA/NSO and NDEP determine that the model is acceptable, tritium and radionuclides with half-lives greater than tritium (12.32 years) will be used as the source term to estimate a contaminant boundary for the CAU. The boundary will be composed of a perimeter boundary and a lower hydrostratigraphic unit boundary. The accepted contaminant boundary and other considerations will form the basis for a negotiated compliance boundary (FFACO, 1996).

The CADD will present the results of the CAI along with an evaluation of the remedial alternatives being considered, and also provide the basis for recommending the proposed remedial alternative. The initial assumption is that long-term monitoring will be the accepted remedial action. NDEP will review the CADD draft and prepare comments, if appropriate. Review criteria are based on guidelines specified in the most recent document outline agreed to by DOE and NDEP prior to document preparation. NDEP approval of the CADD is required prior to initiating any CAP-related activities. During the development of the CADD, a determination will be made either that contaminant control will be required, or that long-term monitoring will provide sufficient CAU surveillance. One of two separate courses of action will follow this juncture, as indicated on the process flow diagram (Figure 2-2 [Appendix VI, Revision No. 1 {December 7, 2000}] of the FFACO [1996]).

The CAP will specify the corrective measures required to achieve contaminant control. The focus of the document will be the tasks to be implemented for contaminant control and the engineering design and specifications for each corrective measure (FFACO, 1996).

The FEHM code developed by LANL was preliminarily selected based on its acceptable performance in modeling the Western Pahute Mesa and Central Pahute Mesa CAUs 101 and 102. If this assessment changes before the Rainier Mesa/Shoshone Mountain CAU model begins, the code selection process as described in Section 5.1.2 will be used to select another code. After a code is selected, the groundwater flow model will be developed. This consists of groundwater data assessment, model setup, and model calibration. Existing geologic and hydrologic data are then compiled and evaluated, and a hydrostratigraphic model is constructed using surface and subsurface geologic and geophysical data obtained from boreholes within or near the CAU model boundary. This hydrostratigraphy model, along with the hydrologic data, is then used to develop the CAU-scale groundwater flow model. The regional groundwater flow model is used to define boundary conditions and initial estimates for the recharge for the CAU-scale groundwater flow model. Hydraulic conductivity data obtained from aquifer tests conducted in the CAU or relevant nearby areas are used to define an initial distribution. Water-level data from boreholes in and near the CAU are used to calibrate the groundwater flow model.

After completion of the groundwater flow model, the contaminant transport model will be developed. This will include transport data assessment, model setup, and model calibration. The primary input parameters to the contaminant transport model are effective porosity, matrix porosity, matrix diffusion, fracture information, dispersivity, source term, and sorption. Effective porosity and dispersivity values are derived from tracer tests conducted in the NTS and vicinity. Matrix porosity and fracture data are obtained from borehole core samples and geophysical logs, as well as from other tracer studies reported in the literature. Matrix diffusion is determined from laboratory studies conducted on core samples, and source term information is obtained from water samples and unclassified source term data. Sorption parameters are derived from laboratory studies, and will be supplemented from studies outside the NTS. Hydrologic and transport data are described in Section 3.0.

After the CAU-scale groundwater flow and contaminant transport model is developed, sensitivity and uncertainty analysis will be performed. The uncertainty analysis will include evaluating the impacts of alternative geologic interpretations and the use of smaller-scale groundwater flow and contaminant transport models to evaluate potential failure scenarios.

Various remedial alternatives will be evaluated and a recommendation made based on the established boundaries. If the recommendation is long-term monitoring, a monitoring network will be designed.

If it is determined that additional data and/or additional modeling are needed, a plan for collecting the data will be prepared as an addendum to the CAIP. This plan would identify and describe the work proposed to be conducted. Upon approval of the plan by NDEP, the plan would be implemented. Any work conducted, whether data collection or modeling, would be part of the CAI.

The results of all data collection activities, the CAU modeling effort, and the evaluation of the remedial alternatives, will be documented in the CADD and presented to NDEP for approval.

2.1.2.2.3 Corrective Action Implementation and CAU Closure

After the CADD is approved, a CAP will be written describing how NNSA/NSO will implement the corrective action. If monitoring is the decision, the CAP will describe the work for installing new wells (if necessary), and the monitoring parameters and schedule for the five-year proof-of-concept period. After successful implementation of the corrective action, the CAU will be proposed for closure and documented in the closure report.

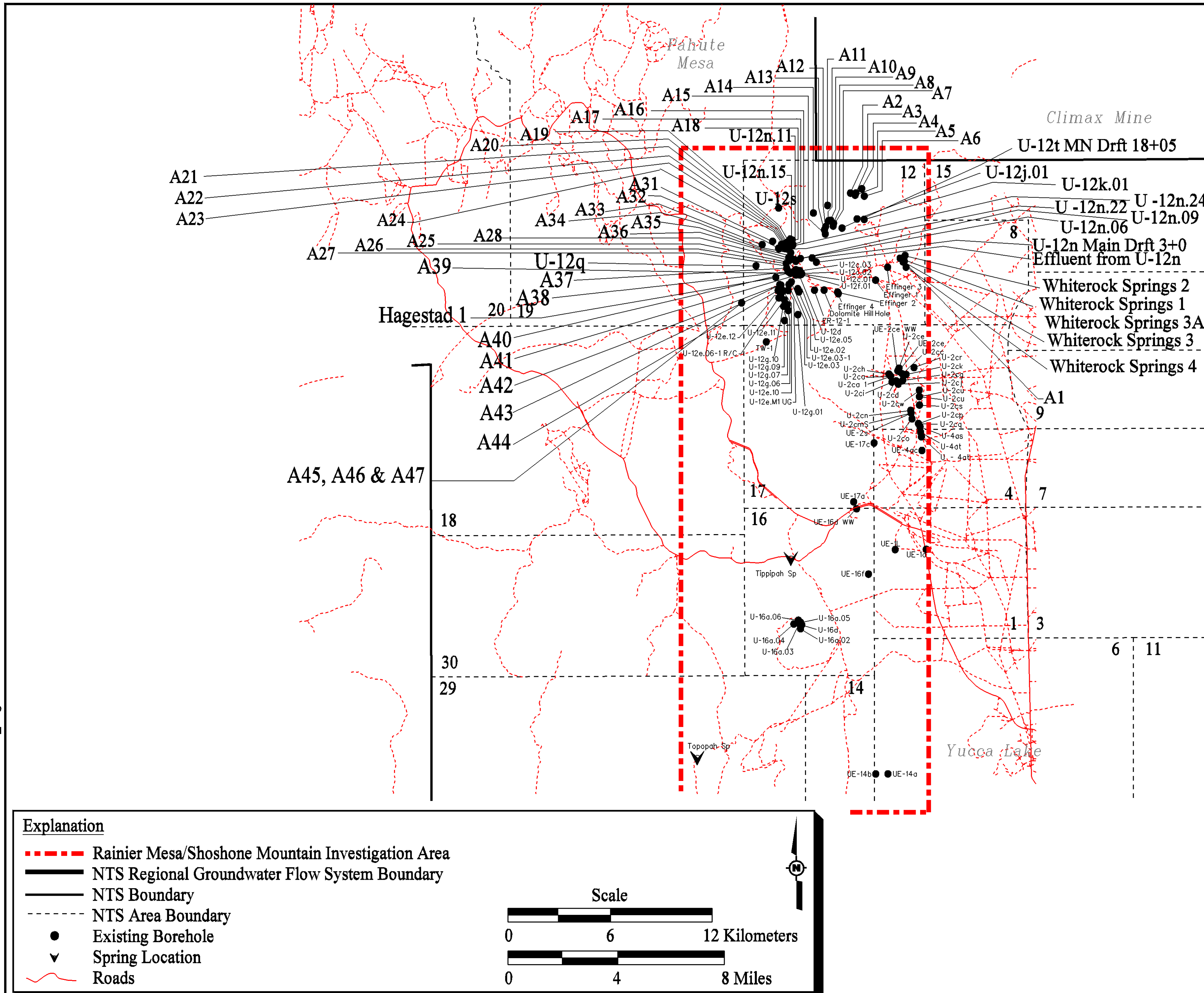
3.0 Description of Corrective Action Unit

This section includes a description of the Rainier Mesa/Shoshone Mountain CAU. The investigation background and operational history of the area are presented first. The CASs are then listed along with their specific attributes (name, date, depth of burial, working point distance above the water table, depth to water table, yield range, cavity radius, and working point HSU). Descriptions of the physical setting, contaminants, and conceptual model of the CAU are provided based on a preliminary evaluation of the existing information. Finally, the preliminary action levels (PALs) for the major contaminants considered in the CAI are presented.

3.1 Investigative Background

Numerous investigations of the Rainier Mesa/Shoshone Mountain area and the surrounding region were completed from the late 1950s to the present. Studies range in scope from investigations that encompass the entire NTS to studies of individual exploratory drill holes and tunnels associated with specific nuclear tests at Rainier Mesa and Shoshone Mountain. The investigations include both surface and subsurface studies, where subsurface data are obtained from existing boreholes and tunnels. Information on the subsurface was also obtained from nonintrusive investigations, including seismic surveys, gravity surveys, and aeromagnetic surveys. Figure 3-1 shows the existing boreholes and known springs in the Rainier Mesa/Shoshone Mountain investigation area. The tunnel complexes at Rainier Mesa and Shoshone Mountain are shown in Figure 1-2 and Figure 1-3, respectively.

An overview of the most notable investigations relevant to understanding the subsurface of the Rainier Mesa and Shoshone Mountain areas and the effects of underground nuclear testing on groundwater is provided in this section. Subject areas of interest are precipitation and recharge, topography, geology, groundwater, groundwater chemistry, radiochemistry, and migration processes. Following a description of general information of interest to this CAI, each of these areas is discussed.



Number	Existing Boreholes	Number	Existing Boreholes
A-1	USGS Shot Hole	A-31	UE-12n.15A & U-12n.22
A-2	U-12p.04	A-32	U-12r
A-3	U-12p.03	A-33	U-12n.04
A-4	UE-12p6	A-34	U-12n.17
A-5	U-12p.02	A-35	U-12n.02
A-6	U-12p.05	A-36	U-12b.10
A-7	U-12t03ug-3	A-37	12b.08
A-8	12t.09	A-38	U-12b.09
A-9	U-12t.03	A-39	U-12b.04
A-10	U-12t..04	A-40	UE - 12d.01
A-11	UE - 12t 7	A-41	U-12 e.18
A-12	U-12 t .08	A-42	U-12e.20
A-13	U-12t.01	A-43	UE -12e.14
A-14	UE -12 + 6	A-44	ER-19-1-1
A-15	U-12t.02	A-45	ER-19-1-2
A-16	U-12n.12	A-46	Er-19-1-3
A-17	U-12n.20		
A-18	U-12n02-UG-01		
A-19	U-12n.21		
A-20	U-12n.18		
A-21	U-12n.19		
A-22	U-12n.10		
A-23	U-12n.05		
A-24	U-12-12b.02		
A-25	U-12n.23		
A-26	U-12b		
A-27	U-12n.07		
A-28	U-12n.11		
A-29	U-12n.15		
A-30	UE-12n.16		

This key provides descriptions of existing boreholes.

Source: Modified from DOE/NV, 1997a

Figure 3-1
Location of Existing Boreholes and Springs in the Rainier Mesa/ Shoshone Mountain Investigation Area

H:\RainierMesa\RMS\RMSMb&s_b.dgn
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General Information

Several documents prepared for the NTS and the UGTA Project are relevant to the Rainier Mesa/Shoshone Mountain CAI. Two documents which cover the scope of the Rainier Mesa/Shoshone Mountain investigation, the NTS site-wide Environmental Impact Statement (DOE/NV, 1996) and the UGTA project-specific Environmental Assessment (DOE/NV, 1992), were developed to satisfy requirements of the *National Environmental Policy Act* (NEPA). Although no assessment of risk to human health was completed for the Rainier Mesa/Shoshone Mountain CAU, a regional risk assessment of UGTA was completed in 1997 (DOE/NV, 1997a).

Precipitation and Recharge

Precipitation is, in principal, the source of groundwater recharge. Researchers at DRI have investigated precipitation and groundwater recharge at the NTS, focusing on precipitation distribution, location and quantity of surface runoff, and location and rate of groundwater recharge (French, 1985; Lyles and Mihevc, 1992). DRI researchers developed a digital precipitation database (French, 1985), a compilation of published data from various precipitation stations on the NTS (French, 1986), and compared recorded precipitation to estimated annual and seasonal precipitation (French, 1987). Threshold precipitation events were investigated as a potential mechanism for groundwater recharge in the arid climate of the NTS (French et al., 1996). Ingraham et al. (1990) investigated the stable isotopic composition of precipitation. Researchers at the USGS have estimated the NTS regional recharge both as part of the Death Valley Regional Flow System (Hevesi et al., 2003) and as part of the Yucca Mountain regional groundwater flow model (D'Agnese et al., 1997). Most recently the USGS has included the NTS into the Death Valley Regional Flow System hydrogeologic ground-water flow model (Belcher, 2004).

Topography

Topographic information is used to locate sites, delineate the top of the geologic domain, provide reference points for depth-to-water measurements, develop insight into possible groundwater flow patterns, and plan field activities. The USGS is the main source of topographic information for the NTS, including the Rainier Mesa/Shoshone Mountain area. Topographic information is available from the USGS in the form of a Digital Elevation Model (DEM) (USGS, 1987) and as topographic maps at various scales. Topographic maps at a scale of 1:24,000 that cover the Rainier Mesa/Shoshone Mountain CAU and adjacent area include:

- Rainier Mesa Quadrangle, Nye County, Nevada (USGS, 1986b)
- Tippipah Spring Quadrangle, Nye County, Nevada (USGS, 1986c)
- Mine Mountain Quadrangle, Nye County, Nevada (USGS, 1986a)

These maps also show the locations of roads, springs, drill holes, and tunnel entrances.

Geology

Geologic information is necessary to conceptualize the physical framework of the groundwater flow system. A preliminary interpretation of the 3-D geologic framework of the Rainier Mesa/Shoshone Mountain area was made using borehole data, geologic maps, and geophysical maps, as part of the regional evaluation (IT, 1996f; DOE/NV, 1997a). Subsequently, an updated interpretation was offered by USGS researchers (Sweetkind et al., 2001). Numerous geologic maps at various scales exist that portray the surface geology of the Rainier Mesa/Shoshone Mountain areas. Several of these maps also contain interpretive cross sections of the subsurface geology. Published geologic maps include:

- Geologic map of the Mine Mountain Quadrangle, Nye County, Nevada, scale 1:24,000 (Orkild, 1968)

- Geologic map of the Rainier Mesa Quadrangle, Nye County, Nevada, scale 1:24,000 (Gibbons et al., 1963)

- Geologic map of the Tippipah Spring Quadrangle, Nye County, Nevada, scale 1:24,000 (Orkild, 1963)

- Geologic map of the Jackass Flats area, Nye County, Nevada, scale 1:48,000 (Maldonado, 1985)

- Geologic map of the Wheelbarrow Peak-Rainier Mesa area, Nye County, Nevada, scale 1:48,000 (Sargent and Orkild, 1973)

- Geologic map of the NTS, southern Nevada, scale 1:100,000 (Frizzell and Shulters, 1990)

- Digital geologic map of the NTS and vicinity, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California, scale 1:120,000 (Slate et al., 1999)

Numerous other reports provide useful information on surface and subsurface geology. Winograd and Thordarson (1975) and Laczniak et al. (1996) describe the regional geology of the NTS. Cole (1997) describes structural controls on the distribution of pre-Tertiary rocks at the NTS. Caskey and Schweickert (1992), Snow (1992), Trexler et al. (1996), Cole and Cashman (1999), and Sweetkind et al. (2001) describe Late Paleozoic and Mesozoic deformation of the NTS and vicinity. Gravity and aeromagnetic data for the NTS were published by McCafferty and Grauch (1997), and more recent compilations of the regional gravity data (Ponce et al., 1999) and regional aeromagnetic data (Ponce, 1999) also were published. Numerous reports exist describing the geology of the tunnels excavated beneath Rainier Mesa, including Hoover and Magner (1990) and Ege and Cunningham (1976) on N-Tunnel, and Emeric and Dickey (1962) on C-Tunnel. Davis (1962) describes the geology in the 16a-Tunnel beneath Shoshone Mountain. Comprehensive lists of geologic references used during the regional evaluation may be found in Appendices C5 through C9, C15, and E2 of Volume I of the regional evaluation documentation (IT, 1996f).

Hydrology

Understanding the hydrology of the groundwater flow system is important to understanding the groundwater transport of contamination from the underground test area. A preliminary interpretation of the Rainier Mesa/Shoshone Mountain subsurface was made as part of the regional evaluation (DOE/NV, 1997a; IT, 1996b through 1996h; IT, 1997). This interpretation will be refined during the CAI data assessment activities as described in Section 5.1.3.2.1 of this report.

Hydrologic information includes water-level measurements, well-test information (including estimates of hydraulic properties), and estimates of recharge and discharge rates into the groundwater flow system. Hydrologic information is available in the form of existing databases and various published and unpublished reports and maps. Major sources of information include the ERP, USGS, DRI, and professional literature.

Several notable studies have been conducted to understand the regional NTS groundwater flow system. Winograd and Thordarson (1975) discussed the hydrogeology and hydrochemistry of the NTS relative to the regional groundwater hydrology. Waddell (1982) developed a two-dimensional (2-D), steady-state groundwater flow model for the subsurface of the NTS in support of the investigation of a potential nuclear waste repository at Yucca Mountain. Laczniak et al. (1996)

described the hydrologic controls at work within the groundwater flow system of the underground test area and the NTS region. Results of a regional evaluation of groundwater flow and contaminant transport using tritium as the modeled contaminant from the underground test area are presented in DOE/NV (1997a). Another regional groundwater flow model was developed for the Yucca Mountain area by D'Agnese et al. (1997), and covers approximately the same area as the UGTA model (DOE/NV, 1997a). The USGS created a more sophisticated model in the Death Valley Regional Ground-water Hydrogeologic and Transient Flow Model (Belcher, 2004) that also includes the NTS. Hess and Jacobson (1984) investigated the hydrogeology of the NTS and southern Amargosa Desert. Hydrologic data can be obtained from the National Water Information System (USGS, 1989) and from Arteaga et al. (1991), which contain compilations of data from wells and test wells located on the NTS and vicinity. Site-specific hydrologic data for Rainier Mesa are available from IT (1995) for Well ER-19-1, from Russell et al. (1996) for Well ER-12-1, and from Russell et al. (2003) for the groundwater impounded within the N- and T-Tunnels. Ground-water flow through the fractured tuffs at Rainier Mesa were investigated by Russell et al. (1987), and perched groundwater at Rainier Mesa was investigated by Thordarson (1965). Comprehensive lists of publications used during the regional evaluation can be found in the reference lists of Volumes II, III, and IV of the regional evaluation documentation (IT, 1996c, d, and e).

Groundwater Chemistry

Groundwater chemistry information has been presented for the NTS by Schoff and Moore (1964) and a digital database of groundwater chemistry was compiled by Perfect et al. (1995). Rose et al. (1997) presented chemical and isotopic data of groundwater in the regional flow system at the NTS. Winograd and Thordarson (1975) used groundwater chemistry to evaluate regional groundwater flow in and around the NTS. Chapman and Lyles (1993) presented groundwater chemistry data collected by DRI. Benson (1976), White et al. (1980), and Jacobson et al. (1986) investigated the changes in groundwater geochemistry as a result of interactions with the vitric tuffs of Rainier Mesa. Ingraham et al. (1990) used stable isotope data to evaluate large-scale hydrologic systems in California and Nevada. Stable isotope data collected at precipitation stations on the NTS and the surrounding area are presented in Milne et al. (1987). Russell et al. (1987) documented stable isotope interpretations of groundwater recharge rates and related hydrologic issues. Benson and Klieforth (1989) used stable isotope data from precipitation and groundwater on the NTS and at Yucca Mountain to evaluate paleoclimatic conditions. Davisson et al. (1999) and Thomas (1999) provide regional-scale interpretations of stable isotopes in southern Nevada groundwater. Thomas (1996) and Thomas et al. (1996) estimated regional flow paths, groundwater age, and travel times based on mass-balance reaction modeling of flow system geochemistry and isotopic data. A comprehensive groundwater chemistry database for the NTS region was developed as part of the UGTA project. This database is updated annually, with the most recent updates contained in GEOCHEM04.

Radiochemistry

Numerous sampling and monitoring programs have contributed to data and reports on the radiochemistry of the groundwater at the NTS. The Long-Term Hydrological Monitoring Program (LTHMP) was initiated in 1972 to determine whether radioactivity from underground nuclear tests contaminated the groundwater in the NTS and near vicinity. Under the LTHMP, radionuclide concentrations in groundwater were monitored on and near the NTS at selected well and spring locations. In the mid 1970s, the Radionuclide Migration (RNM) Project was initiated to investigate the movement of radionuclides away from the nuclear explosion cavities and chimneys by determining the fraction of the radioactive material contained in the cavity region both in melt glass and as the fraction that dissolved or formed colloids that can be transported by groundwater. In 1987 the RNM Project and the LTHMP were merged into the Hydrology and Radionuclide Migration Program (HRMP). The HRMP results are published in annual reports by LLNL and LANL as well as in topical reports by DRI and the USGS. DRI published two reports regarding the occurrence of tritium in groundwater from wells on the NTS (Lyles, 1990 and 1993). The Basic Environmental Compliance and Distribution Program (BECAMP) monitored radionuclide releases to the air and to the water that resulted from activities on the NTS. Within this program, Reynolds Electrical & Engineering Co., Inc. (REECo) conducted environmental surveillance and effluent monitoring, and LLNL, DRI, and the EPA conducted supporting studies related to horizontal and vertical migration of radionuclides and the redistribution of radionuclides from wind and water erosion. The Routine Radiological Environmental Monitoring Program (RREMP) was administered by Bechtel Nevada starting in 1998, and included airborne radiological surveillance and groundwater radiological monitoring both on and off the NTS. As part of the Environmental Restoration Projects (UGTA Project and the predecessor Groundwater Characterization Program [GCP]), DOE contractors have collected groundwater samples from the Rainier Mesa/Shoshone Mountain area during well completion activities and tunnel effluent characterization activities. These groundwater characterization samples are analyzed for a suite of radionuclides. These data are included in a series of well completion reports (e.g., Smith, 1993b; Russell et al., 1996; IT, 1995), as well as annual reports and well-specific letter reports published by LLNL and LANL (Rose, 2003; Aldrich, 2003).

Radionuclide concentration data resulting from RREMP, LTHMP, BECAMP, and ERP are included in published annual site environmental monitoring reports for the NTS and are also included in the comprehensive UGTA groundwater chemistry database, GEOCHEM04.

3.2 Operational History

A summary of nuclear testing in general is presented followed by a description of the operational history of testing at Rainier Mesa and Shoshone Mountain.

3.2.1 General

An overview of the purpose and phenomenology of underground nuclear testing is presented in this section. The purpose of underground nuclear testing was to develop new nuclear weapons, as well as to assess and evaluate the effects of nuclear explosions on military systems and other hardware (U.S. Congress, 1989). The primary objectives of underground nuclear testing were twofold: (1) to obtain the desired experimental information, and (2) to contain radioactive material in the subsurface environment rather than release the contamination to the atmosphere. During the period from 1951 to 1992, an average of 20 tests per year were conducted in either vertical shafts or horizontal tunnels, but as many as 96 tests were conducted in one year (DOE/NV, 2000c). The majority of the vertical drill hole tests were conducted in support of weapons development (U.S. Congress, 1989).

An underground nuclear explosion results in specific physical phenomena that occur on vastly different time frames. These phenomena and the timeframes within which they occur are summarized below from a report prepared by the U.S. Congress (1989) of unclassified information.

- Regardless of the design of a given nuclear device, within microseconds (millionths of a second) of detonation, tremendous energy is released from the nuclear forces acting within the nucleus of billions of atoms. The initial release of this energy manifests itself as a shockwave that spreads outward from the point of origin.

- Within milliseconds (thousandths of a second) thermal energy has vaporized bomb components and an amount of geologic materials surrounding the buried device. The resulting energy forms a high-pressure bubble of plasma and vapor within a cavity.
- Within tenths of a second the cavity expands until the pressure within drops to that of the surrounding rock, equaling lithostatic pressure. At this point the initial cavity has grown to its maximum size. The expanding shock wave crushes and fractures the rock as it expands outward, eventually losing energy until it is too weak to permanently damage the rock. However, the shock wave continues to propagate as seismic energy that can be detected from hundreds to thousands of miles away.
- Within seconds, vaporized rock condenses, and molten rock collects and pools in the bottom of the cavity where it solidifies. Condensation of the vaporized rock results in a decrease of pressure within the cavity until it falls below lithostatic pressure. During this time frame the seismic energy of the initial shock wave has traveled tens of miles through the earth's crust.
- Within minutes to days, the roof of the cavity collapses into the cavity space and further weakens the material above the cavity. This process feeds upon itself as cavity collapse stopes upward, creating a rubble-filled chimney structure. If the collapse chimney approaches the surface, a collapse crater may form on the surface above the initial point of the detonation. During the early part of this time frame the seismic energy of the initial shock wave may traverse the entire planet.

3.2.2 Underground Nuclear Testing in the Rainier Mesa/Shoshone Mountain Area

The operational history of the Rainier Mesa and Shoshone Mountain CAU covers a 35-year time span, from 1957 to 1992. Nuclear tests were completed at 61 underground locations in Rainier Mesa between 1957 and 1992, and at 6 locations in Shoshone Mountain between 1962 and 1971 (DOE/NV, 2000c). Although nuclear devices were tested at the NTS using air-drops, towers, balloons, craters, shafts, and tunnels, at Rainier Mesa and Shoshone Mountain tunnels were used for all but two tests; CLEARWATER and WINESKIN were conducted in shafts. Table 3-1 summarizes the nuclear testing information for the Rainier Mesa/Shoshone Mountain CAU.

The yield of a nuclear device is a measure of energy released expressed as the equivalent in tons of TNT (trinitrotoluene) in kilotons (thousand tons) or in megatons (million tons) (DOE/NV, 2000c). The maximum yield reported for a test in the Rainier Mesa/Shoshone Mountain CAU is 200 kilotons (kt). Several tests have reported yields less than a kiloton. Some of the safety experiment tests (specifically URANUS and VENUS) are recorded as occurring at the surface with yields of less than one ton of TNT (0.001 kt).

Table 3-1
Summary Information on Underground Nuclear Tunnel Detonations Conducted within the Rainier Mesa/Shoshone Mountain CAU

Area	Rainier Mesa	Shoshone Mountain
Operational Period	1957 to 1992	1962 to 1971
Total Locations	61	6
Total Detonations	62	6
Detonations Below Water Table	0	0
Detonations within 100 meters of the Water Table	0	0
Detonations in Volcanic Units	62	6
Maximum Yield Range	0 to 200 kt	<20 kt

Sources: DOE/NV (2000c); DOE/NV (1997a); DOE/NV (1997b); FFACO Appendix III (FFACO, 1996)

Although nuclear devices have been emplaced into alluvial deposits, Tertiary volcanic rocks, Paleozoic carbonate rocks, and Mesozoic intrusive rocks at the NTS, all of the underground nuclear tests conducted at Rainier Mesa and Shoshone Mountain were in Tertiary volcanic rocks. At Rainier Mesa these tests were conducted in zeolitized tuffs of the Tunnel Formation, a Tertiary bedded tuff composed principally of rhyolitic air-fall tuff and nonwelded ash-flow tuff (Slate et al., 1999; BN, 2002a). Underground nuclear tests at the Rainier Mesa/Shoshone Mountain CAU were conducted at working point depths that range from 30 to 545 meters (m) (98 to 1,788 feet [ft]) below ground surface (bgs). These test depths are all above the regional water table, but perched groundwater stored within the fractures of the zeolitized tuff saturated the working points of these tests. Subsequently, the test tunnels have become filled with groundwater originating from the perched aquifers and infiltration of surface water.

The underground tests conducted within the Rainier Mesa/Shoshone Mountain CAU had working points at distances varying from 212 to 890 m above the regional water table. The test closest to the regional water table was CLEARWATER, with a working point located 212 m above the water table, a reported yield ranging from 20 to 200 kt, and an estimated test cavity radius of 72 m (see Table 3-2). Test cavity radii are calculated using the highest of the reported yield ranges. Typically a zone of fractured rock surrounds the test cavity out to a distance two to three times the radius of the test cavity (Bowen et al., 2001). For CLEARWATER this would yield a potential maximum zone of fractured rock with an estimated radius of 216 m, including the test cavity and the enveloping fractured zone (see Table 3-2). This indicates that for this test, the fracture zone may extend to below the regional water table.

Reentry drilling and mining activities associated with the RAINIER test indicate that the mechanical properties of the tuff control to a certain degree the physical responses of the geologic media to the underground nuclear test. RAINIER had a yield of 1,700 tons of TNT and produced an initial test cavity with a radius of 17.4 m, with gross primary rock displacement and grain disaggregation to a radial distance varying from 24 to 40 m. Visible primary fracturing extended out to a radial distance of 46 to 67 m, depending on the proximity of hard, brittle welded tuff. It was found that the denser welded tuff transmitted stresses to a much greater distance than the nonwelded, bedded tuff (Thompson and Misz, 1959). Whereas the fracture distances reported for RAINIER in Thompson and Misz (1959) locally exceed the radius of the initial test cavity by more than a factor of three, they demonstrate that initial fracturing of the rock is greater parallel to the bedding of the tuff, and that secondary shear fractures develop in the vertical direction as a response to initial ground motion (Swift et al., 1957) and to cavity collapse (Thompson and Misz, 1959; Essington and Forslow, 1971). These results suggest that the zones of fractured rock enveloping the underground test cavities are preferentially directed parallel to, or away from, the regional static water table in the predominantly horizontal volcanic beds of Rainier Mesa.

3.3 Corrective Action Sites

A total of 68 underground nuclear detonations were conducted in the Rainier Mesa/Shoshone Mountain CAU (Table 3-1). Sixty-two underground detonations were conducted at Rainier Mesa and six at Shoshone Mountain. Two underground nuclear detonations were conducted at the same CAS location and at two locations on Rainier Mesa (CAS 12-57-040 and CAS 12-57-046) (DOE/NV, 2000c; FFACO Appendix III [FFACO, 1996]). In the FFACO (1996), the underground nuclear tests were identified as CASs either individually or in small groups. The locations of the CASs are shown in Figure 3-2 and on Plate 1. Table 3-2 and Table 3-3 identify each of the CASs of CAU 99 along with their individual features. Each table lists the CAS number, CAS description, test name, detonation date, yield range, depth to burial, distance of the working point above the regional water table, depth to water table, cavity radius, and hydrostratigraphic unit. The radii listed in

Table 3-2 and Table 3-3 are conservative estimates of the test cavity radii calculated using the highest of the reported yield ranges, since the actual yields for many tests are considered classified information. The actual radius of the cavity is a function of the exact yield of the test device, the depth to burial (i.e., the value of the lithostatic pressure at the working point), and the rock type at the working point. Based on the data presented in Table 3-2 and Table 3-3, no tests were conducted below the regional water table.

3.4 Physical Setting

Descriptions of the physical features of interest to the Rainier Mesa/Shoshone Mountain CAI include climate, topography, geology, groundwater hydrology, geochemistry, radiochemistry, and contaminant migration. Data summaries obtained from the regional evaluation (DOE/NV, 1997a) and documentation packages (IT, 1996b through 1996h), as well as from other published sources, are provided. During the CAI process, the current understanding of the Rainier Mesa/Shoshone Mountain CAU conceptual model will be updated following a thorough data assessment process.

3.4.1 Climate

Information on precipitation and recharge was gathered during the regional evaluation (DOE/NV, 1997a) and is provided in Sections 3.0 through 11.0 of Volume III of the documentation package (IT, 1996c). Additional information was collected from the most recent National Oceanic and Atmospheric Administration Air Resources Laboratory data. The locations of recording stations located in the vicinity of the Rainier Mesa/Shoshone Mountain CAU are shown in Figure 3-3. Table 3-4 provides average annual precipitation values at these recording stations.

The Rainier Mesa/Shoshone Mountain CAU lies northeast of the Amargosa Desert and Death Valley. The Amargosa Desert is the most arid part of Nevada, and Death Valley (in California) is even drier. As can be seen from the data in Table 3-4, the average annual precipitation generally increases with increasing elevation. The Area 12 (Rainier Mesa) precipitation station is at 2,283 m and the average annual precipitation for the last 42 years is 12.82 inches per year (in./yr). Tippipah Spring precipitation recording station lies below Shoshone Mountain, the highest point of which lies 648 m above the recording station. The average annual precipitation at Tippipah Spring is 8.52 in./yr, and represents the average annual precipitation expected in the Shoshone Mountain area.

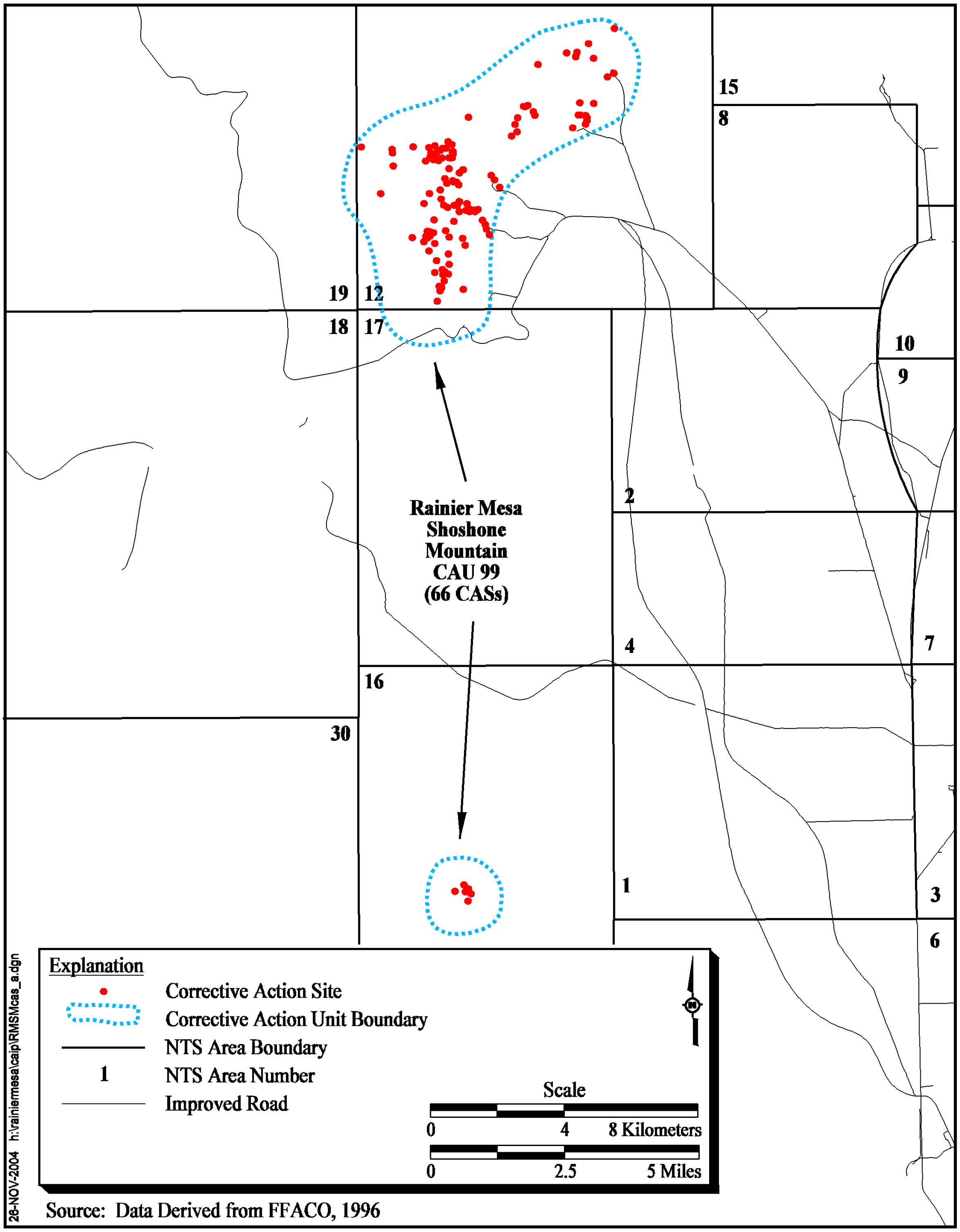


Figure 3-2
Location of Corrective Action Sites in the Rainier Mesa/ Shoshone Mountain Corrective Action Unit

Table 3-2
Corrective Action Sites in Rainier Mesa
(Page 1 of 3)

CAS No.	CAS Description	Event Name	Date	Depth of Burial (ft)	Land Elevation (ft)	Estimated Water Level (ft)	Yield Range	Cavity Radius[a] (ft)	WP HSU
12-57-010	U12c.01 Cavity	URANUS	03/14/1958	114	6,751	4,504	<1 ton	8	BCU
12-57-007	U12c.02 Cavity	SATURN	08/10/1957	128	7,061	4,517	0	0	-
12-57-008	U12c.03 Cavity	NEPTUNE	10/14/1958	98	7,530	4,512	115 tons	40	BCU
12-57-020	U12f.02 Cavity	MARS	09/28/1958	125	6,725	4,523	13 tons	18	BCU
12-57-009	U12d.01 Cavity	VENUS	02/22/1958	100	7,177	4,558	<1 ton	8	BCU
12-57-011	U12e.02 Cavity	LOGAN	10/16/1958	930	7,071	4,519	5 kt	81	BCU
12-57-012	U12e.03a Cavity	ANTLER	09/15/1961	1,319	7,483	4,604	2.6 kt	60	TCU
12-57-013	U12e.05 Cavity	BLANCA	10/30/1958	987	7,126	4,531	22 kt	131	TCU
12-57-014	U12e.10 Cavity	DORSAL FIN	02/29/1968	1,345	7,505	4,631	<20 kt	117	BCU
12-57-015	U12e.11 Cavity	DIESEL TRAIN	12/05/1969	1,375	7,540	4,615	<20 kt	117	BCU
12-57-016	U12e.12 Cavity	HUDSON MOON	05/26/1970	1,386	7,550	4,645	<20 kt	117	BCU
12-57-017	U12e.14 Cavity	DIDO QUEEN	06/05/1973	1,284	7,461	4,666	<20 kt	119	BCU
12-57-018	U12e.18 Cavity	DINING CAR	04/05/1975	1,257	7,430	4,669	<20 kt	119	BCU
12-57-035	U12e.20 Cavity	HYBLA GOLD	11/01/1977	1,263	7,434	4,659	<20 kt	119	BCU
12-57-019	U12f.01 Cavity	MERCURY	09/23/1958	183	6,712	4,508	Slight	193	BCU
12-57-021	U12g.01 Cavity	MADISON	12/12/1962	1,320	7,477	4,522	<20 kt	118	BCU
12-57-022	U12g.06 Cavity	RED HOT	03/05/1966	1,330	7,632	4,583	<20 kt	118	BCU
12-57-023	U12g.07 Cavity	DOOR MIST	08/31/1967	1,463	7,619	4,594	<20 kt	115	BCU
12-57-024	U12g.09 Cavity	CYPRESS	02/12/1969	1,350	7,519	4,603	<20 kt	117	VCU
12-57-025	U12g.10 Cavity	CAMPHOR	06/29/1971	1,390	7,600	4,613	<20 kt	116	BCU
12-57-028	U12n.02 Cavity	MIDI MIST	06/26/1967	1,237	7,306	4,648	<20 kt	120	BCU
12-57-029	U12n.04 Cavity	HUDSON SEAL	09/24/1968	1,130	7,200	4,641	<20 kt	123	BCU
12-57-030	U12n.05 Cavity	MISTY NORTH	05/02/1972	1,234	7,303	4,675	<20 kt	120	BCU
12-57-031	U12n.06 Cavity	DIANA MIST	02/11/1970	1,319	7,401	4,617	<20 kt	118	BCU
12-57-032	U12n.07 Cavity	HUSKY ACE	10/12/1973	1,364	7,430	4,583	<20 kt	117	BCU

Table 3-2
Corrective Action Sites in Rainier Mesa
(Page 2 of 3)

CAS No.	CAS Description	Event Name	Date	Depth of Burial (ft)	Land Elevation (ft)	Estimated Water Level (ft)	Yield Range	Cavity Radius[a] (ft)	WP HSU
12-57-033	U12n.08 Cavity	MING BLADE	06/19/1974	1,272	7,344	4,666	<20 kt	119	BCU
12-57-034	U12n.09 Cavity	HYBLA FAIR	10/28/1974	1,325	7,394	4,600	<20 kt	118	BCU
12-57-036	U12n.10 Cavity	MIGHTY EPIC	05/12/1976	1,306	7,384	4,741	<20 kt	118	BCU
12-57-037	U12n.10a Cavity	DIABLO HAWK	09/13/1978	1,273	7,346	4,707	<20 kt	119	BCU
12-57-038	U12n.11 Cavity	MINERS IRON	10/31/1980	1,278	7,347	4,646	<20 kt	119	BCU
12-57-039	U12n.12 Cavity	MINI JADE	05/26/1983	1,244	7,401	4,635	<20 kt	120	BCU
12-57-040	U12n.15 Cavities (2)	DIAMOND ACE, HURON LANDING	09/23/1982	1,390/1,339	7,412/7,417	4,664/4,664	<20 kt/<20 kt	116/118	BCU
12-57-041	U12n.17 Cavity	MISTY RAIN	04/06/1985	1,275	7,345	4,637	<20 kt	119	BCU
12-57-042	U12n.18 Cavity	TOMME/MIDNIGHT ZEPHYR	09/21/1983	1,328	7,401	4,687	<20 kt	118	BCU
12-57-043	U12n.19 Cavity	DIAMOND BEECH	10/09/1985	1,326	7,403	4,697	<20 kt	118	BCU
12-57-044	U12n.20 Cavity	MILL YARD	10/09/1985	1,217	7,317	4,636	<20 kt	120	BCU
12-57-045	U12n.21 Cavity	MIDDLE NOTE	03/18/1987	1,308	7,383	4,682	<20 kt	118	BCU
12-57-046	U12n.22 Cavity[b]	MINERAL QUARRY, RANDSBURG	07/25/1990	1,278	7,359/7,359	4,763/4,763	<20 kt/<20 kt	119/119	BCU
12-57-047	U12n.23 Cavity	MISTY ECHO	12/10/1988	1,312	7,431	4,661	<150 kt	231	BCU
12-57-048	U12n.24 Cavity	HUNTERS TROPHY	09/18/1992	1,264	7,346	4,689	<20 kt	119	BCU
12-57-053	U12q Cavity	CLEARWATER	10/16/1963	1,788	7,414	4,930	20-200 kt	236	BCU
12-57-054	U12r Cavity	WINESKIN	01/15/1969	1,700	7,514	4,990	20-200 kt	239	VCU
12-57-055	U12t.01 Cavity	MINT LEAF	05/05/1970	1,330	6,957	4,435	<20 kt	118	BCU
12-57-056	U12t.02 Cavity	DIAMOND SCULLS	07/20/1972	1,391	7,020	4,415	<20 kt	116	BCU
12-57-057	U12t.03 Cavity	HUSKY PUP	10/24/1975	1,076	6,769	4,435	<20 kt	124	BCU
12-57-058	U12t.04 Cavity	MIDAS MYTH/ MILAGRO	02/15/1984	1,184	6,811	4,446	<20 kt	121	BCU

Table 3-2
Corrective Action Sites in Rainier Mesa
(Page 3 of 3)

CAS No.	CAS Description	Event Name	Date	Depth of Burial (ft)	Land Elevation (ft)	Estimated Water Level (ft)	Yield Range	Cavity Radius[a] (ft)	WP HSU
12-57-060	U12t.08 Cavity	MIGHTY OAK	04/10/1986	1,294	6,924	4,440	<20 kt	119	BCU
12-57-061	U12t.09 Cavity	MISSION GHOST	06/20/1987	1,054	6,706	4,404	<20 kt	125	BCU
12-57-051	U12p.04 Cavity	DISTANT ZENITH	09/19/1991	865	6,392	4,474	<20 kt	131	TC
12-57-052	U12p.05 Cavity	DIAMOND FORTUNE	04/30/1992	774	6,307	4,419	<20 kt	135	TC
12-57-001	U12b Cavity	RAINIER	09/19/1957	899	7,515	4,568	1.7 kt	57	TC, TCBCU
12-57-002	U12b.02 Cavity	TAMALPAIS	10/08/1958	330	7,019	4,530	72 tons	26	TC, TCBCU
12-57-003	U12b.04 Cavity	EVANS	10/29/1958	840	7,472	4,588	55 tons	19	VA
12-57-004	U12b.08 Cavity	FEATHER	12/22/1961	812	7,443	4,634	150 tons	26	VA
12-57-005	U12b.09 Cavity	CHENA	10/10/1961	838	7,472	4,615	Low	132	VA
12-57-006	U12b.10 Cavity	YUBA	06/05/1963	796	7,438	4,650	3.1 kt	72	TC, TCBCU
12-57-026	U12j.01 Cavity	DES MOINES	06/13/1962	660	5,652	4,268	2.9 kt	74	TC, TCBCU
12-57-027	U12k.01 Cavity	PLATTE	04/14/1962	631	5,650	4,447	1.85 kt	64	TC, TCBCU
12-57-049	U12p.02 Cavity	MISSION CYBER	12/02/1987	888	6,407	4,226	< 20 kt	130	TC, TCBCU
12-57-050	U12p.03 Cavity	DISKO ELM	09/14/1989	857	6,377	4,456	< 20 kt	131	TC, TCBCU

[a]Test cavity radii are calculated using the highest of the reported yield ranges.
[b]The FFACO CAS description for these two detonations is U12n.22 Cavity. DOE/NV (2000c) lists U12n.22 as the location for MINERAL QUARRY and U12n.22a as the location for RANDSBURG.

Sources: DOE/NV (2000c); DOE/NV (1997a); DOE/NV (1997b); FFACO Appendix III (FFACO, 1996); Olsen (1993); Pawloski and Richardson (1990)
WP = Working point of the test
HSU = Hydrostratigraphic unit
BCU = Basal Confining Unit
TC = Tuff Cone
TCBCU = Tuff Confining Unit/Basal Confining Unit
TCU = Tuff Confining Unit
VA = Volcanic Aquifer
VCU = Volcanic Confining Unit

Table 3-3
Corrective Action Sites in Shoshone Mountain

CAS No.	CAS Description	Event Name	Date	Depth of Burial (ft)	Land Elevation (ft)	Estimated Water Level (ft)	Yield Range	Cavity Radius (ft)[a]	WP HSU
16-57-001	U16a Cavity	MARSHMALLOW	06/28/1962	1,020	7,442	3,942	<20 kt	132	VCU
16-57-002	U16a.02 Cavity	GUM DROP	04/21/1965	1,000	6,425	3,935	<20 kt	133	VCU
16-57-003	U16a.03 Cavity	DOUBLE PLAY	06/15/1966	1,075	6,499	3,952	<20 kt	130	BCU
16-57-004	U16a.04 Cavity	MING VASE	11/20/1968	1,010	6,425	3,969	<20 kt	132	VCU
16-57-005	U16a.05 Cavity	DIAMOND DUST	05/12/1970	830	6,321	3,954	<20 kt	139	BCU
16-57-006	U16a.06 Cavity	DIAMOND MINE	07/01/1971	873	6,310	3,966	<20 kt	137	BCU

[a]Test cavity radii are calculated using the highest of the reported yield ranges.

Sources: DOE/NV (2000c); DOE/NV (1997a); DOE/NV (1997b); FFACO Appendix III (FFACO, 1996); Olsen (1993); Pawloski and Richardson (1990)
WP = Working point of the test
HSU = Hydrostratigraphic unit
BCU = Basal Confining Unit
VCU = Volcanic Confining Unit

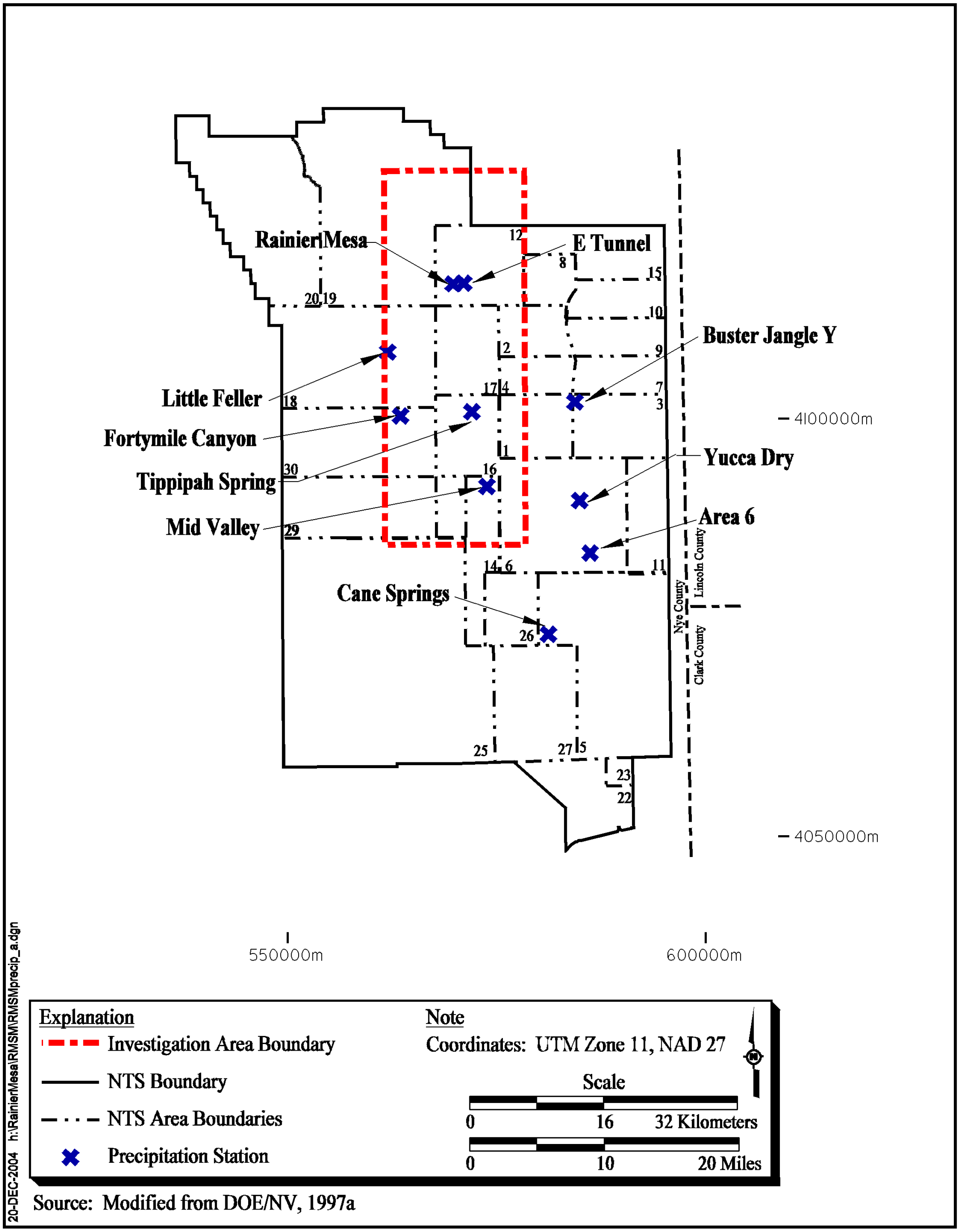


Figure 3-3
Location of Precipitation Stations In and Near the Rainier Mesa/Shoshone Mountain Area

Table 3-4
Average Precipitation Rates in the Vicinity of the Rainier Mesa/Shoshone Mountain CAU

Station ID	Station Name	Easting (meters)	Northing (meters)	Elevation (meters)	Precipitation (cm/yr)	Precipitation (in./yr)	Years recorded
BJY	Buster Jangle Y	584,239	4,102,053	1,241	16.03	6.31	43
UCC	Yucca Dry Lake	584,801	4,090,255	1,197	16.81	6.62	45
A12	Rainier Mesa	569,649	4,116,158	2,283	32.56	12.82	42
MV	Mid Valley	573,706	4,091,939	1,421	22.83	8.99	39
TS2	Tippipah Springs 2	571,899	4,100,860	1,519	21.64	8.52	43
LF2	Little Feller 2	561,843	4,107,992	1,562	20.14	7.93	26
CS	Cane Springs	581,046	4,074,224	1,220	19.51	7.68	39
40MN	40 Mile Canyon	563,357	4,100,361	1,470	20.29	7.99	43
Etu	E Tunnel	570,906	4,116,230	1,906	26.49	10.43	7
A6	Area 6	586,028	4,083,950	1,132	13.34	5.25	6

Source: NOAA, 2004
Location data in UTM Zone 11, NAD 27

Precipitation is highly seasonal, falling predominantly in the winter and summer months. Winter precipitation usually results from relatively large low-pressure systems moving in from the west. In the summer, precipitation is typically from small convective storms that originate south of the study area. As in most arid climates, the relative humidity is low, ranging from 10 to 30 percent in the summer, and 20 to 60 percent in the winter. The potential annual evaporation in this region from standing water, such as lakes or reservoirs, is estimated to range from 60 to 82 in./yr (Meyers and Nordenson, 1962). These evaporation rates are from 5 to 15 times greater than the precipitation rates in the Rainier Mesa/Shoshone Mountain area. However, since no lakes, reservoirs, or other permanent bodies of surface water exist in or near the CAU, the effect of these evaporation rates is much less. For precipitation that accumulates as snow or cold rain during the winter, a much smaller percentage of it is expected to evaporate than is suggested by the evaporation data. That is, infiltration of winter precipitation in the porous soil and alluvium is expected to be higher than infiltration of summer precipitation due to less evaporation during cold weather. No evapotranspiration (ET) is known to occur from groundwater in the regional aquifer in the Rainier

Mesa or Shoshone Mountain area. However, local springs and seeps in both areas discharge groundwater from perched aquifers located within the volcanic strata, and ET from these springs and the vegetation surrounding them will occur locally.

The movements of large-scale pressure systems control the seasonal changes in wind direction. During the summer, the predominating winds are from the south and in the winter from the north. At a more local scale, a characteristic diurnal wind change occurs such that winds blow down-slope during the day and upslope during the night. This diurnal reversal is strongest during the summer and occasionally overrides the seasonally prevailing wind (DOE/NV, 1992).

3.4.2 Topography

Information on the topography of the NTS region, including Rainier Mesa and Shoshone Mountain, has been previously provided in Appendix F of Volume I of the regional evaluation documentation package (IT, 1996f), and in Section 2.2 of the regional evaluation report (DOE/NV, 1997a). The area of the Rainier Mesa/Shoshone Mountain CAU is covered by USGS 7.5 minute topographic maps, including the Rainier Mesa Quadrangle, the Tippipah Spring Quadrangle, and the Buckboard Mesa quadrangle. The Beatty, Nevada-California and the Pahute Mesa, Nevada 1:100,000-scale topographic maps provide a more regional geographic context for the Rainier Mesa/Shoshone Mountain CAU. The regional terrain is dominated by Basin and Range topography formed by north-south oriented horsts and grabens that are locally modified by thick accumulations of volcanic rocks from the Southwestern Nevada Volcanic Field (SWNVF). To the southeast of the study area the fault block mountain ranges are twisted to the west by the Las Vegas Valley shear zone and related strike-slip faults.

Rainier Mesa forms a relatively flat-topped mesa that ranges in elevation from 2,243 to 2,340 m. Rainier Mesa is connected at its northeast corner to Aqueduct Mesa, which is several hundred feet lower in elevation. Rainier Mesa lies northeast of Timber Mountain and northwest of Yucca Flat. Shoshone Mountain lies about 16 km south of Rainier Mesa. Shoshone Mountain is a much more topographically complex area than Rainier Mesa. The western and southwestern part of Shoshone Mountain comprises an area of high rugged ridges and deep, steep-sided canyons. The central portion of Shoshone Mountain is more flat-topped and mesa-like, but contains several peaks and canyons. The northeastern portion of Shoshone Mountain forms a flat ridge with canyons eroded into the western and eastern flanks. The tunnels excavated for underground nuclear tests are located in the northeastern portion of Shoshone Mountain. Elevations in the central portion of Shoshone Mountain range from 1,585 to 2,166 m. In the western and southwestern portion of Shoshone Mountain, the ridge tops rise 1,433 to 1,859 m, whereas the canyon bottoms are around 1,190 to 1,400 m. In the northeastern part of Shoshone Mountain the ridge lies between 1,950 and 2,073 m, whereas the canyons go down from 1,950 to 1,646 m. Shoshone Mountain lies southeast of Timber Mountain, and is separated from Timber Mountain by Fortymile Canyon. Mid Valley lies to the east of Shoshone Mountain, and Shoshone Basin and Calico Basin lie to the south.

3.4.3 Surface Water

Surface water for the NTS region, including Rainier Mesa and Shoshone Mountain, is discussed in detail in Section 5.0, Section 8.0, and Appendix A of Volume III of the regional documentation package (IT, 1996c). A summary was also provided in Section 5.7.2.1 of the regional evaluation report (DOE/NV, 1997a). Springs and seeps in the region of the Rainier Mesa/Shoshone Mountain CAU have been described by Hansen et al. (1997).

There are no standing bodies of water in the Rainier Mesa/Shoshone Mountain area, and the nearest significant source of surface water is located at Ash Meadows in the Amargosa Desert, 50 km to the south-southwest. All of the drainages and washes in the Rainier Mesa and Shoshone Mountain area are dry except during storm events or with melt-water from snow. This component of precipitation is hydrologically significant and probably provides some recharge to the groundwater. In the Rainier Mesa and Shoshone Mountain area this recharge contributes to the groundwater in the perched aquifers within the volcanic strata, and may contribute to the deeper regional groundwater in the Lower Carbonate Aquifer (LCA). However, at present it is not known how surface water recharge is partitioned between the perched volcanic aquifers and the deeper regional aquifer. Surface water runoff also enters into alluvium in the washes and arroyos, and into the alluvial fan deposits at the mouths of the canyons and washes, where it may also recharge both the volcanic aquifers and the deeper regional aquifers. The various washes, arroyos, and canyons that drain the Rainier Mesa area drain eastward into Yucca Flat, north into Kawich Valley, or southwest into Stockade Wash and Fortymile Canyon. At Shoshone Mountain, the washes, arroyos, and canyons drain eastward into Mid Valley, southward into Calico Basin and Jackass Flats, or westward into Fortymile Canyon.

There are springs and seeps in both the Rainier Mesa and the Shoshone Mountain areas. In every case where spring discharge is not consumed by plants and animals it seeps back into the alluvium after traveling a short distance. Springs and seeps historically recorded in and around the Rainier Mesa/Shoshone Mountain CAU include Rainier Seep, Captain Jack Spring, Tippipah Spring, Topopah Spring, and Whiterock Spring (Figure 3-4).

3.4.4 Geology

An overview of the geology of the NTS region is presented, followed by a detailed description of the geology of the Rainier Mesa/Shoshone Mountain area. The description is based on the regional geologic model (IT, 1996f; DOE/NV, 1997a), which was interpreted using the information available at that time. Sources of data include the underground nuclear testing activities at the NTS and other public and private sources.

3.4.4.1 Regional Geology

The geology of the NTS and the surrounding area is the product of a complex geologic history. The historical events that shaped the stratigraphy and structure of the region during the Precambrian, Paleozoic, Mesozoic, and Tertiary geologic times are described below. The stratigraphic nomenclature and correlation of the Precambrian and Paleozoic units in the region are shown in Table 3-5. Stratigraphic nomenclature of the Tertiary rocks (Ferguson et al., 1994) is shown in Table 3-6. For a view of the surficial geology of the region, the reader is referred to the State of Nevada geologic map (Stewart and Carlson, 1977) and to the geologic map of the NTS and vicinity (Slate et al., 1999).

Precambrian and Paleozoic History

The oldest and stratigraphically lowest rocks in the NTS region are Precambrian in age. From the Late Precambrian through the Devonian this region of the western United States was a stable continental margin. During the Late Precambrian and Early Cambrian a thick sequence of clastic sedimentary rocks, with minor interbedded carbonates, was deposited throughout the region of the NTS. From the Mid-Cambrian until the Late Devonian the region evolved into a stable carbonate platform where a thick sequence of limestone and dolomite was deposited upon the older sandstones, siltstones, and shale. During the Late Devonian through Mississippian Antler Orogeny, uplift to the

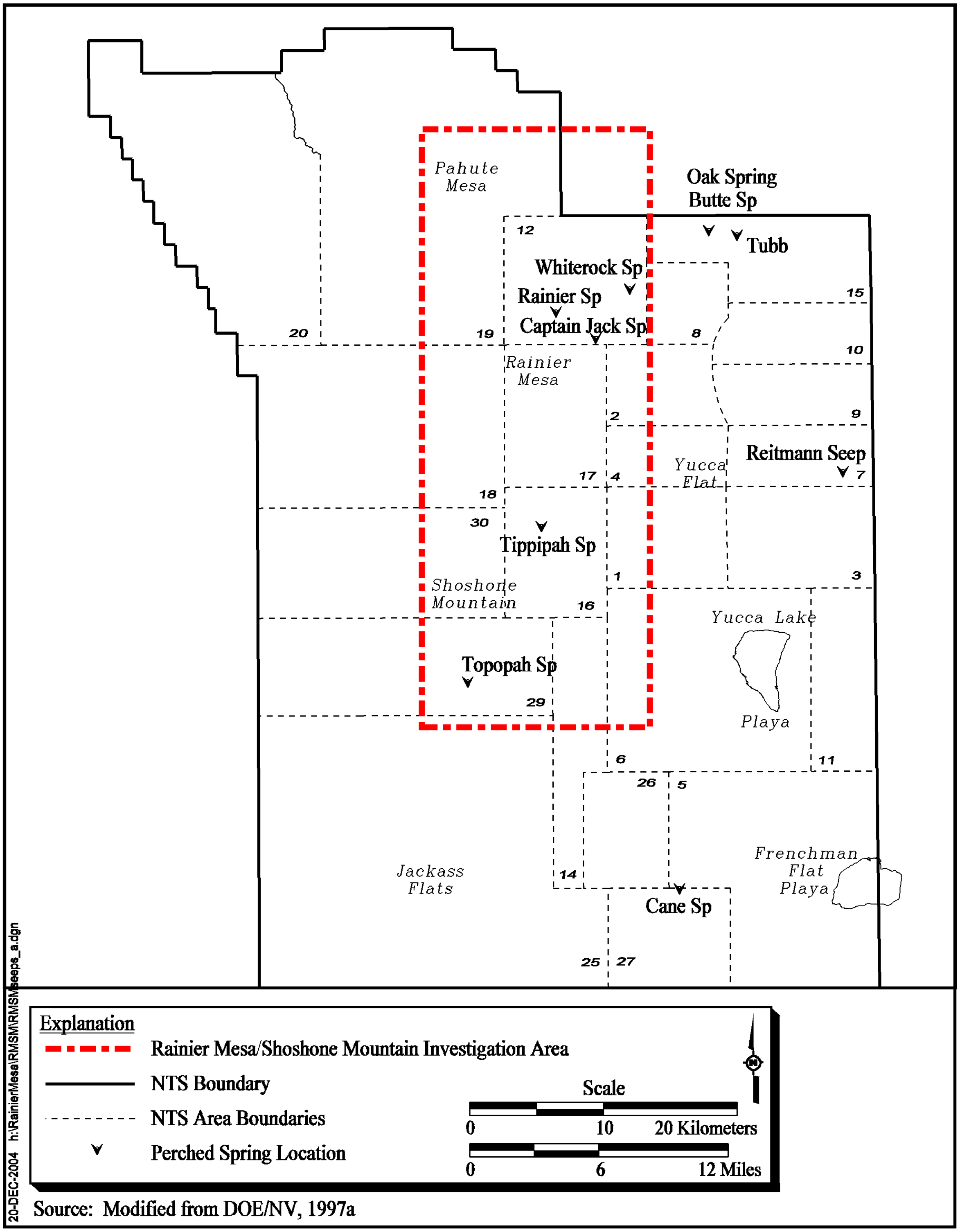


Figure 3-4
Location of Perched Springs or Seeps In and Near the Rainier Mesa/Shoshone Mountain CAU

Table 3-5
Precambrian and Paleozoic Stratigraphic and Hydrostratigraphic Correlation Chart for the NTS and Vicinity

<table>
<tr><th>Age</th><th>Nevada Test Site</th><th>Bare Mt</th><th>Cactus Range</th><th>Belted Range</th><th>Montgomery Mountains</th><th>Funeral Mountains</th><th>HSU</th></tr>
<tr><td>Pennsylvanian</td><td>Tippipah Limestone</td><td></td><td></td><td></td><td>Bird Spring Limestone</td><td></td><td>UCA</td></tr>
<tr><td>Mississippian</td><td>Eleana Fm Chainman Shale</td><td>Eleana Fm</td><td>Eleana Fm</td><td>Eleana Fm</td><td>Monte Cristo Limestone</td><td>Perdido Fm Tin Mt Limestone</td><td>UCCU</td></tr>
<tr><td>U. Devonian</td><td>Guilmette Fm</td><td rowspan="2">Rocks of Tarantula Canyon</td><td rowspan="2">Simonson Fm</td><td rowspan="2">Simonson Fm</td><td>Guilmette Fm</td><td rowspan="2">Lost Burro Fm</td><td rowspan="9">LCA/ LCA3</td></tr>
<tr><td>M. Devonian</td><td>Simonson Fm</td><td>Simonson Fm</td></tr>
<tr><td>L. Devonian</td><td>Sevy Dolomite</td><td>Lone Mt Dolomite</td><td>Sevy Dolomite</td><td>Sevy Dolomite</td><td rowspan="2">Hidden Valley Fm</td><td rowspan="2">Hidden Valley Fm</td></tr>
<tr><td>Silurian</td><td>Laketown Dolomite</td><td>Roberts Mt. Fm</td><td>Roberts Mt. Fm</td><td>Laketown Dolomite</td></tr>
<tr><td>U. Ordovician</td><td colspan="6">Ely Springs Dolomite</td></tr>
<tr><td>M.Ordovician</td><td colspan="6">Eureka Quartzite</td></tr>
<tr><td rowspan="3">L. Ordovician</td><td>Antelope Valley</td><td colspan="5" rowspan="3">Pogonip Group</td></tr>
<tr><td>Ninemile</td></tr>
<tr><td>Goodwin</td></tr>
<tr><td>U. Cambrian</td><td colspan="6">Nopah Formation</td></tr>
<tr><td>M. Cambrian</td><td colspan="6">Bonanza King Fm</td></tr>
<tr><td>L. Cambrian</td><td colspan="6">Carrara Fm</td><td rowspan="4">LCCU</td></tr>
<tr><td rowspan="4">Precambrian (Proterozoic)</td><td colspan="6">Wood Canyon Fm</td></tr>
<tr><td colspan="6">Stirling Quartzite</td></tr>
<tr><td colspan="6">Johnnie Fm</td></tr>
<tr><td colspan="6">Older Precambrian Metamorphic Rocks[a]</td><td>LCCU[a]</td></tr>
</table>

Source: DOE/NV, 1997a

Fm = Formation
HSU = Hydrostratigraphic unit
UCA = Upper Carbonate Aquifer, composed of limestone and dolomite
UCCU = Upper Clastic Confining Unit, composed of shale and siltstone
LCA = Lower Carbonate Aquifer, composed of limestone and dolomite, with minor shale and siltstone
LCA3 = Lower Carbonate Aquifer as it exists in the upper plate of thrust faults
LCCU = Lower Clastic Confining Unit, composed of sandstone, siltstone, shale, and metamorphic rocks

[a]Within the NTS and CAU models, the older Precambrian metamorphic rocks are not differentiated from the younger Precambrian siliciclastic rocks in the LCCU

Table 3-6
Tertiary Stratigraphy of the Nevada Test Site Region
(Page 1 of 2)

Stratigraphic Unit/Group	Stratigraphy Symbol
Thirsty Canyon Group	**Tt**
Gold Flat Tuff	Ttg
Trail Ridge Tuff	Ttt
Pahute Mesa Tuff	Ttp
Rocket Wash Tuff	Ttr
Volcanics of Fortymile Wash	Tf
Rhyolite of Shoshone Mountain	Tfs
Beatty Wash Formation	Tfb
Timber Mountain Group	**Tm**
Intrusive Rocks of Timber Mountain	Tmi
Ammonia Tanks Tuff	Tma
Caldera Collapse Breccia of Timber Mountain	Tmc
Rainier Mesa Tuff	Tmr
Paintbrush Group	**Tp**
Rhyolite of Windy Wash	Tpw
Rhyolite of Comb Peak	Tpr
Rhyolite of Vent Pass	Tpv
Tiva Canyon Tuff	Tpc
Yucca Mountain Tuff	Tpy
Middle Paintbrush Group rhyolites	Tpm
Pah Canyon Tuff	Tpp
Topopah Spring Tuff	Tpt
Volcanics of Area 20	**Ta**
Calico Hills Formation	Tac
Wahmonie Formation	Tw
Intrusive rocks of Wahmonie	Twi
Salyer Formation	Tws
Crater Flat Group	**Tc**
Prow Pass Tuff	Tcp
Bullfrog Tuff	Tcb
Rhyolite of the Crater Flat Group	Tcr
Tram Tuff	Tct

Table 3-6
Tertiary Stratigraphy of the Nevada Test Site Region
(Page 2 of 2)

Stratigraphic Unit/Group	Stratigraphy Symbol
Belted Range	**Tb**
Dead Horse Flat Formation	Tbd
Grouse Canyon Tuff	Tbg
Commendite of Split Ridge	Tbgs
Older Basalt	Tob
Tram Ridge Group	**Tr**
Lithic Ridge Tuff	Trl
Rhyolite of Picture Rock	Trr
Dikes of Tram Ridge	Trd
Tunnel Formation	Tn
Volcanics of Quartz Mountain	Tq
Volcanics of Big Dome	Tu
Tub Spring Tuff	Tub
Commendite of Emigrant Valley	Tue
Older Volcanics	To
Tunnel Bed 2	Ton2
Tuff of Yucca Flat	Toy
Tunnel Bed 1	Ton1
Redrock Valley Tuff	Tor
Tuff of Twin Peaks	Tot
Rhyolite of Belted Peak	Tkr
Paleocolluvium	Tl

Source: Ferguson et al., 1994; Slate et al., 1999; Potter et al., 2002

north and west resulted in the deposition of a thick sequence of shale into a foreland basin that developed in this region. During the Pennsylvanian Period shallow marine carbonate rocks were deposited upon the older shale. More than 10,600 m of Paleozoic and Late Precambrian sedimentary rocks were deposited in the NTS region (DOE/NV, 1997a).

Mesozoic History

Starting in the Permian Period and lasting throughout the Mesozoic Era, crustal shortening dominated the geologic history of the western United States. The Nevadan Orogeny and the Sevier Orogeny produced dominantly east- to southeast-vergent folds and thrust faults that resulted from the collision of island arc systems with western North America. The entire NTS region was affected by the crustal shortening and contractional tectonics. Throughout the NTS region the Paleozoic stratigraphy has been duplicated vertically as older formations were thrust over younger formations (Armstrong, 1968; Cole and Cashman, 1999; Potter et al., 2002; Sweetkind et al., 2001). Intrusion of granitic plutons occurred during the Jurassic and Cretaceous Periods.

Tertiary and Quaternary History

Following the Sevier Orogeny, this region of southern Nevada and eastern California was a highland area subjected to erosion. Locally erosion removed nearly all Paleozoic strata, exposing Early Cambrian and Late Precambrian rocks. In other locations strata as young as Late Cretaceous were exhumed from beneath the overlying upper plate of thrust faults. No Early Tertiary sedimentary deposits are preserved in the NTS region as erosion dominated this period of time. However, isolated exposures of preserved Oligocene sedimentary rocks in the region of Death Valley and the NTS indicate that this area was becoming involved in early crustal extension as numerous local basins developed that received coarse clastic sedimentation from adjacent uplifted blocks (Snow and Lux, 1999; Fridrich, 1999). Volcanic eruptions within the southwest Nevada volcanic center occurred throughout the Miocene, burying much of the NTS in thick deposits of tuff and local deposits of lava that were deposited upon Oligocene clastic rocks and more broadly upon the older Paleozoic and Precambrian strata. Successive eruptions produced at least six large and partially overlapping calderas that were subsequently filled with intra-caldera tuffs, lava flows, and epiclastic deposits (Sawyer et al., 1994). Volcanic rocks now cover much of the NTS. Westward crustal extension occurred contemporaneous with Miocene volcanism (Fridrich, 1999), followed by northwest directed crustal shear strain within the Walker Lane (Stewart, 1988). Basins formed by continued extension of the region were filled with thick accumulations of alluvial debris derived from adjacent highlands.

3.4.4.2 Geology of the Rainier Mesa/Shoshone Mountain Vicinity

The geology of Rainier Mesa/Shoshone Mountain has been described in Appendix C, Volume I of the regional evaluation documentation package (IT, 1996f). Stratigraphic information for boreholes located on the NTS are included in Appendix B of Volume II (IT, 1996e). Geologic information is also summarized in Section 4.0 of the regional evaluation report (DOE/NV, 1997e). A summary of the geology of the Rainier Mesa/Shoshone Mountain vicinity is presented below. Geologic information used in this interpretation includes borehole data, tunnel data, geophysical data, gravity data, and published geologic maps and cross sections. The locations of boreholes in the Rainier Mesa vicinity for which geologic information is available are shown in Figure 3-5, Figure 3-6, and Figure 3-7. This interpretation will be refined during the CAI.

The geologic setting of the Rainier Mesa and Shoshone Mountain area includes most of the rock units that are found in the NTS region. These include the Precambrian and Paleozoic sedimentary rocks, Mesozoic intrusive rocks, Tertiary volcanic and epiclastic rocks, and Quaternary alluvial deposits, as listed above in Section 3.4.4.1. The stratigraphic nomenclature specific to Rainier Mesa and Shoshone Mountain are given in Table 3-7. The surficial geology, including mapped faults and exposed stratigraphy, is shown on Plate 2.

Quaternary colluvium, rock fall deposits, and slope-failure deposits mantel many of the steep slopes and canyon walls within and surrounding Rainier Mesa and Shoshone Mountain. Quaternary alluvial deposits are confined primarily to the deeper washes and canyons in and around Rainier Mesa and Shoshone Mountain. Specifically, Tongue Wash east of Rainier Mesa and Stockade Wash south of Rainier Mesa contain alluvial deposits. In the Shoshone Mountain area, Fortymile Canyon, Tiva Canyon, Topopah Wash, and Pah Canyon contain alluvial deposits. Deeper and more extensive deposits of Quaternary alluvium are found in Yucca Flat east of Rainier Mesa, Mid Valley east of Shoshone Mountain, and in Calico Basin and Jackass Flats south of Shoshone Mountain (Gibbons et al., 1963; Maldonado, 1985; Orkild, 1968; Orkild and O’Conner, 1970).

Tertiary Volcanic rocks of the SWNVF were deposited upon a substrate of Precambrian, Paleozoic, and Mesozoic rocks. Welded and nonwelded ash-flow tuffs and air-fall tuffs belonging to the Timber Mountain Group, Paintbrush Canyon Group, Crater Flat Group, Tunnel Formation, Belted Range Group, Tuff of Yucca Flat, and the Redrock Valley Tuff crop out at Rainier Mesa. Most of the tunnels

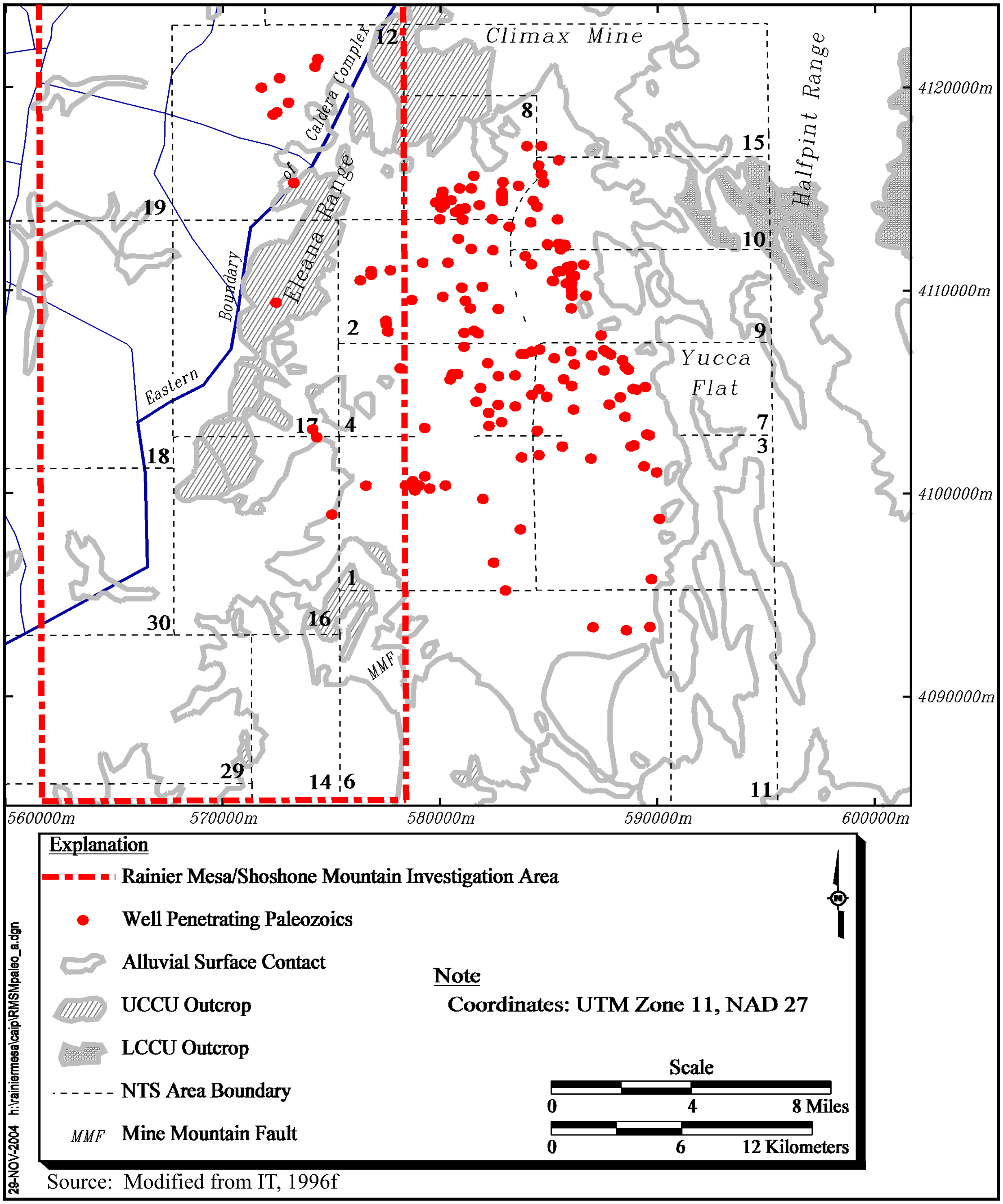


Figure 3-5
Location of Boreholes Penetrating Paleozoic Rocks Near Rainier Mesa and Shoshone Mountain

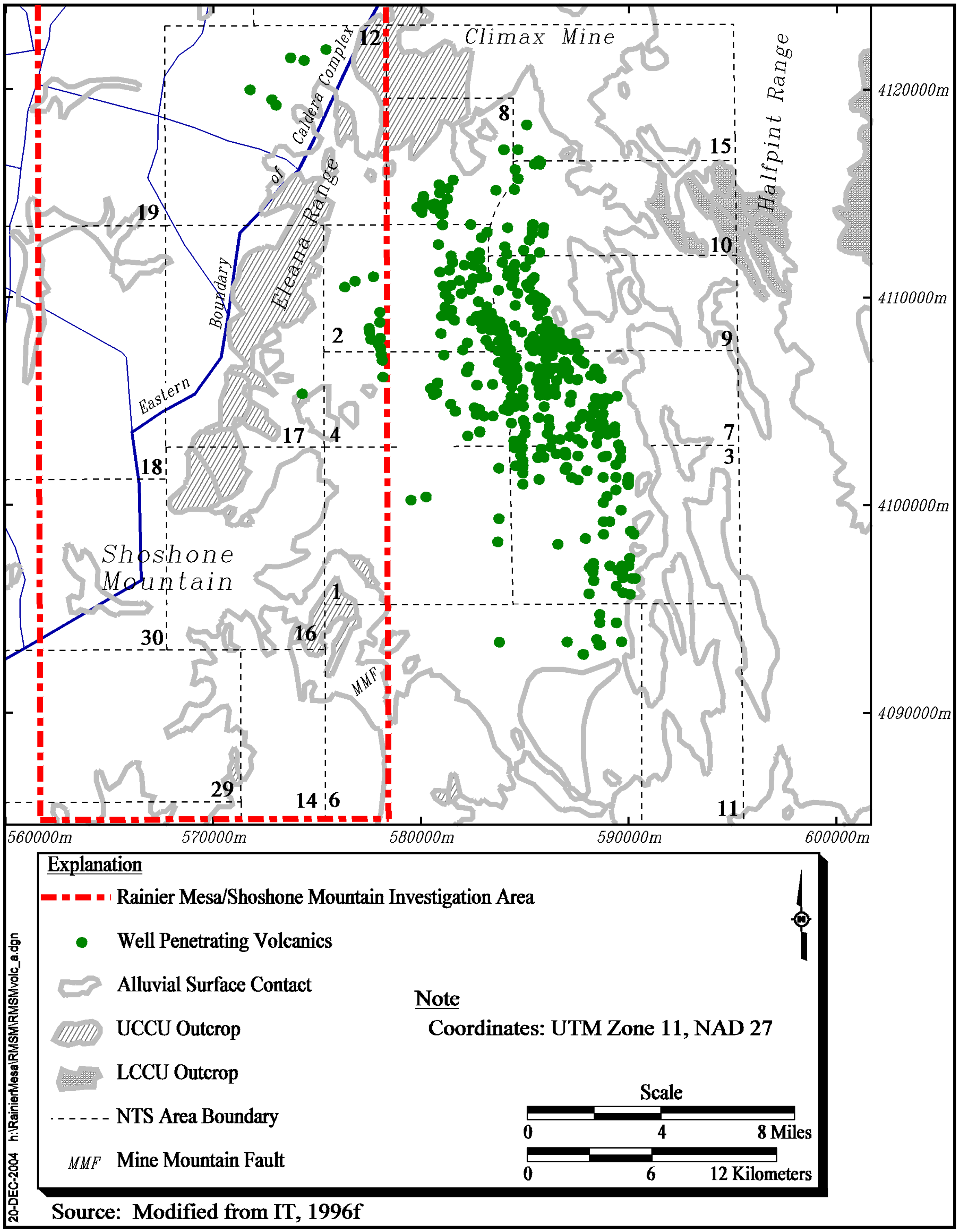


Figure 3-6
Location of Boreholes Penetrating Volcanic Rocks Near Rainier Mesa and Shoshone Mountain

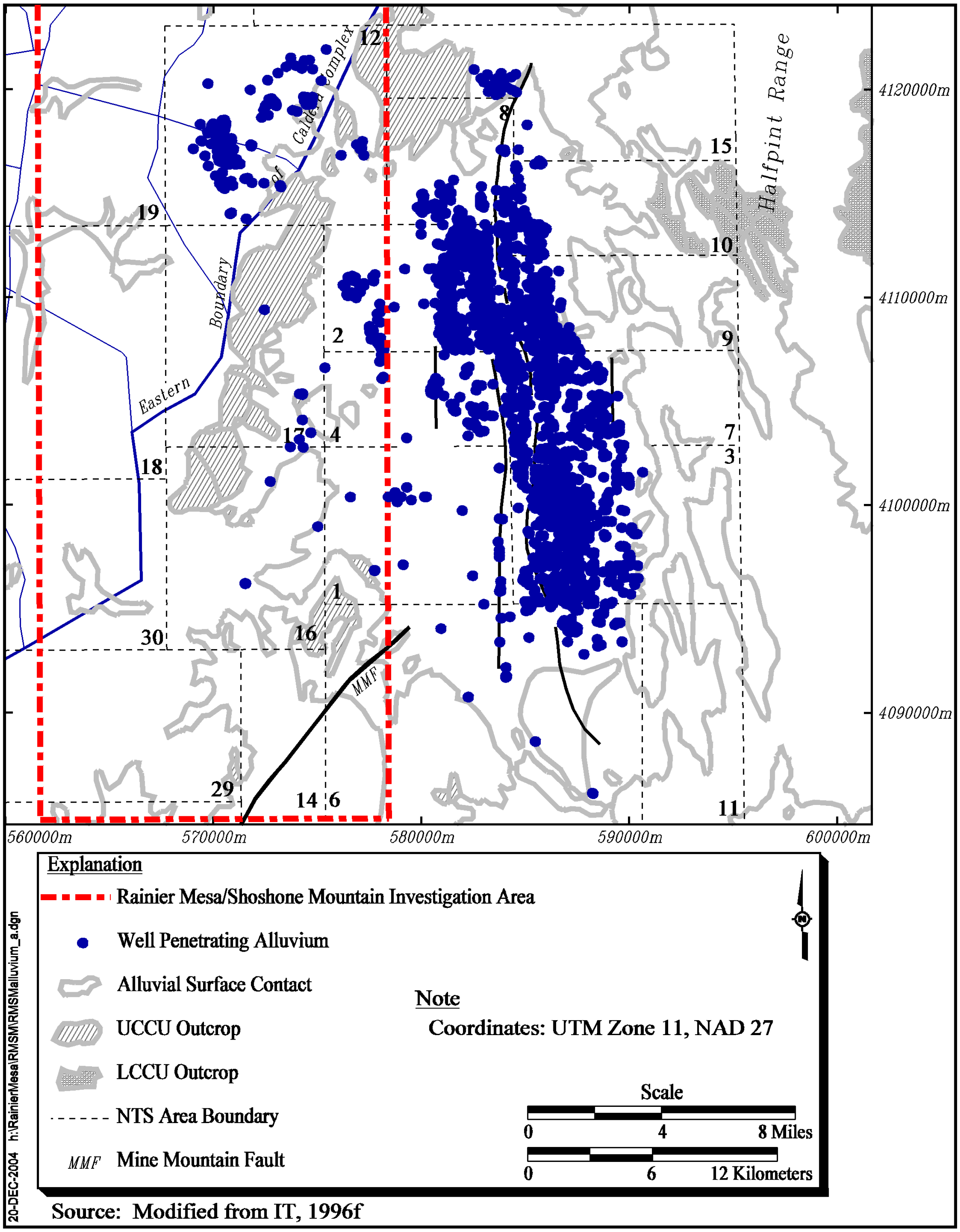


Figure 3-7
Location of Boreholes Penetrating Alluvium Near Rainier Mesa and Shoshone Mountain

Table 3-7
Stratigraphic Units in the Rainier Mesa/ Shoshone Mountain Vicinity
(Page 1 of 2)

Age	Group	Formation or Unit	Symbol	RM	SM
Quaternary	Surficial Deposits	Younger Alluvium	Qay	X	X
		Intermediate Alluvium	Qai	X	X
		Colluvium	QTc		X
		Older Alluvium	QTa	X	X
Tertiary		Younger Tertiary Sediments	Tgy		X
		Caldera Moat Sediments	Tgc	X	X
	Thirsty Canyon	Pahute Mesa Tuff	Ttp	X	X
	Volcanics of Fortymile Canyon	Rhyolite of Shoshone Mountain	Tfs		X
		Lavas of Dome Mt	Tfd		X
		Beatty Wash Fm	Tfb		X
	Timber Mountain	Ammonia Tanks Tuff	Tma	X	X
		Rainier Mesa Tuff	Tmr	X	X
	Paintbrush Canyon	Rhyolite of Comb Peak	Tpr		X
		Tiva Canyon Tuff	Tpc		X
		Middle Paintbrush rhyolites	Tpm		X
		Pah Canyon Tuff	Tpp		X
		Topopah Spring Tuff	Tpt	X	X
	Volcanics of Area 20	Calico Hills Fm	Tac	X	X
	Wahmonie Fm	Wahmonie Fm	Tw		X
	Crater Flat	Prow Pass Tuff	Tcp		X
		Bullfrog Tuff	Tcb	X	X
	Belted Range	Grouse Canyon Tuff	Tbg	X	
		Lithic Ridge Tuff	Trl		X
		Redrock Valley Tuff	Tor	X	X
	Tunnel Formation	Tunnel Formation	Tn	X	X
	Older Volcanics	Older Tunnel Beds	Ton	X	

Table 3-7
Stratigraphic Units in the Rainier Mesa/
Shoshone Mountain Vicinity
(Page 2 of 2)

Age	Group	Formation or Unit	Symbol	RM	SM
Tertiary	Older Volcanics	Tuff of Yucca Flat	Toy	X	
		Tuff of Redrock Valley	Tor	X	
		Tuff of Twin Peaks	Tot	X	
Cretaceous	--	Granite Intrusions	Kg	X	
Permian	--	Tippipah Limestone	Pht		X
Mississippian	--	Chainman Shale	Msc		X
		Eleana FM	MDe	X	X
Devonian	--	Guilmette Fm	Dg	X	
		Simonson Dolomite	Ds	X	X
		Sevy Dolomite	DSs	X	X
Ordovician	Pogonip Group	Antelope Valley Ls	Op	X	
Cambrian/Precambrian	--	Wood Canyon Fm	CZw	X	

Source: Slate et al., 1999; Russell et al., 1996
RM = Rainier Mesa; SM = Shoshone Mountain
X = Unit present

excavated into Rainier Mesa for the purposes of underground nuclear testing are located in Tunnel Beds 3 and 4, formally part of the Tunnel Formation (Hoover and Magner, 1990; Ege and Cunningham, 1976; Emerick and Dickey, 1962; Sawyer et al., 1994), although the U12p tunnel is located in undifferentiated nonwelded tuffs of the Paintbrush Group (BN, 2002a). At Shoshone Mountain, tuffs and lavas of the Rhyolite of Shoshone Mountain, the Timber Mountain Group, the Paintbrush Canyon Group, the Calico Hills Formation, the Crater Flat Group, and the Tram Ridge Group are exposed at the surface. The 16a-Tunnel complex at Shoshone Mountain was excavated into nonwelded zeolitic and bedded tuffs identified as part of the Oak Springs Formation by Davis (1962). These beds were correlated with Tunnel Beds 3 and 4 in the E-Tunnel complex at Rainier Mesa (Emerick and Dickey, 1962), which is part of the Tunnel Formation (Sawyer et al., 1994). No deep drill holes are located in the Shoshone Mountain area so the extent of older tuffs in the subsurface is not known. All of these volcanic formations manifest lateral changes in thickness, welding, and stratigraphic detail within and between Rainier Mesa, Shoshone Mountain, and adjacent areas. At most localities, only a partial stratigraphic section is present for any given group. A detailed chart of stratigraphic units known or suspected to exist in the study area is presented in Table 3-7. North of the NTS, volcanic units other than those listed in Table 3-6 and Table 3-7 are present. These units were not differentiated during the regional evaluation (DOE/NV, 1997a; IT, 1996c).

Tertiary crustal extension and deformation occurred during and after the eruption and deposition of the volcanic rocks of the SWNVF. The extensional deformation caused large vertical displacements, severe local tilting of strata, and local detachment faulting in the area of the NTS (Sweetkind et al., 2001). However, severe rotation of volcanic strata and detachment faulting are absent in and around the Rainier Mesa/Shoshone Mountain CAU.

Mesozoic rocks in and near the area of investigation consist of the granite of the Gold Meadows stock just north of Rainier Mesa, the granite, monzonite, and granodiorite of the Climax Mine stock east of Rainier Mesa, and dikes of lamprophyre encountered in drill hole ER-12-1 that are associated with the Gold Meadows stock (Barnes et al. 1963; Snyder, 1977; Russell et al., 1996). The Gold Meadows stock has been dated at 91.8 +/- 2.6 million years (m.y.) using potassium (K)/argon (Ar) age dating methods, and the Climax stock has been dated at 93 m.y. (Snyder, 1977). Recent geophysical data from the USGS (Phelps, 2004) indicate that these two intrusives likely join at depth.

Precambrian and Paleozoic sedimentary rocks underlie Rainier Mesa and Shoshone Mountain. At Rainier Mesa surface mapping and borehole data reveal that the Devonian and Silurian carbonates have been thrust over the Mississippian Eleana Formation in one area, and that the Precambrian Wood Canyon Formation has been thrust over the Mississippian Eleana Formation in another area (Gibbons et al., 1963; IT, 1995; Russell et al., 1996). Subsurface lithologic data from several drill holes show these juxtapositions to comprise a complex imbricate thrust fault system referred to as the Belted Range thrust (Cole et al., 1994; Sweetkind et al., 2001). At the Calico Hills in the Shoshone Mountain area, Tertiary volcanic rocks are deposited upon Mississippian and Devonian sedimentary rocks. Here, Devonian carbonate rocks have been thrust upon the Mississippian Eleana Formation (Orkild and O’Conner, 1970). In the eastern part of Shoshone Mountain, Tertiary volcanic rocks are deposited upon shale of the Mississippian Eleana Formation and Devonian limestone and dolomite of the Devils Gate and Nevada Formations. Here, the Paleozoic rocks are in proper stratigraphic order, but 6 km to the east the Devonian rocks have been thrust over the Mississippian rocks by the Mine Mountain thrust fault (Orkild, 1968). The Mine Mountain thrust has been correlated with a thrust fault in the CP Hills called the CP thrust (Cole et al., 1994; Sweetkind et al., 2001).

The Belted Range thrust is projected to go from the northern part of the Belted Range southward to Shoshone Mountain, where the buried trace of this fault is projected to turn to the west into the Timber Mountain Caldera Complex (Sweetkind et al., 2001). Based on borehole data from wells at Rainier Mesa, Cole et al. (1994) hypothesized that the Belted Range thrust locally had experienced reverse movement, juxtaposing the Precambrian Wood Canyon formation in the hanging wall against the Eleana Formation in the footwall. The Belted Range thrust is a major foreland-vergent thrust fault, whereas the CP thrust is a smaller hinterland-vergent back-thrust (Cole et al., 1994; Cole and Cashman, 1999).

The Timber Mountain Caldera Complex lies just west of Rainier Mesa and Shoshone Mountain and comprises a series of nested and partially overlapping collapse calderas that resulted from eruption of the Ammonia Tanks Tuff and the Rainier Mesa Tuff. The Claim Canyon Caldera, which overlaps the Timber Mountain Caldera, comprises a part of the caldera complex, and resulted from the eruption of the Tiva Canyon Tuff (Byers et al., 1976). Facies relations indicate that the Topopah Spring Tuff also erupted from a caldera located at Timber Mountain, but that this entire caldera was consumed by subsequent caldera-forming eruptions (Dickerson and Drake, 1998). Caldera formation initially results in a steep-sided collapse feature structurally defined by a steep inward-dipping ring fault. The sides of the collapse caldera are usually unstable and collapse into the caldera shortly after the initial subsidence, forming thick mega-breccias. For particularly voluminous ash-flow eruptions, the collapsing caldera becomes simultaneously filled with thick deposits of intracaldera ash-flow tuff mixed with collapse megabreccias. Within a few years, erosion weathers the caldera walls back until a stable angle of repose has been established. Hence, the typical caldera manifests a structural boundary defined by ring faults and thick, densely-welded intracaldera ash-flow tuffs, and a larger topographic boundary defined by erosion and thin, intercalated moat deposits of fallout tephra, local lava flows, and epiclastic deposits (Lipman, 1976). The structural boundary of the Rainier Mesa caldera lies about 10 km southwest of Rainier Mesa whereas the topographic boundary lies only about 4 km to the southwest (Slate et al., 1999). Rainier Mesa is composed of thinner welded and nonwelded outflow deposits of the ash-flow tuffs whereas the caldera complex to the west contains several thick, densely-welded intracaldera tuffs and lesser amounts of the fallout tuff, small-volume lava flows, and epiclastic deposits that typify moat deposits (Byers et al., 1976). The structural boundary of Rainier Mesa and the Ammonia Tanks Caldera lies just west of Shoshone Mountain, and local map data indicate that the topographic boundary of the Timber Mountain Caldera Complex projects through the middle of Shoshone Mountain. As such, the geology of Shoshone Mountain includes both intracaldera-type deposits and outflow deposits. Specifically, proximal facies of the Ammonia Tanks, the Rainier Mesa, Tiva Canyon, Pah Canyon, and Topopah Spring Tuff outflow deposits form much of the volcanic stratigraphy exposed at Shoshone Mountain, but western Shoshone Mountain also contains numerous lava domes associated with moat deposits. The Rhyolite of Shoshone Mountain is composed of numerous lava flows, small-volume ash-flow tuffs, and intrusive plugs and dikes typical of ring fault-controlled, post-caldera volcanism.

3.4.5 Hydrology

Descriptions of the regional hydrogeology of the NTS and the hydrology of the Rainier Mesa/ Shoshone Mountain vicinity are presented in this section. All descriptions are based on the regional evaluation report and supporting documentation (DOE/NV, 1997a; IT, 1996b through h; IT, 1997).

3.4.5.1 Regional Hydrogeology

The regional hydrogeology of the NTS is described in detail in the regional evaluation report (DOE/NV, 1997a) and the *Regional Geologic Model Data Documentation Package* (IT, 1996f). A summary including descriptions of the hydrostratigraphy and groundwater of the region is provided in the following sections.

3.4.5.1.1 Hydrostratigraphy

Groundwater flowing beneath the NTS region passes through diverse rocks that differ substantially in terms of age, composition, and water-bearing properties. These rocks form a complex 3-D framework of groundwater conduits and barriers that can be grouped into hydrostratigraphic units (HSUs), rock units with similar hydraulic properties. The HSUs may be aquifers or confining units, depending on their ability to store and transmit water. The HSU present at the working points of each underground nuclear test is provided in Table 3-2 and Table 3-3. Cross sections showing the distributions of the HSUs in the Rainier Mesa and Shoshone Mountain region are shown in Plate 3.

During the regional evaluation, the NTS regional framework was subdivided into 26 HSUs as depicted in Table 3-8 (IT, 1996f). Some of the HSUs were grouped into hydrostratigraphic model layers. A total of 20 hydrostratigraphic model layers were defined for the NTS region (Table 3-8). Seven HSUs were defined to represent the Rainier Mesa/Shoshone Mountain area. The details of the methodology used to group the stratigraphic units into HSUs are available in the *Regional Geologic Model Data Documentation Package* (IT, 1996f).

Three major aquifer types were defined: the carbonate aquifers, the volcanic aquifers, and the alluvial aquifer. The carbonate aquifers include the LCA and the thrust faulted Lower Carbonate Aquifer (LCA3) in the upper plate of the Belted Range thrust (Table 3-8). The volcanic aquifers include the Timber Mountain Aquifer (TMA), Basal Aquifer (BAQ), and the Volcanic Aquifer (VA) (Table 3-8). The Alluvial Aquifer (AA) forms a single HSU. All other HSUs listed in Table 3-8 are confining units. The LCA and the Lower Clastic Confining Unit (LCCU) are the most extensive HSUs in the area. The LCA is the most important aquifer due to its wide distribution and high hydraulic conductivity, and hence its potential as a pathway for large-scale transport of contaminants. The LCCU generally underlies the other HSUs and has extremely low hydraulic conductivities. The LCCU is assumed to be the basement of the groundwater flow system. The LCA and the LCCU predominantly control regional groundwater flow. The regional distribution and thickness of the LCA is spatially variable and controlled by the structural position of the underlying LCCU. In general, the LCA is thin or missing on structural highs and thickest in structural lows.

The available hydraulic conductivity data (Appendix A of Volume IV of the regional evaluation documentation [IT, 1996d]) were compiled and reduced to provide estimated values for the major HSUs defined in the regional model (IT, 1996b). These data were obtained from hydraulic tests conducted in selected wells of the NTS region. Results of the hydraulic testing provide estimates of the local HSU hydraulic properties. These results were extrapolated to incorporate the entire NTS regional groundwater system. Hydraulic tests considered in the analysis included mostly single-well tests from 89 wells (Appendix C of Volume IV of the regional evaluation documentation [IT, 1996d]). Core hydraulic conductivities measured in the laboratory, although available, were not included.

Table 3-8
Hydrostratigraphic Units and Geologic Model Layers of the Nevada Test Site Region

Model Layer Name	HSU Name	Description
Alluvial Aquifer	AA	Alluvium and valley-fill deposits
Timber Mountain Aquifer	TMAQ-7	Uppermost welded tuffs
Tuff Cones	TPTC-6	Laterally variable tuffs and lava flows of the Paintbrush Group
	TPTC-5	Laterally variable tuffs and lavas of the Calico Hills Fm
Bullfrog Confining Unit	TCBCU-4	Non-welded tuffs
Belted Range Aquifer	TBAQ-3	Welded tuffs above BCU-2
Basal Confining Unit	BCU-2	Non-welded tuffs
Basal Aquifer	BAQ-1	Welded tuffs
Volcanic Aquifer	WTA	Welded-tuff aquifer
	VTA	Vitric-tuff aquifer
	TCU-2	Zeolitized tuff confining unit (upper)
	TPTA	Topopah Springs tuff aquifer
	WLA	Wahmonie lava aquifer
Volcanic Confining Unit	TCU-1	Zeolitized tuff confining unit (lower)
	VCCU	Volcaniclastic confining unit
Volcanics Undifferentiated	VU	Volcanics – undifferentiated
Tertiary Sediments	TS DVS	Tertiary sedimentary rocks Death Valley sedimentary section
Lower Carbonate Aquifer-Upper Plate	LCA3	Lower Paleozoic limestone and dolomite in the upper thrust-fault plate
Upper Clastic Confining Unit	UCCU	Upper Paleozoic siltstone and mudstone
Lower Carbonate Aquifer	LCA	Lower Paleozoic limestone and dolomite
Lower Clastic Confining Unit-Upper Plate	LCCU	Precambrian and Cambrian quartzite, siltstone, and mudstone in upper thrust-fault plate
Lower Carbonate Aquifer-Upper Plate	LCA1	Lower Paleozoic limestone and dolomite in upper thrust-fault plate
Lower Clastic Confining Unit	LCCU1	Precambrian and Cambrian quartzite, siltstone, and mudstone in upper thrust-fault plate
Lower Carbonate Aquifer-Lower Plate	LCA2	Lower Paleozoic limestone and dolomite in lower thrust-fault plate
Lower Clastic Confining Unit-Lower Plate	LCCU2	Precambrian and Cambrian quartzite, siltstone, and mudstone in lower thrust-fault plate
Intrusives	I	Granitic intrusions

Source: Modified from DOE/NV, 1997a

Hydraulic conductivity ranges for the main aquifers are summarized in Table 3-9. The mean conductivity of the AA is smaller than that of the carbonate aquifers, but higher than that of the VA. The ranges extend over many orders of magnitude. For example, within the LCA the range of hydraulic conductivity is estimated to be between 0.0008 and 1,570 meters per day (m/d), representing both matrix and fractures. This large range suggests that at the local scale, large variability in hydraulic conductivity can be expected. At larger scales, the degree of fracturing controls the heterogeneity. Similar ranges of values for different rock types have been reported in Freeze and Cherry (1979), indicating that the data from the NTS region are not unusual. The details regarding the hydraulic parameters estimated for the HSUs are presented in the *Hydrologic Parameter Data Documentation Package* (IT, 1996d).

Table 3-9
Ranges of Hydraulic Conductivity for the Major Aquifers of the Nevada Test Site Region

Aquifer	Arithmetic Mean (m/d)	Range (m/d)
Alluvial Aquifer	8.44	0.00006 – 83.0
Volcanic Aquifers	1.18	0.0003 – 12.0
Carbonate Aquifers	31.71	0.0008 – 1,570

Source: DOE/NV, 1997a

The hydraulic conductivity data set (Appendix C of Volume IV of the regional evaluation documentation package [IT, 1996d]) was also used to estimate the total depth of the flow system and to define the relation between hydraulic conductivity and depth for the model aquifers (IT, 1996f; DOE/NV, 1997a). The analysis of data available for all rock types shows that a decreasing linear trend exists for the logarithm of hydraulic conductivity with increasing depth. That is, hydraulic conductivity is interpreted to decrease exponentially with depth. The relation is illustrated by the equation:

$$K_{depth} = K_0(10^{-\lambda d}) \tag{3-1}$$

Where:

K_{depth} = The horizontal hydraulic conductivity at specified depth (m/d)
K_0 = The horizontal hydraulic conductivity at land surface (m/d)
λ = The hydraulic conductivity decay coefficient (1/m)
d = The depth from land surface (m)

Equation 3-1 was applied to data available for all types of rocks, and to data available for each rock type individually. In equation 3-1, K_h is equal to K_0 for depth zero. Therefore, K_0 represents a calculated hydraulic conductivity for the saturated medium at zero depth, i.e., at land surface. It is calculated as the intersection of the line representing the mean through the measured hydraulic conductivity data with the land surface (Figure 5-1, DOE/NV, 1997a). The hydraulic conductivities calculated using equation 3-1 and the data available for all rock types are meaningful only for depths greater than the depth-to-water at any given location. The data displayed in the "Hydraulic Conductivity at Land Surface" columns in Table 3-10 are not meant to imply that these rocks are saturated at the surface. K_0 is simply the reference horizontal hydraulic conductivity applied to the saturated zone model. Using equation 3-1 and the data available for volcanics and carbonates (the rocks present at great depths), it is found that a depth of 3,000 m approximately represents the bottom of the flow system. At greater depths the extrapolated mean hydraulic conductivity values are less than 10^{-7} m/d. The analysis of hydraulic conductivity for each of the major aquifers (AA, VA, LCA) showed that within each of the aquifers, hydraulic conductivity also decreased exponentially with depth. However, as shown in Table 3-10, the rate of decrease varies from one aquifer to the next (IT, 1996c). Additional information about hydraulic conductivity versus depth may be found in Section 6.2 of Volume IV of the regional evaluation documentation package (IT, 1996d), and in Section 5.5.1.5 of the regional evaluation report (DOE/NV, 1997a).

3.4.5.1.2 Groundwater

A conceptual model of the regional groundwater flow system was developed during the regional evaluation (DOE/NV, 1997a). A summary description is provided in this section. A detailed description can be found in Section 6.0 of the regional model report (DOE/NV, 1997a). A map depicting the characteristics of the regional groundwater flow system, including the boundary, areas of recharge, and areas of ET, is presented in Figure 3-8.

Table 3-10
Hydraulic Conductivity Decay Coefficients with Depth

Aquifer	λ, Decay Coefficient (m^{-1})			K_0, Horizontal Hydraulic Conductivity at Land Surface (m/d)		
	Lower 95 Percent C.I.	Mean	Upper 95 Percent C.I.	Lower 95 Percent C.I.	Mean	Upper 95 Percent C.I.
Alluvial	0.00402	0.00563	0.00724	6.04	21.18	74.25
Volcanics	0.00205	0.00256	0.00306	2.15	7.75	27.87
Carbonate	0.00044	0.00102	0.00160	2.60	6.76	17.59

Source: IT, 1996d; DOE/NV, 1997a
C.I. = Confidence interval

Saturated alluvial materials are present only in canyons, washes, and arroyos immediately down gradient from springs and seeps, and represent an inconsequential part of the Rainier Mesa/Shoshone Mountain area. Saturated Tertiary volcanic rocks are present as perched aquifers at Rainier Mesa and at Shoshone Mountain. There are likely saturated volcanic rocks within the Timber Mountain Caldera Complex to the southwest of Rainier Mesa and to the west of Shoshone Mountain. The distribution and thickness of the AA is inconsequential, whereas the distribution of the VA is more widespread, but nonetheless highly variable and discontinuous. The AA is confined to basins surrounding Rainier Mesa and Shoshone Mountain, such as Yucca Flat to the east, Mid Valley to the southeast, and Calico Basin and Jackass Flats to the south. In general, the AA and the VA are considered depositional elements overlying the regional flow system and only influence the regional flow in localized areas. The underlying LCA is the principal aquifer in the 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 intrusions.

Based on the water level dataset compiled during the regional evaluation (Appendix A of IT [1996g]), depth to groundwater beneath the NTS and surrounding region vary greatly. Groundwater depths in the southern NTS range from 23 m beneath Fortymile Wash to 209 m at WW5B in Frenchman Flat. These compare to more than 610 m beneath Pahute Mesa in the northern part of the NTS (IT, 1996f; and DOE/NV, 1997a). Perched groundwater is found locally throughout

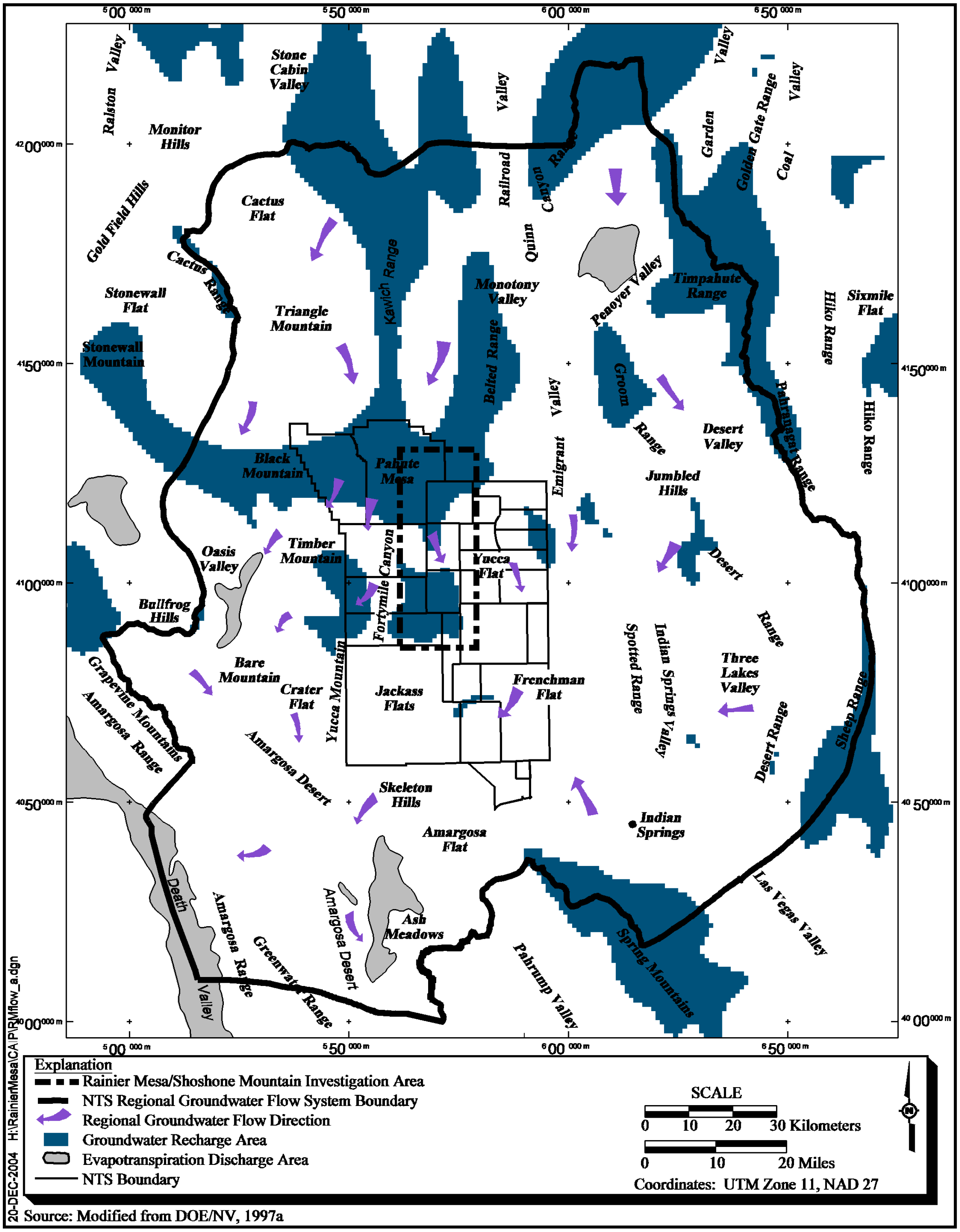


Figure 3-8
Features of the Nevada Test Site Regional Groundwater Flow System

the NTS. In the highlands, springs emerge from perched water zones. Spring discharge rates are low and this water is used only by wildlife.

Based on the existing water level database (IT, 1996e), the general direction of groundwater flow is from north to south in the northern portion of the flow system, and from northeast to southwest in the southern portion (Figure 3-8). The direction of groundwater flow is locally influenced by structural and stratigraphic conditions that affect the thickness and distribution of the LCA. In some areas of the regional flow system, groundwater encounters geologic conditions, such as structurally high areas of LCCU, which promote an upward flow of groundwater. The upward flow brings water to discharge at the surface in the form of wet playa or springs. The discharge is then lost from the flow system by ET. Conversely, there is groundwater flow between basins in the form of subsurface inflow and outflow. Ultimately, groundwater is lost to ET at discharge sites located down gradient.

Horizontal gradients are low to the east and west of the NTS. In other areas, the prevailing flow direction and hydraulic gradients can be influenced locally by the structural position of geologic units with significantly lower hydraulic conductivity than that of the LCA. If the lower-hydraulic conductivity units are structurally oriented so that they are perpendicular to flow, then flow might be significantly altered, causing steep hydraulic gradients. If their structural orientation is parallel to the prevailing flow direction, their effect may be insignificant. Structural uplifts of the LCCU and the distribution of the Upper Clastic Confining Unit (UCCU) have caused several of the observed steep hydraulic gradients within the flow system. Low permeability sedimentary units along the Funeral Mountains also cause a steep hydraulic gradient between the Amargosa Desert and Death Valley.

Groundwater recharge from precipitation occurs by infiltration through the unsaturated zone (UZ). Discharge occurs naturally as ET and potential underflow beneath discharge areas in the Amargosa Desert and in Death Valley. Artificial discharge occurs as groundwater is pumped from drinking water supply wells (public and domestic), agricultural wells, and industrial wells. Public, domestic, and industrial supply wells for the NTS produce water from the carbonate, volcanic, and alluvial aquifers. South of the NTS, private and public water supply wells are completed primarily in the valley-fill aquifer. At the regional scale, groundwater discharge from wells is not considered significant. An estimate of the regional, steady-state groundwater budget is provided in Table 3-11. These data were derived from analysis of recharge and discharge data to provide an approximate mass-balance calculation for the groundwater budget for the NTS. Details of this analysis are presented in greater detail in DOE/NV (1997a). The groundwater budget for Rainier Mesa/Shoshone Mountain is likely much different than that of the regional NTS groundwater flow system as a whole.

Table 3-11
Estimated Steady-State Groundwater Budget for the Nevada Test Site Regional Groundwater Flow System

Recharge	
Recharge from precipitation	177,484 to 289,410 m^3/day
Subsurface inflow	5,405 to 70,100 m^3/day
Total Natural Recharge	**182,889 to 359,510 m^3/day**
Discharge	
Surface discharge (evapotranspiration and springs)	135,340 to 300,700 m^3/day
Subsurface outflow	850 to 5,100 m^3/day
Total Natural Discharge	**136,190 to 305,800 m^3/day**

Source: DOE/NV, 1997a
m^3/d = Cubic meters per day

3.4.5.2 Hydrology of the Investigation Area

The hydrology of Rainier Mesa and Shoshone Mountain vicinity will be further investigated during the CAI. The current understanding is predominantly based on the regional evaluation results (DOE/NV, 1997a; IT, 1996b through h; IT, 1997). A summary including descriptions of the hydrostratigraphy and groundwater of the area is provided in the following sections.

3.4.5.2.1 Hydrostratigraphy

The hydrostratigraphy of Rainier Mesa and Shoshone Mountain has previously been described in Volume I of the regional evaluation documentation package (IT, 1996f). Specific descriptions can be found in Appendices C5 through C9, C15, E2, and F (IT, 1996f). The information was also summarized in Section 4.0 and Section 6.2.1 of the regional evaluation report (DOE/NV, 1997a). The hydrostratigraphy of the Rainier Mesa/Shoshone Mountain vicinity is based on interpretations made during the development of the regional model (IT, 1996f), as well as on the hydrostratigraphy developed for the Pahute Mesa CAU scale model. These interpretations will be refined during the CAI for Rainier Mesa/Shoshone Mountain.

The HSUs of the Rainier Mesa/Shoshone Mountain investigation area are the AA, TMA, VA, Basal Confining Unit (BCU), Volcanic Confining Unit (VCU), LCA3, UCCU, LCA, LCCU, and Mesozoic Granite Confining Unit (MGCU), as displayed on cross section A-A' on Plate 3 of this report. Cross sections drawn east to west through Rainier Mesa and Shoshone Mountain show additional hydrostratigraphic units. The hydrostratigraphic units portrayed on cross sections A-A', B-B', and C-C' on Plate 3 include provisional hydrostratigraphic units developed for the Pahute Mesa CAU, but are included on these sections because of the similarity of the volcanic stratigraphy in both locations. Final hydrostratigraphic units contained within the Rainier Mesa/Shoshone Mountain CAU-scale model might well be modified from those presented here on Plate 3. For Rainier Mesa, section B-B' also displays the Bullfrog Confining Unit (BFCU), the Belted Range Aquifer (BRA), the Pre-Belted Range Composite Unit (PBRCM), and the LCCU in the upper plate of the Belted Range thrust fault (LCCU1). For Shoshone Mountain, section C-C' also displays the Paintbrush Composite Unit (PCM), the Yucca Mountain Crater Flat Composite Unit (YMCFCM), the PBRCM, the Fortymile Canyon Composite Unit (FCCM), the Timber Mountain Composite Unit (TMCM), the Subcaldera Volcanic Confining Unit (SCVCU), and the Rainier Mesa Intrusive Confining Unit (RMICU). To aid in understanding the hydrostratigraphy of the investigation area, these cross sections were constructed using the regional hydrostratigraphic model (IT, 1996f). Detailed geologic cross sections are also available on USGS geological maps for Rainier Mesa (Gibbons et al., 1963) and for Shoshone Mountain (Orkild, 1963 and 1968).

The LCCU is the hydrologic basement of the Rainier/Shoshone Mountain CAU. It occurs throughout the Rainier Mesa/Shoshone Mountain investigation area. The LCCU represents the Precambrian and lower Cambrian siliciclastic deposits described previously. The LCCU is the principal HSU beneath the basins east and south of the Rainier Mesa/Shoshone Mountain CAU. The structural position of the LCCU has controlled the elevation of the overlying LCA. Portions of the LCCU are also part of the upper plate of the Belted Range thrust fault, and are labeled as LCCU1.

The LCA is the regional aquifer in the Rainier Mesa/Shoshone Mountain CAU. The LCA represents the lower Paleozoic carbonate strata, which lies between the LCCU and the upper Devonian to Mississippian siliciclastic rocks. The LCA is exposed east of Shoshone Mountain at Mine Mountain and in the CP Hills. The base of the LCA is not exposed within the investigation area.

The UCCU represents the upper Devonian to Mississippian age siliciclastic deposits. The UCCU is the principal HSU beneath the volcanic strata along the eastern flank of Rainier Mesa and Shoshone Mountain. The UCCU overlies the LCA in the subsurface and in outcrops in the eastern portions of Rainier Mesa and Shoshone Mountain, and south of Shoshone Mountain in the Calico Hills.

Pennsylvanian-age carbonate rocks overlie the UCCU and crop out at Syncline Ridge, just east of Shoshone Mountain. They are represented as the Upper Carbonate Aquifer (UCA) in the NTS area, but are depicted as LCA3 in cross sections derived from the 3-D hydrostratigraphic model. The LCA3 represents several isolated, mostly buried erosional remnants of Cambrian through Silurian carbonate rocks in the upper plates of thrust faults that lie upon younger strata along the eastern part of the Rainier Mesa/Shoshone Mountain CAU. These carbonates are called LCA3 to differentiate them from the regional LCA, which normally lies beneath the UCCU. LCA3 carbonates have been interpreted as belonging to the upper plate of the CP thrust, which is interpreted as a hinterland-vergent back thrust that lifted LCA stratigraphic units upon the UCCU in the NTS area (Cole and Cashman, 1999). Because of the similar spatial positions of the UCA and LCA3 with respect to the LCA in the greater Rainier Mesa and Shoshone Mountain area, they have been mapped together as LCA3.

The VCU overlies all older Paleozoic strata which include the LCA, UCCU, and LCA3 in the Rainier Mesa/Shoshone Mountain CAU. The VCU represents the nonwelded and altered (typically zeolitized) volcanic tuffs of the area. The VCU generally separates the upper Tertiary aquifers from the LCA. The VCU may be locally saturated, as evidenced by perched ground water discharging from seeps and springs in and around Rainier Mesa and Shoshone Mountain. The Tertiary paleocolluvium that occurs along the basal Tertiary contact in Yucca Flat acts as a local confining unit and is considered a part of the VCU (Laczniak et al., 1996). However, available drill hole data suggest that it does not exist in the Rainier Mesa area. The possible extent of the early Tertiary paleocolluvium in the Shoshone Mountain area is not known. The east-to-west cross sections through Rainier Mesa and Shoshone Mountain show additional volcanic confining units associated with specific formations or groups of formations where the stratigraphic data are sufficient to make this determination. These include the BFCU, SCVCU, and the RMICU.

At both Rainier Mesa and Shoshone Mountain the VA overlies the VCU and lies at or near the surface. The VA is composed of welded and unaltered tuffs and lava flows, and has about the same distribution as the VCU. Southwest of Rainier Mesa and west of Shoshone Mountain, the VA is much thicker and more extensive because of the thick accumulations of densely welded intracaldera tuff within the Timber Mountain Caldera Complex. The thick section of VA west of the Rainier Mesa/Shoshone Mountain CAU potentially represents a pathway for groundwater flow away from the CAU. The east-to-west cross sections through Rainier Mesa and Shoshone Mountain also show additional volcanic aquifers associated with specific formations or groups of formations, including the BRA. Additional hydrostratigraphic units within the Tertiary volcanic rocks include the PBRCM, PCM, YMCFCM, PBRCM, FCCM, and TMCM. Composite units contain strata that locally behave as aquifers and other strata that locally behave as confining units.

The youngest Tertiary and Quaternary alluvium and valley fill deposits comprise the AA. These deposits are thin, poorly developed, and of limited extent at Rainier Mesa and Shoshone Mountain, so the AA is of little consequence within the CAU. However, the AA is much thicker and better developed in the Yucca Flat basin just east of Rainier Mesa, and in Mid Valley and Calico Basin southeast and south of Shoshone Mountain. The AA is also present in the moat of the Timber Mountain Caldera. The AA is locally in contact with the LCA3 and various volcanic units in these basins peripheral to Rainier Mesa and Shoshone Mountain, and potentially offer groundwater pathways away from the CAU into these other basins, as well as into the Timber Mountain Caldera Complex.

Cretaceous granitic intrusions exist northwest and northeast of Rainier Mesa at the Gold Meadows Stock and the Climax Mine Stock, and comprise the MGCU hydrostratigraphic unit. These rocks are relatively impermeable except for fracture-controlled porosity. Geophysical evidence suggests that these two intrusions are joined at depth (Snyder, 1977). These intrusions are located upgradient from the CAU and potentially restrict the regional flow of groundwater into the CAU area from the north. However, these intrusions may potentially have minimal affect on groundwater movement within the CAU. Tertiary intrusive rocks are likely to lie beneath the Timber Mountain Caldera, representing the chilled and crystallized remains of the magma chamber that supplied material for those series of volcanic eruptions. This Tertiary intrusion forms the RMICU hydrostratigraphic unit. Although the depth at which the potential batholith exists (Sweetkind et al., 2001) is not likely to effect groundwater movement within Rainier Mesa, at Shoshone Mountain there are intrusive rocks that potentially could affect groundwater paths. Dikes and plugs representing some of the eruptive vents of the Rhyolite of Shoshone Mountain crop out at the surface and may be more extensive in the subsurface beneath Shoshone Mountain. These rocks likely represent zones of low permeability beneath Shoshone Mountain, and are represented on cross section C-C' as unit RMICU.

The entire Paleozoic stratigraphic section dips to the west beneath Yucca Flat, and surface structural data from outcrops on the east side of Rainier Mesa and Shoshone Mountain indicate a dominantly westward dip locally modified by folds associated with the thrust faults. This regional dip is portrayed in the model as extending beneath the rest of the CAU until all Paleozoic strata are disrupted by caldera-related structures and intrusions. South of Shoshone Mountain the Paleozoic strata exposed in the Calico Hills are domed, with rocks dipping away from the center of the dome.

The major structural controls on the HSUs in the Rainier Mesa and Shoshone Mountain area are the Belted Range thrust and the Tertiary normal faults. The Belted Range thrust juxtaposes the LCA above the UCCU, and locally the LCCU above the UCCU (IT, 1995). The trace of the Belted Range thrust is approximately parallel with the direction of groundwater flow at Rainier Mesa, but the trace of the fault curves around to the west beneath Shoshone Mountain (Sweetkind et al., 2001), across the flow direction at an angle. The CP thrust lies too far to the east and is located structurally at an elevation too high to have much affect on the geometry of the HSUs beneath Rainier Mesa or Shoshone Mountain. Tertiary-age normal faults are oriented along a dominantly north-south trend, parallel to the direction of flow for the regional groundwater in this part of the NTS. It is possible that normal faults act to channelize groundwater flow parallel to the strike of the fault (Dickerson and Drake, 2003), although this phenomena was not extensively tested on the NTS, nor was it represented in the regional model.

Hydraulic conductivity data for the HSUs present within the area of interest were first compiled during the regional evaluation (Appendices A and C, IT, 1996f). A summary of the HSU hydraulic conductivities, compiled from all known sources, is presented in Table 3-12. The data include those derived from well tests (Well ER-12-1, UE-16d, UE-16f) and laboratory measurement of cores (from multiple tunnel drifts and shafts). The data sources are listed in Table 3-12. Additional hydraulic testing data are available for several test holes in Rainier Mesa (e.g., Hagestad #1, Test Well 1)

Table 3-12
Summary of Hydraulic Conductivity Data

Regional Model HSU	Hydraulic Conductivity (m/d)
VCU	0.000122 - 0.000815[a]
UCCU	0.003[b] - 0.025[c]
LCA3 LCA or LCA3 LCA3 and UCCU	0.077[d] - 0.74[e] 0.03[c] 0.011[d]

[a]Core measurement (Thordarson, 1965)
[b]UE-16f slug test (Dinwiddie and Weir, 1979)
[c]ER-12-1 drill stem test (Russell et al., 1996)
[d]ER-12-1 pump test (Russell et al., 1996)
[e]UE-16d pump test (Dinwiddie and Weir, 1979)

(Thordarson, 1965); however, the unit of measurement for these data is specific capacity. Further analysis is required for the conversion of specific capacity to hydraulic conductivity.

In general, the carbonate aquifers (LCA and LCA3), in which flow is fracture dominated, have the highest hydraulic conductivity of all HSUs. In particular, the carbonates have a higher hydraulic conductivity than the faulted and fractured UCCU. In the UCCU, the hydraulic conductivity can potentially increase with fracture porosity, which is not represented by the data contained in Table 3-12. The VCU has the lowest hydraulic conductivity of all measured units; flow through the VCU is primarily porous with local fracture flow. In Yucca Flat, hydraulic conductivity decreases with depth in open interval tests; this trend is assumed to exist throughout the NTS. The full hydrologic parameter data set, including hydraulic conductivity data, is available in Appendices A and C of Volume IV of the regional evaluation documentation (IT, 1996f). A discussion is available in Sections 3.0 to 8.0 of the regional evaluation documentation (IT, 1996f) and in Section 5.5 of the regional evaluation report (DOE/NV, 1997a).

Primary sources of uncertainty pertaining to hydraulic conductivity include the lack of multiple measurement locations (both well locations and completion intervals) within the carbonates and multiple interpretations of existing well-test (i.e., drawdown) data. Also pertinent to the carbonates, additional sources of uncertainty include the variability of hydraulic conductivity that results from depth decay and the presence of karst. Lastly, the hydraulic properties of fault zones are unknown.

The CAU porosity, saturation, and water content data were gathered from drill holes and from the tunnels during tunnel construction and during reentry operations following underground tests (BN, 2002a). The data presented in Table 3-13 represent average values for data collected from the tunnels and from test-related drill holes. These data are from the Tunnel Formation, which comprises a portion of the VCU. The source document cautioned of the unequal sampling distribution of the data, noting that the test horizon is overrepresented whereas the strata below and above the test horizon are underrepresented (BN, 2002a). Inspection of these data indicates that water content increases with porosity but saturation does not. The source document additionally noted that the location and volume of ground water in the zeolitized test beds was controlled primarily by faults and fractures, and occasionally by bedding planes. Most of this water existed as low volume "weeps" and "seeps" from faults and fractures that dried after a few hours to a few days exposure during mining operations. However, several fracture systems were encountered that produced considerable amounts of water over periods of many years. All of the water encountered in the tunnels, drill holes of the Tunnel Formation, and in the strata above the Tunnel Formation is from perched aquifers.

Table 3-13
Average Hydrologic Properties of Common Lithologies In and Near the Rainier Mesa Test Beds

	Water Content (percent by wet weight)	Porosity (percent)	Saturation (percent)
Welded tuff above test horizon	4.2	11	90
Vitric Bedded Tuff above test horizon	22.6	45	86
Zeolitic Bedded Tuff in test horizon	19.4	38	96

Source: BN, 2002

3.4.5.2.2 Groundwater Hydrology

Groundwater occurrence, movement, and hydraulics within the investigation area are discussed in this section, with emphasis on the Rainier Mesa/Shoshone Mountain area. The descriptions are based on the available water-level data and recharge/discharge estimates compiled and assessed during the regional evaluation (IT, 1996e; DOE/NV, 1997a). Information on the water levels may be found in Sections 3.0 through 10.0, Appendix A, and Appendix C of Volume II of the regional evaluation documentation package (IT, 1996e). The same information is also summarized in Section 5.6 of the regional evaluation report (DOE/NV, 1997a). Information on recharge estimates can be found in Sections 3.0 through 11.0 of Volume III of the regional evaluation documentation package (IT, 1996c).

Figure 3-9 shows the predevelopment groundwater contours for the NTS region. The groundwater contours are based on predevelopment heads derived from the historical water-level data set (IT, 1996g). Water-level measurement points are shown on the figure. Those boreholes that provide water-level data representative of Rainier Mesa/Shoshone Mountain include UE-16f, UE-1a/b/c, UE-1L, UE-17a, ER-18-2, UE-18t, UE-2ce, TW-1, ER-12-2, ER-19-1-1/2/3, ER-12-1, UE-12t 6, U-12s, U-19bh, U-19bh, U-19v PS 1D, UE-19c-WW, and U-19bj. The approximate location of the regional water table is shown on the cross sections through Rainier Mesa and Shoshone Mountain (Plate 3).

Within the Rainier Mesa/Shoshone Mountain area, regional groundwater occurs within the LCA3, LCA, and UCCU, and it likely exists within the deeper LCCU. Regional groundwater occurs in the AA, VA, VCU, LCA, and LCCU in Yucca Flat just east of Rainier Mesa. Perched groundwater occurs in the VA at Rainier Mesa.

Regional groundwater flow within the Rainier Mesa/Shoshone Mountain area is driven by subsurface inflow from the north and northwest. Rainier Mesa, the Belted Range, and Shoshone Mountain are recharge areas from the precipitation that occurs at these higher elevations. A portion of the recharge from precipitation goes to the perched groundwater within the volcanic units, and some portion potentially goes into the deeper regional groundwater. At Rainier Mesa, water is perched above the regional aquifer within the TCU. There is abundant water present in the fracture systems of three of the tunnel complexes at Rainier Mesa (SNJV, 2004b). It is not known how well the fracture water at Rainier Mesa is connected, if at all, to the regional groundwater system. This water currently is permitted to flow from E-Tunnel; however, water is believed to have filled the open drifts behind barriers built in the N- and T-Tunnels. G-Tunnel has only a few minor seeps of water, while the other tunnel complexes are relatively dry. No water inflows were encountered during mining at Shoshone Mountain. It is currently not known how recharge is partitioned between the perched groundwater at Rainier Mesa and Shoshone Mountain and the regional groundwater beneath Rainier Mesa and Shoshone Mountain.

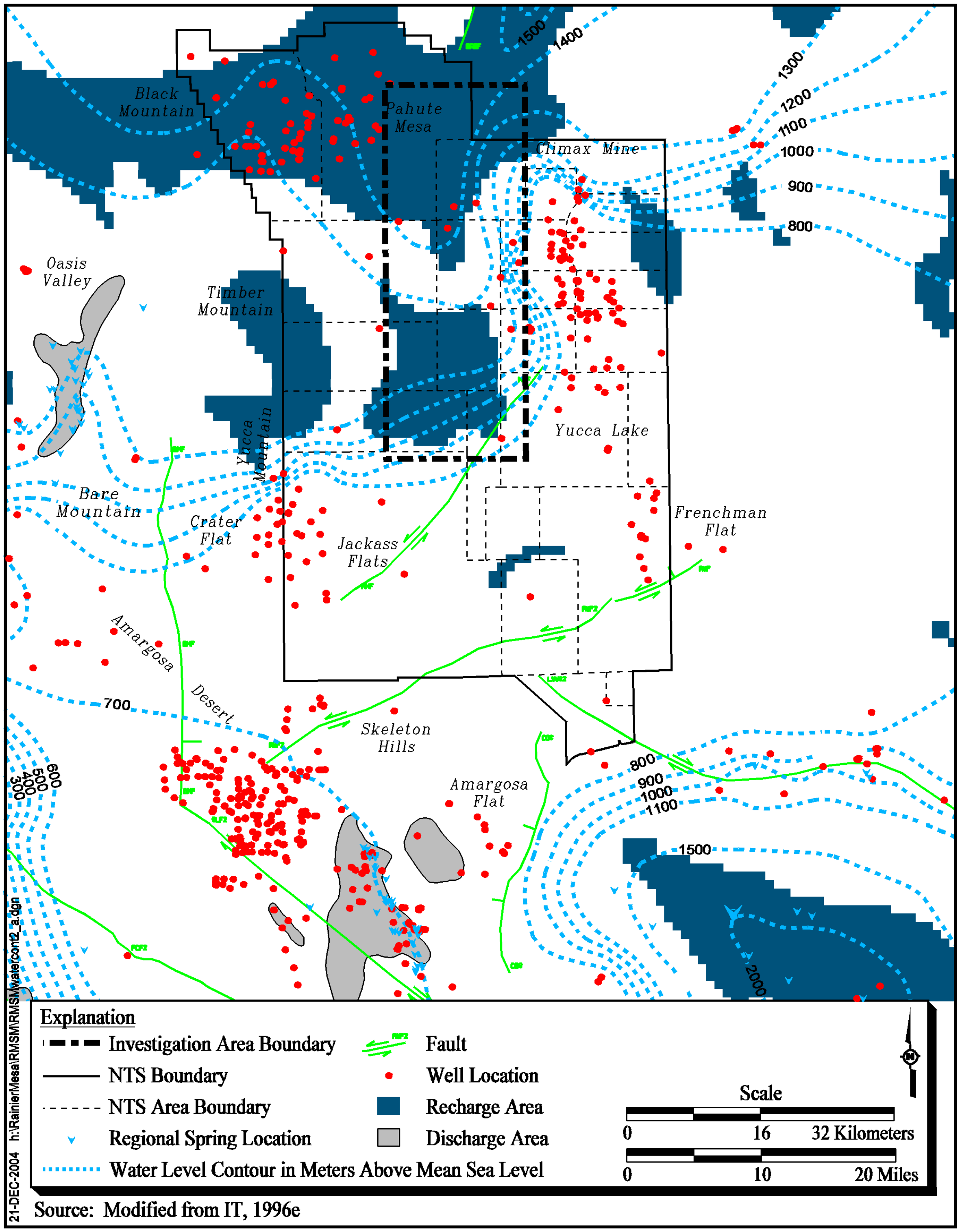


Figure 3-9
Composite Predevelopment Water-Level Contour Map for the Rainier Mesa/Shoshone Mountain Investigation Area

Based on the existing data and as interpreted from the regional groundwater flow model (DOE/NV, 1997a), the overall groundwater flow in the investigation area is to the south and southwest. However, there are several different flow paths for the regional groundwater to follow from the CAU to the eventual discharge sites to the south in the Amargosa Desert and in Death Valley. Some of the regional groundwater in the eastern part of Rainier Mesa flows to the east down a steep hydraulic gradient into Yucca Flat, where it joins with the rest of the groundwater in the Yucca Flat Basin to flow south and southwest. However, most of the regional groundwater at Rainier Mesa flows to the southwest where it encounters volcanic aquifers in the Timber Mountain Caldera Complex and eventually flows southward along Fortymile Canyon and Fortymile Wash into the Amargosa Desert (SNJV, 2004b). Particle path simulations for groundwater flow from Shoshone Mountain indicate that it flows generally to the south and southwest, paralleling regional groundwater flow from Rainier Mesa (SNJV, 2004b).

The potentiometric surface is relatively flat and occurs at a relatively high elevation (between 1,400 and 1,200 m in the Rainier Mesa and Shoshone Mountain area, but drops steeply down to the east and south (Figure 3-9). In Yucca Flat, to the east of Rainier Mesa/Shoshone Mountain, the potentiometric surface occurs at an elevation of about 740 m. In Mid Valley and Jackass Flats to the south of Rainier Mesa/Shoshone Mountain, the potentiometric surface is also at an elevation of about 750 to 730 m (Tucci and Burkhardt, 1995). The locally high potentiometric surface at Rainier Mesa/Shoshone Mountain likely results from the structurally high LCCU in the upper plate of the Belted Range thrust in the subsurface, and by the relatively high precipitation rates that result from the high topographic elevation. Within the Rainier Mesa/Shoshone Mountain CAU there exists a ridge in the potentiometric surface that coincides with the topographic high of Rainier Mesa. Groundwater flow is affected by the shape of the topographic surface as follows; some groundwater flows from Rainier Mesa east into the lower Yucca Flat, some of the flow from Rainier Mesa flows west into the volcanic aquifers of the Timber Mountain Caldera Complex and then southward into Jackass Flats, and flow from both Rainier Mesa and Shoshone Mountain flows south into Jackass Flats.

The influence of temperature on water levels and hydraulic gradients in the Rainier Mesa/Shoshone Mountain CAU is presently unknown. The DRI is currently evaluating heat flow and temperature profiles in wells throughout the NTS and vicinity, and variations are apparent across the NTS and in the Rainier Mesa/Shoshone Mountain area. These data suggest that temperature effects may need to be considered in the groundwater flow model.

3.4.6 Groundwater Chemistry

Groundwater chemistry data provide a means for determining the origin, pathway, and timescale of groundwater flow that is independent of estimates based on conventional hydraulic data and are an important consideration during the evaluation of the groundwater flow system. Geochemical and hydraulic data reflect distinct but complimentary aspects of a groundwater flow system, and must be considered in unison in order to develop a consistent, comprehensive, and defensible flow system assessment. For example, geochemical data may identify flow paths and source areas that would otherwise not be recognized on the basis of hydraulic information alone; however, these flow paths must be consistent with potentiometric data in order to be valid (and vice versa). Geochemical data, specifically groundwater chemistry and reactive mineral distribution, are also important constraints on solute transport.

This section describes the available groundwater geochemistry data for wells, springs, and tunnel seeps within the Rainier Mesa/Shoshone Mountain investigation area (Figure 3-1). Selected geochemistry data are also presented for various areas within the region. The data used for these evaluations were primarily obtained from the GEOCHEM04 database, but data from other sources (Russell et al., 1993; Rose et al., 1997) were used when available. Additional sources of data will be referenced accordingly.

3.4.7 Major Ion Chemistry

The dissolved constituents in groundwater provide a record of the minerals encountered as water moves through geologic materials. Accordingly, major ion water chemistry can be used to characterize the interaction and help trace the movement of groundwater through aquifer materials. The group of parameters comprising the major ions typically consists of calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), sodium (Na^{+}), chloride (Cl^{-}), sulfate (SO_4^{2-}), bicarbonate (HCO_3^{-}), and carbonate (CO_3^{2-}). Other constituents (such as silica or boron) are occasionally at concentrations high enough to be considered major constituents of groundwater. However, these constituents occur more commonly as minor or trace constituents at significantly lower concentration levels.

Evaluation of the major ion characteristics of groundwater can provide insights on the source areas and flow directions for groundwater movement. Using the dissolved constituents in groundwater to provide a record of the minerals encountered as water moves through an aquifer, 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. These hydrochemical facies are defined as follows (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.

The dominant anion (>60 percent) is HCO_3^- in each of the three hydrochemical facies identified for the NTS.

3.4.7.1 Regional Major Ion Chemistry

Numerous reports have been published describing the hydrogeology and geochemistry of the regional flow system (e.g., Schoff and Moore, 1964; Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Chapman and Lyles, 1993; Laczniak et al., 1996, Rose et al., 1997; Thomas et al., 1996; Thomas et al., 2002). The reader is, therefore, referred to these reports for more detailed discussions of the regional groundwater chemistry data. This section provides representative major ion data for several areas within the region to allow comparisons to that reported for the Rainier Mesa/Shoshone Mountain investigation area.

Figure 3-10 is a Piper diagram presenting the major ion data for groundwater samples collected from the NTS and surrounding area. Piper diagrams illustrate water chemistry types based on the major ion composition. The lower triangles show the relative proportions of cations (left triangle) and

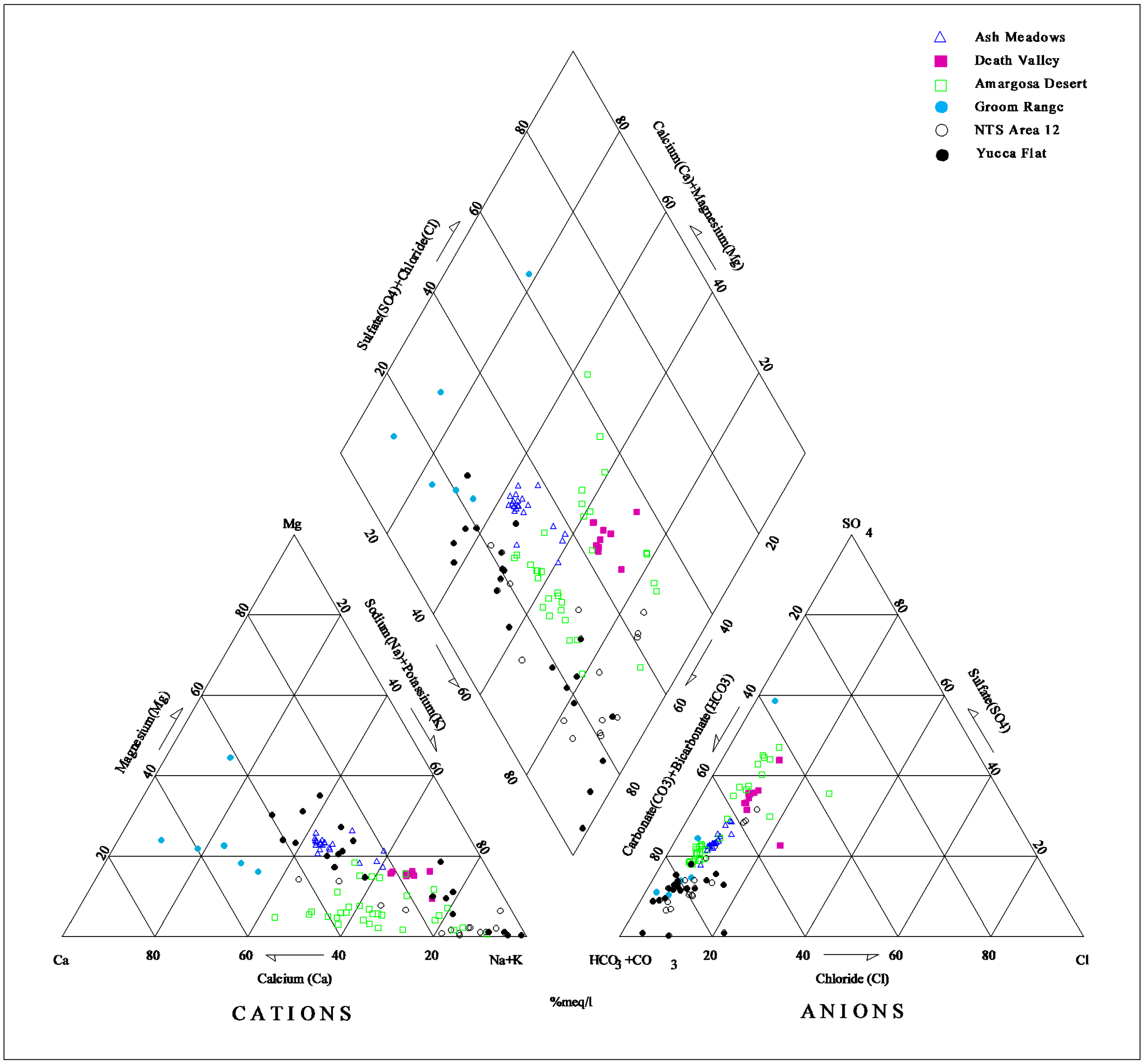


Figure 3-10
Groundwater Chemistry Piper Diagram for the NTS Site and Surrounding Area

anions (right triangle) in groundwater. The diamond-shaped plot in the center combines the cation and anion data. Piper diagrams are useful in evaluating trends in groundwater chemistry, and in identifying unique or anomalous groundwaters. Representative concentrations, grouped by area, are plotted on Figure 3-10. Data are grouped by area (e.g., Yucca Flat, Amargosa Desert). Most groundwaters in the region are classified as either a Na-K-HCO_3 or mixed type (Ca-Mg-Na-HCO_3), based on the classification system by Schoff and Moore (1964). Anions in groundwater from the NTS site and surrounding area plot along a trend ranging from predominantly bicarbonate to approximately 50 percent HCO_3^- and 50 percent SO_4^{2-} (lower right triangular plot, Figure 3-10). Chloride concentrations are relatively constant, with only a slight increase as SO_4^{2-} increases, possibly reflecting the effects of evaporation on water chemistry or the less conservative nature of SO_4^{2-} within some of the flow systems. The cation composition of groundwater in the NTS region shows more variability compared to the anion composition. Sodium generally constitutes greater than 40 percent of the total cationic charge, while Ca^{2+} and Mg^{2+} typically constitute no more than 30 to 40 percent, respectively (lower right triangular plot, Figure 3-10). The following is a brief discussion of each group of data presented in Figure 3-10:

- Ash Meadows – groundwater samples from Ash Meadows plot in a relatively tight group on Figure 3-10. The samples were collected from a line of springs that represent a discharge location for the Ash Meadows groundwater sub-basin. The regional carbonate aquifer is the major aquifer in the sub-basin (Laczniak et al., 1996). The mixed type chemistry shown in Figure 3-10 indicates some influence of volcanic rocks in the groundwater in the flow system. Ash Meadows groundwater contains more sodium than would be expected if the flow system contained only carbonate rock.

- Death Valley – groundwater samples collected from Death Valley plot in a relatively tight group in Figure 3-10. The samples were collected from springs, primarily in the Furnace Creek Ranch area, that are part of the Alkali Flat-Furnace Creek Ranch groundwater sub-basin (Laczniak et al., 1996). Sodium is the predominant cation in groundwater from the Death Valley area, and bicarbonate followed by sulfate are the dominant anions. The relatively higher chloride and sulfate content of waters from Death Valley suggests evaporation may have affected the chemistry.

- Amargosa Desert – Winograd and Thordarson (1975) concluded that the Amargosa Desert receives groundwater from several sources. The variability in groundwater chemistry shown in Figure 3-10 supports their conclusion. Many of the samples from the Amargosa Desert contain relatively lower concentrations of magnesium, relative to water samples collected from other areas. Also, the anionic composition of groundwater from the Amargosa Desert exhibits greater variability, relative to the composition in other areas of the NTS region.

- Groom Range – groundwater samples collected from the Groom Range are calcium-bicarbonate type waters. The groundwater chemistry does not exhibit the influence of volcanic rock, and for that reason, is unlike the chemistry of groundwater from most other areas of the NTS region (Figure 3-10).

- Rainier Mesa (NTS Area 12) – groundwater composition from the Rainier Mesa area ranges from the Na-K-HCO_3 hydrochemical facies (typical of water from volcanic units) to the mixed type (see Figure 3-10). The variation may reflect data from both the saturated and unsaturated (perched groundwater) zones.

- Yucca Flat – groundwater from Yucca Flat is variable in composition, reflecting the relative complexity of the Yucca Flat hydrogeology. Groundwater samples from Yucca Flat compose four groups based on cation composition: mixed with sodium < 40 percent, mixed with sodium > 50 percent dominant with 20 percent calcium + magnesium, and sodium dominant with 90 percent sodium. Bicarbonate is the dominant anion in Yucca Flat groundwater samples. The mixed waters are hypothesized as being dominantly from Paleozoic carbonate units, and the sodium-dominant water samples are hypothesized as being dominantly from volcanic units.

3.4.7.2 Groundwater Chemistry of the Investigation Area

Available major ion data from wells and springs within the Rainier Mesa/Shoshone Mountain investigation area (Figure 3-1) were compiled from the UGTA groundwater chemistry database (GEOCHEM04). This data set contains samples collected during the period of 1957 to 2004 and represents a wide range in data quality. For this reason, a subset of the major ion data was selected based on anion-cation charge balance criterion (Hem, 1985). Samples with a 5 percent or better anion-cation charge balance were then selected for further evaluations. These data are shown in the Piper diagrams in Figure 3-11 and Figure 3-12. The mean concentrations for each location, along with the lithology of the saturated open interval, are listed in Table 3-14.

A wide variability in the major ion data, similar to that of the regional data, is observed in the groundwaters of wells within the study area (Figure 3-11). This variability reflects the complex geology of the area. Complex structure (e.g., Basin and Range faulting), combined with compositionally distinct geologic units (e.g., carbonate and silicious volcanic rocks) lead to the variations in groundwater chemistry observed in the Rainier Mesa/Shoshone Mountain investigation area. Groundwater sampled from Tertiary volcanic units is dominated by Na^+ and K^+ and exhibits the chemical characteristics of the Na-K-HCO_3 hydrochemical facies (Figure 3-11). These samples plot in the right corner of the cation triangle within the Piper diagram (Figure 3-11). Groundwater sampled from the carbonate aquifer is dominated by Ca^{2+} and Mg^{2+}, and exhibits chemical characteristics that range from the Ca-Mg-HCO_3 (UE-2ce) hydrochemical facies to the Ca-Mg-SO_4 (ER-12-1) hydrochemical facies. These samples plot toward the center to left-of-center on the cation triangle within the Piper diagram (Figure 3-11). The elevated level of SO_4^{2-} in the groundwater of ER-12-1 may be due to the use of bentonite mud in the borehole and not representative of levels present in the formation waters (Russel et al., 1996). Well UE-2ce is a satellite well located 183 m south of the NASH emplacement hole in Yucca Flat. The groundwater within this well has been

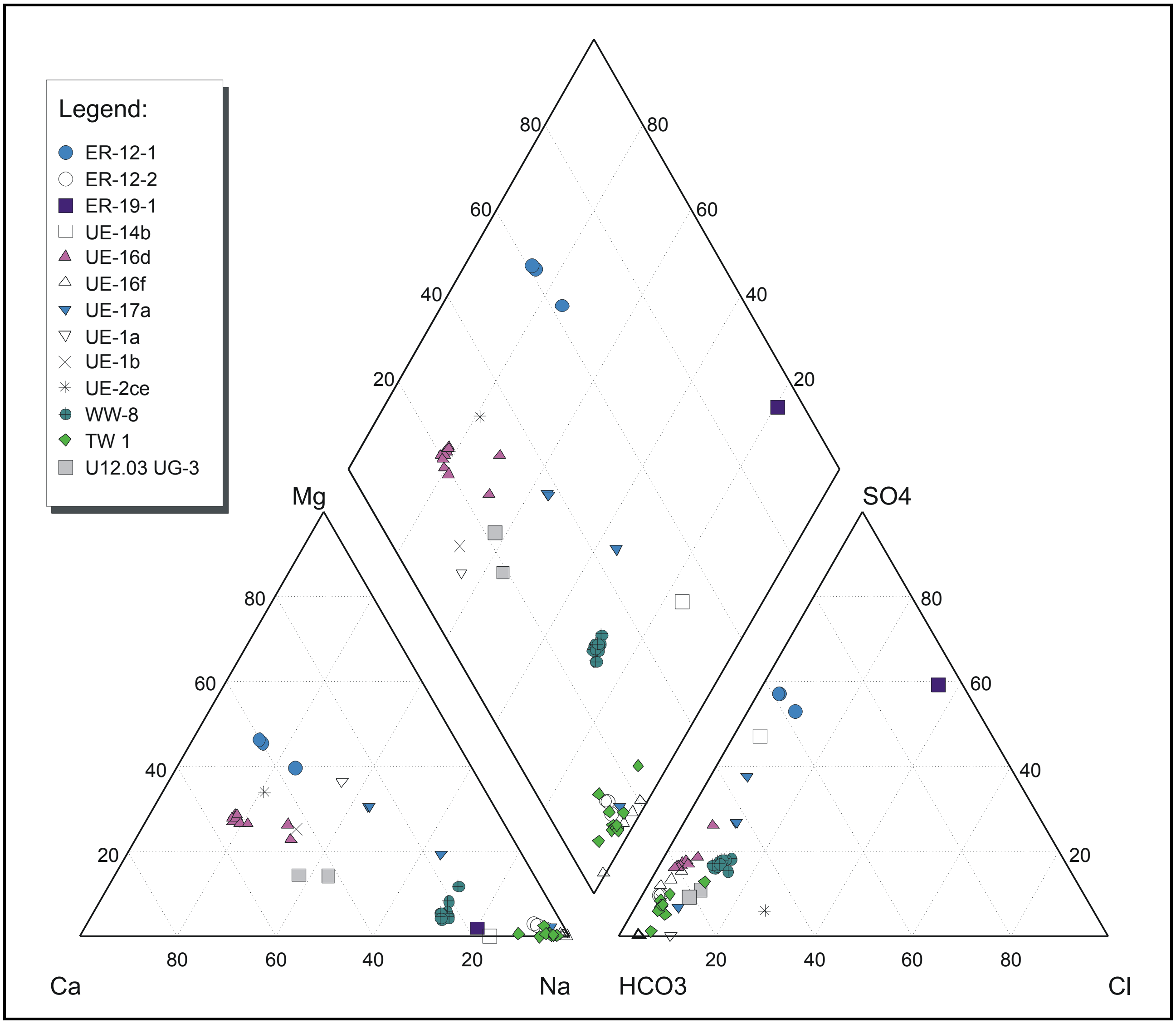


Figure 3-11
Piper Diagram Showing Percent Milliequivalents per Liter of Major Ions in Groundwaters of Wells Within the Rainier Mesa/Shoshone Mountain Investigation Area

impacted by the NASH event (Allen et al., 2003). The argillites of the Eleana Formation make it an aquitard, and any water produced from it comes from fracture porosity that likely originated from subjacent or superjacent formations. As such, the groundwater sampled from the Eleana Formation exhibits the chemical characteristics of three different hydrochemical facies. Groundwater from well UE-16d exhibits the chemical characteristics of the Ca-Mg-HCO_3 hydrochemical facies, and likely originated from the carbonate aquifer. Groundwater from wells UE-17a, UE-1a, and UE-1b, exhibits

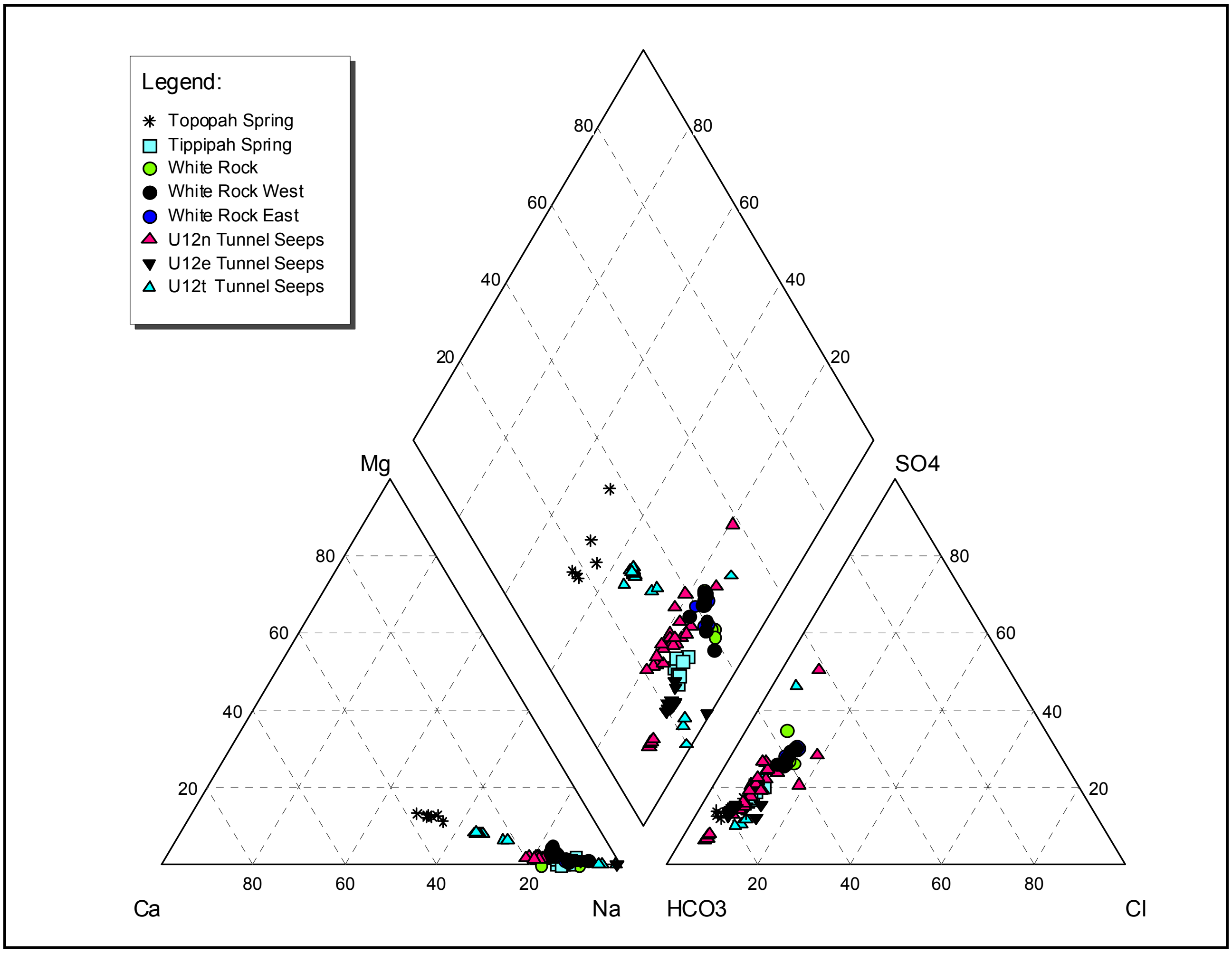


Figure 3-12
Piper Diagram Showing Percent Milliequivalents per Liter of Major Ions in Groundwaters of Tunnel Seeps and Springs Within the Rainier Mesa/Shoshone Mountain Investigation Area

chemical characteristics that are borderline Ca-Mg-HCO_3 to mixed (Ca-Mg-Na-HCO_3) hydrochemical facies, and this water may represent water from the carbonate aquifer with some mixing with water from volcanic rocks, or from small amounts of water derived from the mudstones of the Eleana Formation, as such water would typically contain more Na^+ than water from carbonate rocks. Groundwater from wells ER-12-2 and UE-16f exhibit the chemical characteristics of the Na-K-HCO_3 hydrochemical facies, and likely originated from volcanic rocks (Figure 3-11). Well ER-19-1, a low producing well (IT, 1995), exhibits anomalous CO_3^{2-}, Cl^-, and SO_4^{2-} concentrations (as well as an elevated pH) relative to other groundwater within the study area. This suggests the presence of cement in the groundwaters of Well ER-19-1. The pH of groundwaters of the wells

Table 3-14
Mean Groundwater Chemistry Data for Groundwater Within the Rainier Mesa/Shoshone Mountain Investigation Area

SITE_ID	Lithology of Saturated Open Interval	HCO3 (mg/L)	CO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	δD (per mil)	$\delta^{18}O$ (per mil)	DIC $\delta^{13}C$ (per mil)	DIC ^{14}C (pmc)	DIC ^{14}C, Uncorrected Age (years)
ER-12-1	Carbonate	292.0	ND	17.3	340.0	89.3	4.0	62.7	35.3	-94	-12.4	-9.2	10.7	18500
ER-12-2	Eleana argillite and quartzite	301.2	6.1	6.8	27.3	5.5	3.1	1.8	114.3	-101	-13.7	-4.9	1.5	34800
ER-19-1-1	Siltstone	5.0	95.7	19.4	44.2	15.9	3.9	1.2	82.4	-105	-13.9	NA	NA	NA
TW-1 (HTH#1)	Tuff	97.3	14.0	3.7	6.3	1.8	0.6	0.2	48.7	-111	-14.9	-10.2	30.1	9934
U12.03 UG-3	NA	132.0	ND	10.1	13.5	24.5	5.3	4.8	25	NA	NA	NA	NA	NA
UE-14b	Tuff	119.0	1.1	7.4	92.5	13.4	1.1	0.3	80.4	-112	-14.5	NA	NA	NA
UE-16d	Eleana argillite and quartzite; Carbonate	342.8	0.3	11.8	59.2	76.1	6.6	23.8	34.4	-95	-12.9	-10.1	7.99	20890
UE-16f	Eleana argillite and quartzite	889.8	49.5	25.9	98.3	4.0	1.9	1.0	421	-106	-13.5	-11.7	3.4	27928
UE-17a	Eleana argillite and quartzite	391.3	ND	30.4	99.1	29.2	4.0	21.1	147	-100	-13.3	-9.9	4.9	25000
UE-1a	Eleana argillite and quartzite; tuffaceous sediments (colluvium)	402.5	ND	28.5	1.0	44.8	10.5	28.1	54.8	-103	-13.5	-8.6	60.5	4153
UE-1b	Eleana argillite; tuff	248.0	ND	7.7	20.3	37.9	11.5	13.5	31.6	-104	-13.65	-4.5	16	15144
UE-2ce	Carbonate	423.1	ND	60.6	32.0	77.4	26.8	34.7	43	-100	-12.9	NA	NA	NA
WW-8	Tuff	77.5	0.1	7.7	14.9	7.4	3.5	1.3	29.8	-104	-13.75	-9.5	24.9	11506
White Rock East	Perched Spring	82.5	ND	10.5	32.0	5.5	6.4	0.7	43.6	NA	NA	NA	NA	NA
White Rock West	Perched Spring	82.6	ND	10.2	31.3	5.3	6.2	0.7	43.5	NA	NA	NA	NA	NA
Whiterock Spring	Perched Spring	75.0	ND	9.3	28.8	4.6	6.5	0.1	41.5	NA	NA	-11.2	91	<780
Tippipah Spring	Perched Spring	88.0	ND	7.04	17.7	4.70	2.91	0.21	39.6	NA	NA	NA	NA	NA
Topopah Spring	Perched Spring	52.0	NA	2.9	8.1	6.7	6.01	1.4	11.4	-88	-12.3	NA	NA	NA

Source of lithology data: DOE/NV (2000a), Chapman and Lyles (1993), Pawloski (1.982), Lyles et al. (1991), IT (1995), Russell et al. (1996), Dinwiddie and Weir (1979), and Weir and Hodson (1979)
ND = Not detected NA = Data not available DIC = Dissolved inorganic carbon

within the Rainier Mesa/Shoshone Mountain region, in general, range from 7 to 9. Rainier Mesa water is relatively oxidized, based on the presence of dissolved oxygen.

The groundwater impounded within the T-, U-, and E-Tunnels reflects the geochemistry of the perched ground water at Rainier Mesa infiltrating into underground test cavities. A Piper diagram illustrating the groundwater major ion chemistry for the T-, U-, and E-Tunnels, as well as Tippipah and Whiterock springs, is shown in Figure 3-12. All samples included in this Piper Diagram exhibit the chemical characteristics of the Na-K-HCO_3 hydrochemical facies typical of groundwater from the Tertiary volcanic rock aquifers. The tunnel seep data included in the Piper diagram consists primarily of samples collected in 1991. These samples were collected to characterize the tunnel effluents and to evaluate temporal variations within the chemistry data (Russell et al., 1993). A large degree of variation is observed in the concentration of HCO_3^-, and to a lesser degree, Cl^- and SO_4^{2-}, in the N-Tunnel seep samples (Figure 3-12). This variation is thought to be due to increases in HCO_3^- or CO_3^{2-} originating from grouting operations or the introduction of water in the tunnel that originated from outside sources (Russell et al., 1993). The N-Tunnel seep samples can be separated into two groups representing high-flow versus low-flow conditions (Russell et al., 1993). The two samples collected during low-flow conditions have significantly higher levels of Na^+ and K^+ (plot in the right corner of the cation plot) and lesser amounts of HCO_3^- than those representing high-flow conditions (Figure 3-12). All of the E-Tunnel seep samples plot relatively closely on the Piper diagram. This indicates that the geochemical processes affecting water in the E-Tunnel remained relatively constant throughout the period of the study (Russell et al., 1993).

A more recent evaluation of monitoring data from impounded water within the N- and T-Tunnels is described by Russell et al. (2003). In this study, anion and trace element data were evaluated as a function of time. Samples collection dates for anion samples ranged from 1996 to 2002 and those for trace element analysis ranged from 1993 to 2002. Three main observations, regarding these data, were reported (Russell et al., 2003). First, the concentration of iron (Fe) was a factor of up to 22 (or more) times greater in T-Tunnel. The average concentrations of Fe were 752 micrograms per liter (μg/L) behind the N-Tunnel extension drift gas seal plugs (GSP) and 503 μg/L behind the N-Tunnel Main Drift GSP, and were 1,500 μg/L behind the N-Tunnel GSP and 17,000 μg/L behind the N-Tunnel gas seal door (GSD). Next, the concentrations of SO_4^{2-} were, on average, 100 times less for N-Tunnel GSD samples than those observed in other tunnel structures. These observations suggest that geochemical processes operating behind the N-Tunnel GSD, and to a lesser extent the N-Tunnel GSP, are creating large amounts of Fe and were depleting SO_4^{2-}. This is indicative of reducing conditions behind T-Tunnel GSD and to a lesser extent behind the T-Tunnel GSP. Finally, a decline in Cl^- concentrations over time was observed for N-Tunnel waters whereas the Cl^- concentrations in T-Tunnel were fairly constant over time. This trend was hypothesized as indicating limited circulation of water within N-Tunnel and little to no circulation in the T-Tunnel (Russell et al., 2003). The pH values from groundwater effluent from the N-Tunnel has ranged from 7.2 to 9.4, with a mean value of 8.43, and for the T-Tunnel pH ranges from 7.37 to 9.25, with a mean value of 8.01 (Russell et al., 2003).

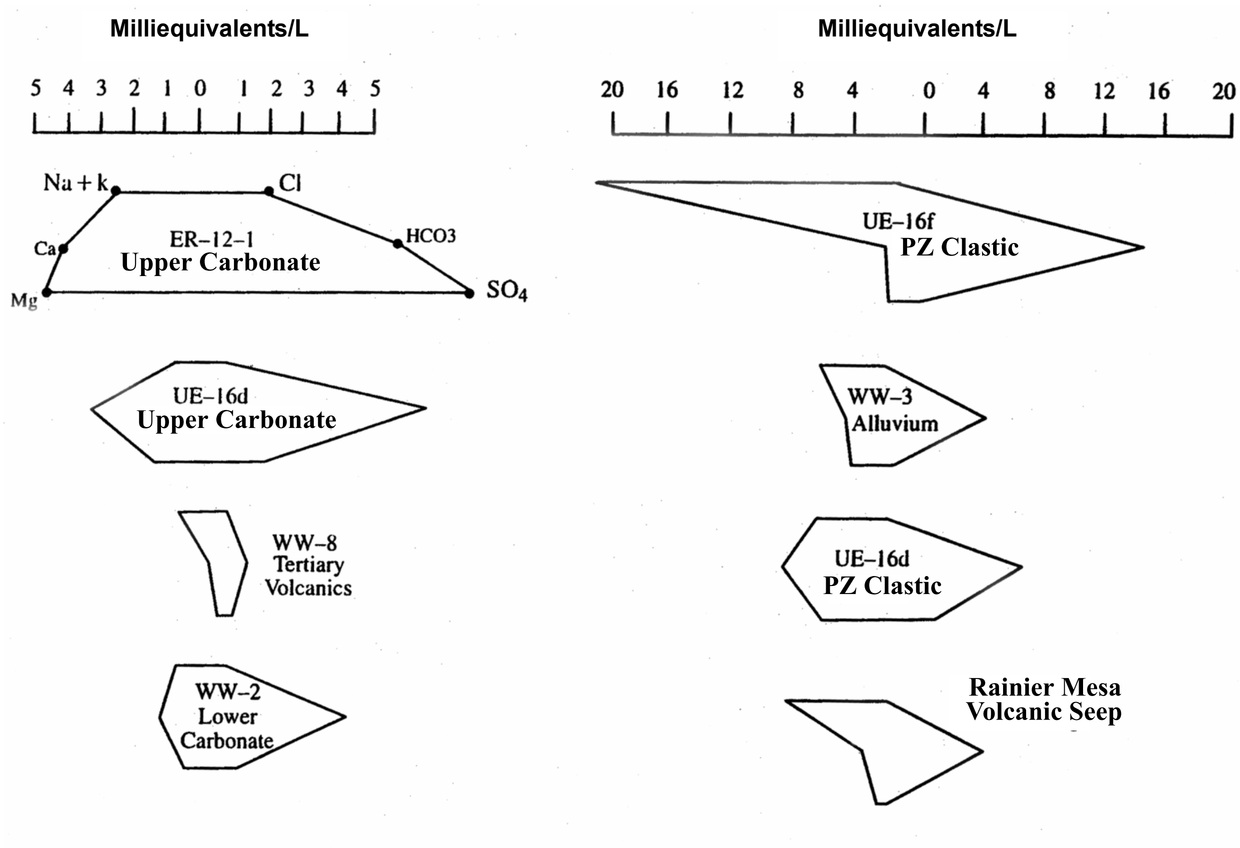
The major ion chemistry of a subset of groundwaters with the Rainier Mesa/Shoshone Mountain investigations area is further illustrated in the Stiff Diagrams shown in Figure 3-13. Data for two additional wells (WW-2 and WW-3) are included in Figure 3-13 to demonstrate the major ion chemistry of the alluvial and lower carbonate aquifers, respectively. The concentration, in milliequivalents per liter, of the major cations are plotted on the left and the major anions are plotted on the right in the Stiff diagrams (Figure 3-13). The water of the Rainier Mesa volcanic seeps, Tertiary volcanics, as well as the alluvium is dominated by Na^+ and K^+. The groundwater of the carbonate units is dominated by Ca^{2+} and Mg^{2+}, and the groundwater of the Paleozoic clastic aquitard (Eleana Formation) is dominated by Na^+ and K^+ (Well UE-16f) or Ca^{2+} (Well UE-16d) as discussed earlier. Bicarbonate (HCO_3^-) is the dominate anion in all major hydrostratigraphic units within this region. The anomalous SO_4^{2-} enrichment observed in the groundwater of Well ER-12-1 was discussed earlier. The relative total dissolved solids within these waters are reflected in the size of each of the Stiff diagrams.

3.4.7.3 Isotope Chemistry

This section includes a discussion of the hydrogen and oxygen isotopes, followed by a discussion of carbon isotopes.

3.4.7.3.1 Hydrogen and Oxygen

The stable isotopes of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) are perhaps the most conservative of all environmental tracers because they are uniquely intrinsic to the water molecule. In the water cycle,



Stiff diagrams for carbonate, clastic, and volcanic wells.

Source: Russell et al. (1996)

Figure 3-13
Stiff Diagram Showing Milliequivalents per Liter of Major Ions in Groundwaters Within the Rainier Mesa/Shoshone Mountain Investigation Area and Near Vicinity

hydrogen and oxygen isotopes are fractionated (partitioned) between the liquid and vapor phases during evaporation and condensation processes. Once the precipitation has infiltrated the water table, the stable isotope values are unaffected by water-rock interaction at temperatures below approximately 100 degrees Celsius (°C), and can be used to trace the groundwater origin and flow path, and to quantitatively determine mixing ratios of different water masses.

Figure 3-14 shows the stable oxygen (delta [δ] ^{18}O) and hydrogen isotope (δ deuterium [D]) composition of groundwater in the Rainier Mesa/Shoshone Mountain investigation area. Data are presented in Figure 3-14 as isotope ratios in δ as per mil (parts per thousand) differences relative to a

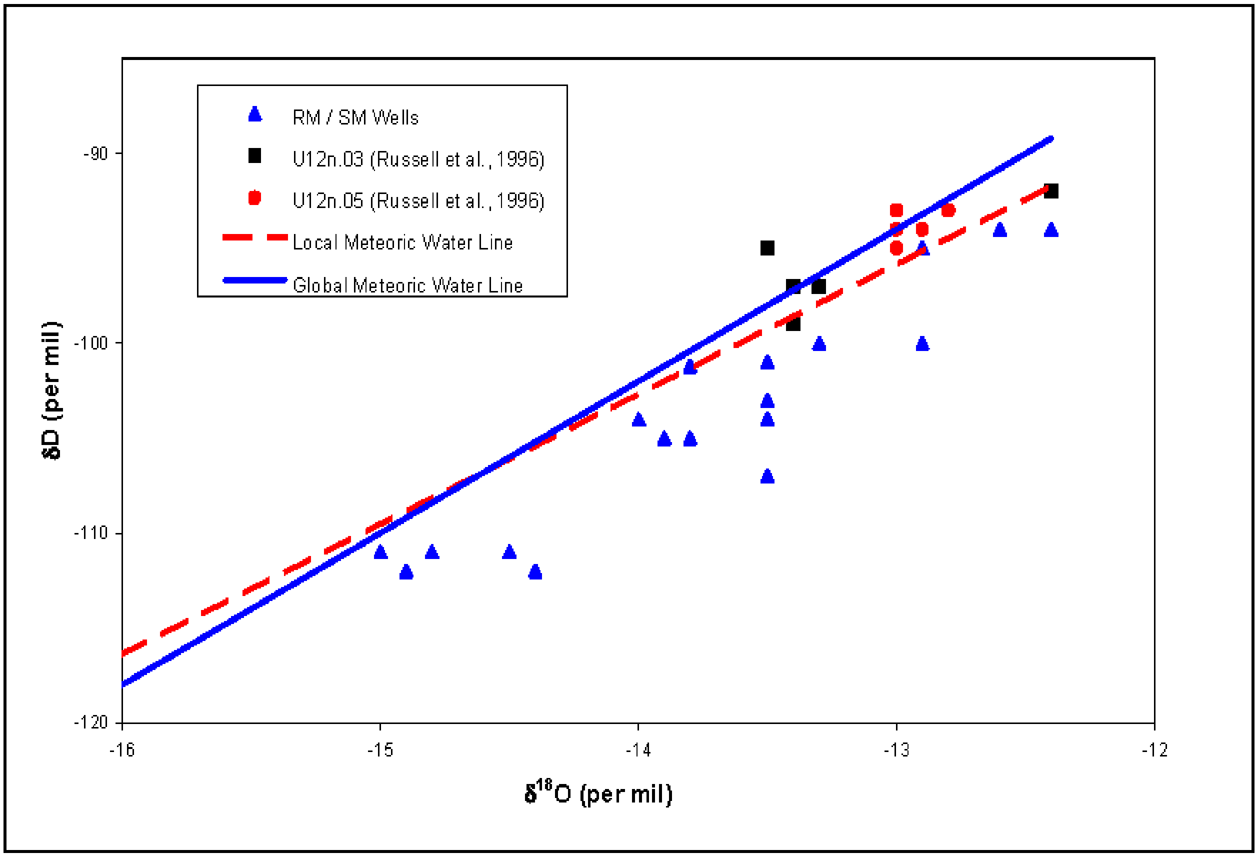


Figure 3-14
Stable Isotope Composition of Groundwater in the Rainier Mesa/Shoshone Mountain Investigation Area

standard known as standard mean ocean water (SMOW). A local meteoric water line (MWL) and the global MWL are also shown (Figure 3-14). The global MWL represents the observed correlations in $\delta^{18}O$-δD values of precipitation samples from around the world and is defined by the equation $\delta D = 8\delta^{18}O + 10$ (Craig, 1961). The local MWL ($\delta D = 6.87^{18}O - 6.5$) represents the observed correlations in $\delta^{18}O$-δD values of precipitation samples collected by DRI at 14 sites at the NTS (Ingraham et al., 1990).

Most groundwater data lie roughly parallel to, but below, the MWLs (Figure 3-14). Groundwater that plot below the MWL indicate that secondary fractionation has occurred. Since the local MWL describes local precipitation data, fractionation during evaporation of modern precipitation can be ruled out as causing the isotopic signature observed in these groundwaters. Another possible explanation for the lighter isotopic signature groundwaters is that they were recharged elsewhere or were recharged under climatic conditions significantly different than those present today. Seepage from the N-Tunnel (U12n.03 and U12n.05) plot along the MWLs and is, therefore, distinct from the regional groundwaters within the investigation area. These samples are instead isotopically equivalent to current winter precipitation (Russell et al., 1987).

3.4.7.3.2 Carbon Isotopes

The geochemical behavior of carbon in groundwater systems is very complex and includes interactions with the atmosphere, biosphere, and geosphere involving multiple sources and sinks of carbon that can vary in both time and space (Kalin, 2000). Nevertheless, ^{14}C is the tracer most often used to estimate the residence time of groundwaters that are less than ~40,000 years in age. Most of the dissolved inorganic carbon (DIC) in groundwater is the product of biochemical production of carbon dioxide (CO_2) gas in the soil zone and the chemical dissolution of carbonate minerals. Variations in the stable isotope ($\delta^{13}C$) and ^{14}C characteristics of these two main carbon reservoirs provides insight into the chemical evolution of DIC in groundwater.

Table 3-14 presents dissolved inorganic carbon (DIC) isotope data from groundwaters of the Rainier Mesa/Shoshone Mountain investigation area. These data consist of: (1) δ carbon-13 ($\delta^{13}C$) which is a measure of the $^{13}C/^{12}C$ ratio, relative to the Pee Dee Belemnite (pdb) reference standard, (2) carbon-14 (^{14}C) as percent modern carbon (pmc), and (3) uncorrected ^{14}C groundwater age (Table 3-14). Where more than one value is available for a well, the mean is listed. The ^{14}C groundwater ages presented in Table 3-14 cannot be interpreted as the actual groundwater ages. The interpretation of DIC ^{14}C ages requires significant corrections based on the careful evaluation of mineral dissolution and isotope exchange processes (Mook, 1980). Uncertainties associated with these age estimates are quite large. Due to the relatively low organic content of many of the HSUs at the NTS, dissolved organic carbon (DOC) ^{14}C ages are generally considered to be more reliable indicators of the mean aquifer residence time of the dissolved carbon in groundwater. Currently, DOC ^{14}C ages are only available for one well, ER-12-2, within the Rainier Mesa/Shoshone Mountain investigation area.

Figure 3-15 shows groundwater ^{14}C activity as a function of $\delta^{13}C$ for the wells within the investigation area and also two wells within Pahute Mesa (UE-19c WW and UE-19h) and three wells in Emigrant Valley (Watertown #1, #3, and #4). The general location of these areas are shown in Figure 3-8. Also included in Figure 3-15 are carbon isotope data for Whiterock Spring (Figure 3-4). This spring

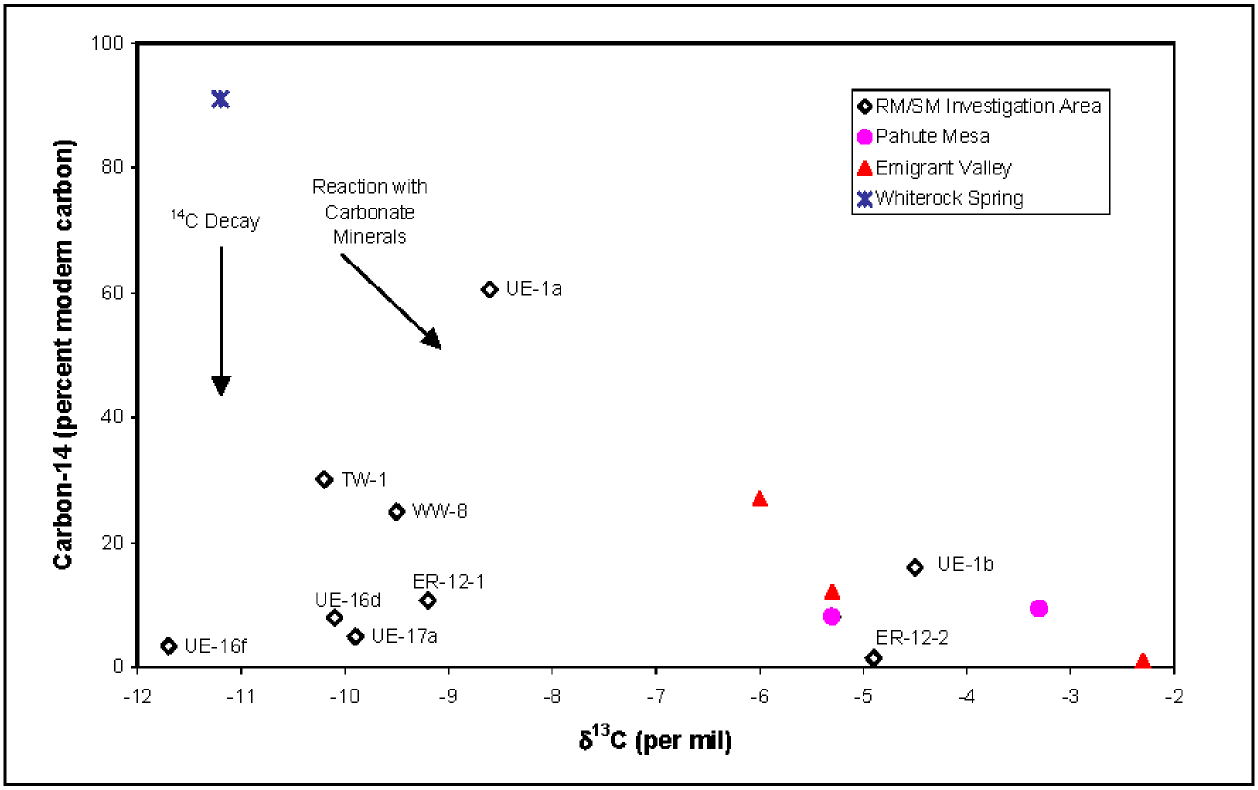


Figure 3-15
Carbon-14 Versus Delta Carbon-13 for Groundwater

represents perched groundwater with a ^{14}C activity close to the modern atmospheric value (~100 pmc) and a relatively "light" (negative) $\delta^{13}C$ value that is distinctive of biogenic soil CO_2 gas. This sample is typical of recent groundwater recharge that has undergone very little reaction with carbonate minerals (e.g., Rose and Davisson, 2003).

As with the major ion chemistry, a large variability in the carbon isotope data is observed (Figure 3-15). The carbon isotope values likely reflect the combined effects of radioactive decay and chemical dissolution of carbonate minerals. Radioactive decay (without chemical reaction) will drive DIC carbon isotope compositions toward lower ^{14}C values at constant $\delta^{13}C$ values. If radioactive decay alone was responsible for observed changes in ^{14}C activity along the flow path, the carbonate isotopic signature of groundwater would follow the arrow marked "^{14}C decay" in Figure 3-15. In contrast, groundwater interaction with carbonate minerals tends to drive the composition of the DIC toward higher (less negative) $\delta^{13}C$ values and lower ^{14}C values (due to the absence of ^{14}C in the calcite). Although data are not available for carbonates within the investigation area, secondary calcite that is present in the alluvial and volcanic HSUs in nearby Yucca Flat has an average $\delta^{13}C$

value between about -2.5 and -3.0 per mil, and carbonate bedrock samples from the NTS have an average $\delta^{13}C$ value near +0.5 per mil (see Hershey et al., 2004, for data summary). The DIC isotopic composition of groundwaters will approach that of the rock that is encountered along a flow path as rock - water interaction is increased. Many of the groundwaters plotted in Figure 3-15 show evidence of reaction with carbonate minerals.

Two groups of groundwaters within the study region, based on the DIC isotope data, are observed in Figure 3-15. The majority of the groundwater within the investigation area are characterized by lighter $\delta^{13}C$ values (-11.7 to -8.6 per mil) that suggest very modest reaction with carbonate minerals. The second group, consisting of UE-1b and ER-12-2, exhibits heavier $\delta^{13}C$ values (-4.9 to -4.5 per mil). The DIC isotopic compositions of these groundwaters are similar to those observed in regional groundwaters beneath Pahute Mesa and Emigrant Valley (Figure 3-15). These values are consistent with a greater extent of water rock interaction.

3.4.8 Groundwater Radiochemistry

This section presents information on the nature and extent of radioactivity in groundwater within the Rainier Mesa/Shoshone Mountain Investigation area, as well as a selected number of potentially downgradient locations that are outside of the NTS boundaries. Radionuclide data generated by the RREMP, the ERP, as well as the RNM Program are presented.

3.4.8.1 Routine Radiological Environmental Monitoring Program

The Long-Term Hydrological Monitoring Program (LTHMP) was instituted in 1972 to determine whether radioactivity from underground nuclear tests contaminated the groundwater in the vicinity of the NTS. Under the interagency agreement, the U.S. Environmental Protection Agency (EPA) operated the LTHMP. The EPA Radiation and Indoor Environmental National Laboratory, Las Vegas (formerly the Radiation Sciences Laboratory and Environmental Monitoring Systems Laboratory) performs routine radiological monitoring of groundwater from wells on the NTS and springs near the NTS. In 1999, the RREMP replaced the LTHMP (BN, 1998b). The “Nevada Test Site Routine Radiological Monitoring Plan” was prepared by a team of scientists from NNSA/NSO, BN, Shaw Environmental Inc., DRI, and the Joint Testing Organization (BN, 1998b). This plan, recently revised (BN, 2003b), provides one central, sitewide, integrated approach for routine radiological monitoring on and off the NTS, and also at associated NNSA facilities. The monitoring plan focuses on the need to ensure that the public and the environment are protected, that compliance with the letter and the spirit of the law is achieved, and that good land stewardship is practiced (BN, 2003b). Results from the LTHMP and the RREMP are published in the NTS annual site environmental reports (REECo and EPA, 1990; REECo, 1991, 1992, 1993, 1994, 1995; BN, 1996a, 1996b, 1997a, 1997b, 1998a, 1999, 2000a, 2001a, 2002c, 2003a, 2004). The sampling frequency, sampling methods, QA plans, and various information on the monitoring wells are documented in the RREMP. Generally, at least one analysis per year from each location was performed for gamma-emitting radionuclides and for tritium. Figure 3-16 shows the RREMP on- and off-site regional groundwater monitoring sites, and Figure 3-17 shows the RREMP surface water radiological monitoring sites.

The primary parameter of interest for the routine radiological monitoring of groundwater and surface water is tritium (BN, 2003b). Tritium is the radionuclide species created in the greatest quantity during the nuclear detonation and is believed to be the most mobile. The action level for tritium is 10 percent of the drinking water standard (20,000 picocuries per liter [pCi/L]; SDWA, 1996). Tritium results for the RREMP groundwater monitoring locations within the Rainier Mesa/Shoshone Mountain investigation, as well as various other monitored locations that are off of the NTS but are potentially downgradient of the Rainier Mesa/Shoshone Mountain CAU (Ash Meadows and Amargosa Valley), are presented in Table 3-15. If the data listed in Table 3-15 are given as a year only, the tritium result is an annual average; otherwise the tritium result is for a discrete sample collected on the date listed. Two methods were used for analyzing tritium, the conventional method and the electrolyte enrichment method. The minimum detectable concentration (MDC) for the conventional method was typically 300 to 500 pCi/L, whereas the MDC for the electrolyte enrichment method was approximately 10 pCi/L. Negative values reported for concentrations indicate that the measured tritium activity is similar to background tritium levels observed in analytical blank samples and are below the MDC. Although Table 3-15 does not distinguish the detection method used to determine the tritium concentration in these water samples, results reported in the 300 to 500 pCi/L range should be considered potentially at or below the MDC, and fluctuations within this range cannot be interpreted as significant. Table 3-15 thus shows that tritium was not consistently detected in groundwater from any of the off-NTS sampling locations, and that these results largely reflect variability in measuring concentrations that are below the MDC.

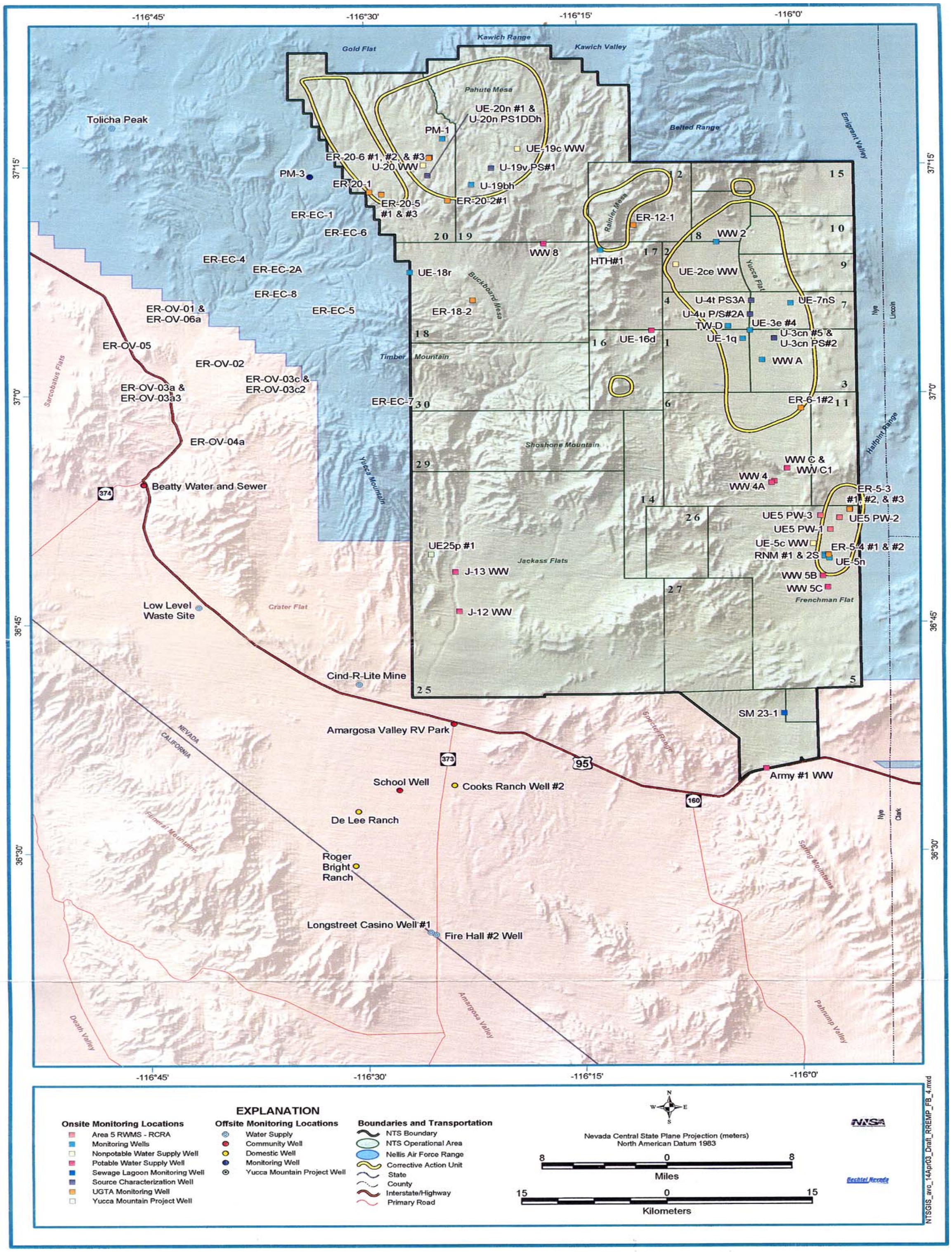


Figure 3-16
RREMP On- and Off-site Regional Groundwater Monitoring Sites (BN, 2003b)

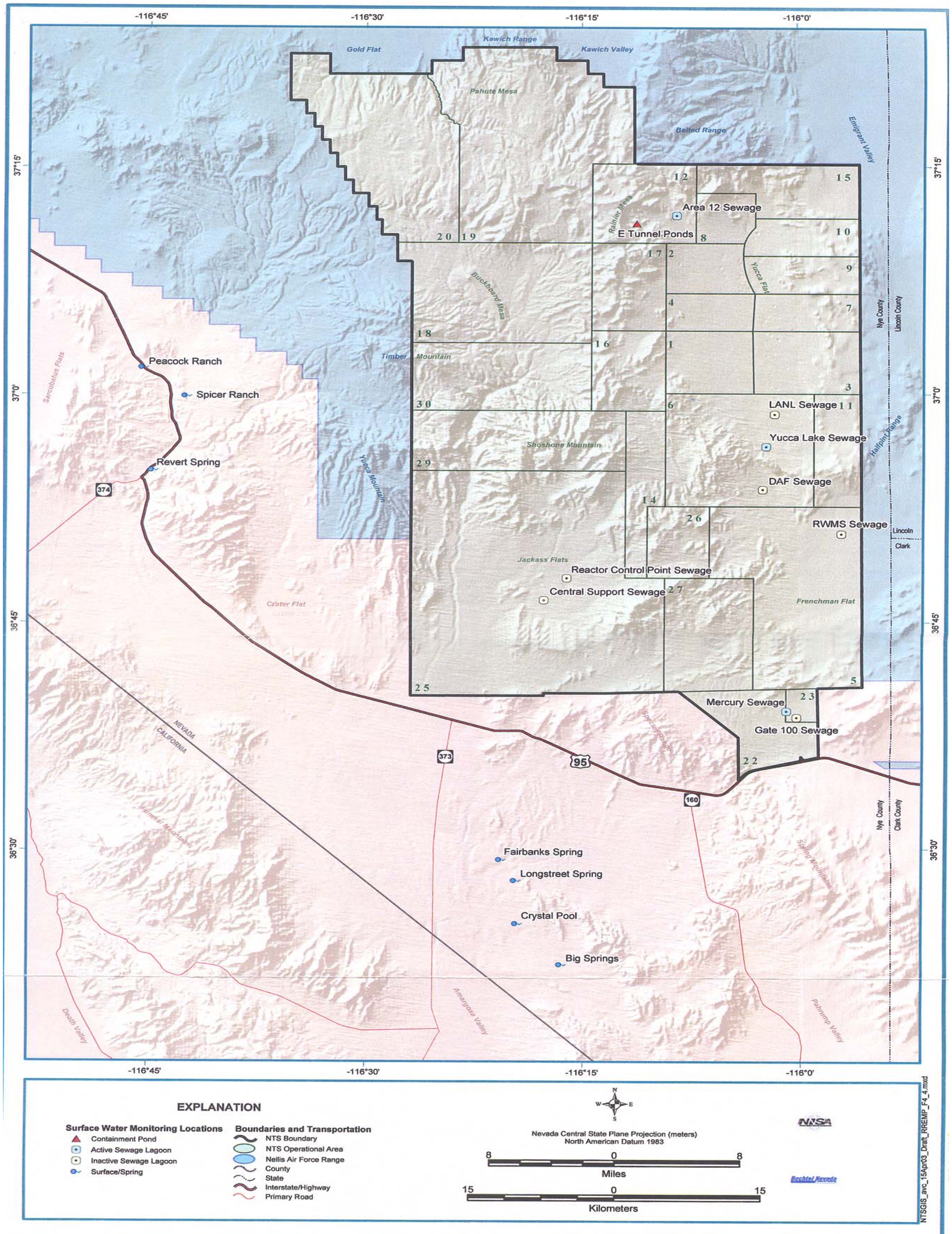


Figure 3-17
RREMP Surface Water Radiological Monitoring Sites (BN, 2003b)

Table 3-15
Tritium Concentrations in Groundwater from the NTS On- and Offsite Regional Groundwater Radiological Monitoring Sites
(Page 1 of 3)

HTH#1 (NTS Area 17)		UE-16d (NTS Area 17)		WW-8 (NTS Area 18)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
1990	39	1990	0.41	1990	-3.0
1991	35	1991	-6.2	1991	8.2
1992	-2.1*	1992	-1.1*	1992	-8.6*
1993	12.0	1993	2.4*	1993	2.7*
1994	15	1994	-0.19	1994	1.1*
1995	27	1995	0.05	1995	1.4
1996	-77*	1996	2.1*	1996	0.29
1997	180*	1997	4.1*	1997	0.4*
1998	-62*	1998	-4.3*	1998	-1.9
1999	0.66*	1999	-0.44*	1999	3.02
07/12/2000	3.84*	01/26/2000	-5.26*	01/26/2000	-6.56*
04/19/2001	-8.65*	04/19/2000	-3.83*	04/19/2000	0.53*
02/27/2002	5.80*	07/19/2000	-3.33*	07/19/2000	-3.69*
02/27/2002	0.62*	10/25/2000	5.90*	10/25/2000	9.20*
02/27/2002	1.75*	02/06/2001	-11.38	02/06/2001	-13.25
02/27/2002	17.73	07/31/2001	8.06	04/03/2001	-6.10
03/12/2003	-0.627	10/30/2001	-5.90	07/31/2001	4.29
03/12/2003	5.12*	02/19/2002	-0.68*	10/30/2001	-6.16
03/12/2003	-5.96*	04/23/2002	-4.87*	02/19/2002	2.18*
03/12/2003	0.914*	07/16/2002	-1.24*	04/23/2002	-5.91*
		10/15/2002	-9.76*	07/16/2002	4.85*
		01/28/2003	3.16*	10/15/2002	-10.48*
		04/29/2003	-5.50*	01/28/2003	-6.32*
		07/01/2003	-3.30*	04/29/2003	-14.5*
		10/07/2003	6.92*	07/01/2003	-7.73*
				10/07/2003	-1.82*
ER-19-1 (NTS Area 19)		**ER-12-1 (NTS Area 12)**		**Big Spring (Ash Meadows, NV)**	
Date	**Tritium Concentration (pCi/L)**	**Date**	**Tritium Concentration (pCi/L)**	**Date**	**Tritium Concentration (pCi/L)**
06/29/2000	3.39*	1999	27.90	1997	1.3*
05/31/2001	-1.04*			1998	0*
05/29/2002	0.18*			1999	-3.2*
05/29/2002	5.60*			06/16/2000	-9.50*
				11/06/2000	-5.50*
				07/23/2001	-2.75*
				04/18/2002	-11.63*
				08/13/2003	-6.74*

Table 3-15
Tritium Concentrations in Groundwater from the NTS On- and Offsite Regional Groundwater Radiological Monitoring Sites
(Page 2 of 3)

Fairbanks Springs (Ash Meadows, NV)		Crystal Pool (Ash Meadows, NV)		Cook's Ranch Well #2 (Amargosa Valley, NV)	
Date	**Tritium Concentration (pCi/L)**	**Date**	**Tritium Concentration (pCi/L)**	**Date**	**Tritium Concentration (pCi/L)**
02/17/1989	-10 +/- 6.0*	02/01/1989	3.9 +/- 6.6*	1999	0.41*
03/01/1989	-5 +/- 6.0*	09/07/1989	38 +/- 290	12/05/2000	9.50*
09/07/1989	0 +/- 300*	05/09/1990	-0.2 +/- 2.8*	11/28/2001	-0.43*
05/09/1990	-1 +/- 3.5*	11/21/1990	320 +/- 140*	08/20/2003	-20.1*
11/21/1990	170 +/- 140*	05/10/1991	-2.8 +/- 2.8*		
05/10/1991	0.4 +/- 2.8*	11/19/1991	80 +/- 73*		
11/14/1991	0 +/- 73*	05/07/1992	4.6 +/- 3.7*		
05/07/1992	-2.3 +/- 4.6*	11/02/1992	140 +/- 140*		
11/02/1992	-410 +/- 140*	05/12/1993	-1.6 +/- 1.4*		
05/12/1993	2.0 +/- 1.7*	11/09/1993	1.1 +/- 1.5*		
11/09/1993	-0.9 +/- 2.1*	1994	0.77*		
1994	2.3*	1995	0.77*		
1995	-1.5*	1996	-0.3*		
1996	-0.8*	1997	0.3*		
1997	0.7*	1998	0.37*		
1998	0.76*	1999	-4.4*		
1999	-1.9*	0616/2000	-0.66*		
06/16/2000	-2.57*	11/06/2000	-8.70*		
11/06/2000	-7.30*	07/23/2001	-2.79*		
07/23/2001	5.05*	7/23/2001	-3.21*		
07/23/2001	2.87*	04/18/2002	-18.60*		
04/18/2002	-5.16*	8/13/2003	-2.34*		
08/13/2003	0.799*				
Cind-R-Lite Mine (Amargosa Valley)		**De Lee Ranch (Amargosa Valley, NV)**		**School Well (Amargosa Valley, NV)**	
Date	**Tritium Concentration (pCi/L**	**Date**	**Tritium Concentration (pCi/L)**	**Date**	**Tritium Concentration (pCi/L)**
1999	1.17*	1999	4.09*	1999	3.88*
11/15/2000	-1.60*	12/05/2000	3.60*	12/04/2000	-7.00*
11/29/2001	-6.63	11/28/2001	-5.99*	11/28/2001	-5.69*
08/06/2003	9.44	08/20/2003	-13.2*	12/11/2002	76.20*
				08/20/2003	-6.84*

Table 3-15
Tritium Concentrations in Groundwater from the NTS On- and Offsite Regional Groundwater Radiological Monitoring Sites
(Page 3 of 3)

Amargosa Valley RV Park (Amargosa Valley, NV)		Roger Bright Ranch (Amargosa Valley, NV)		Longstreet Spring (Amargosa Valley, NV)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
1999	3.7*	1999	-.051*	1997	1.7*
11/14/2000	1.40*	12/05/2000	4.70*	1998	0.34*
11/28/2001	7.85*	06/14/2001	-1.00*	1999	-2.42*
08/20/2003	-10.4	12/11/2002	195*	06/16/2000	-1.81*
		08/20/2003	-7.86	11/06/2000	-4.20*
				04/18/2002	-17.94*
				08/20/2003	15.4*

Sources: REECo and EPA, 1990; REECo, 1991, 1992, 1993, 1994, 1995; BN 1996a, 1996b, 1997a, 1997b, 1998a, 1999, 2000a, 2001a, 2002c, 2003a, and 2004
* Where information was available to make a determination, the given concentration was less than the minimum detectable value.
ND = Not detected

In addition to tritium, several other radionuclides of concern for Environmental Restoration Sites were identified (BN, 2003b). These radionuclides, listed in descending order of expected concentration in groundwater and surface water are: strontium-90 (^{90}Sr), cesium-137 (^{137}Cs), technetium-99 (^{99}Tc), plutonium-239+240 ($^{239+240}$Pu), plutonium-238 (^{238}Pu), and ^{14}C. These radionuclides were identified as those having large UGTA inventories and low retardation factors (BN, 2003b). Naturally occurring radionuclides are not listed, although radium-226 (^{226}Ra), radium-228 (^{228}Ra), and uranium may be a concern in groundwater (BN, 2003b). Table 3-16 presents the reported average annual activities of gross alpha, gross beta, ^{90}Sr, $^{239+240}$Pu, and ^{238}Pu in groundwater from wells within the Rainier Mesa/Shoshone Mountain investigation region. The locations of these wells are shown in Figure 3-16. Table 3-16 also shows the Minimum Detectable Activities (MDAs) for the 1992 through 2003 data only, as MDAs were not listed in the annual site environmental reports prior to 1992. A comparison of sample data with these MDAs indicates that radionuclide activities in these groundwaters were generally below the MDC during the period of

Table 3-16
Average Annual Groundwater Activity Data for the Nevada Test Site Environmental Monitoring Program
(Page 1 of 3)

Well	Date	Gross Alpha (pCi/L)	Gross Beta (pCi/L)	Plutonium-239/240 (pCi/L)	Plutonium-238 (pCi/L)	Strontium-90 (pCi/L)
Water Well UE-15d (Area 15)	1989	NA	17	2.90×10^{-3}	2.00×10^{-3}	NA
	1990	14	19	4.50×10^{-3}	3.30×10^{-2}	-0.11
	1991	NA	20	-3.00×10^{-2}	2.40×10^{-2}	NA
UE-16D (Area 16)	1990	7.4	8.0	2.7×10^{-3}	2.5×10^{-2}	-9.3×10^{-2}
	1991	16	7.4	4.6×10^{-3}	9.2×10^{-3}	1.8×10^{-2}
	1992	9.4	7.4	1.3×10^{-2}	2.6×10^{-2}	0.19
	1993	8.7	6.5	-5.5×10^{-3}	-8.0×10^{-3}	5.7×10^{-2}
	1994	8.1	9.1	2.6×10^{-3}	7.8×10^{-4}	1.6×10^{-1}
	1995	5.3	6.4	-3.1×10^{-3}	7.7×10^{-4}	-3.8×10^{-2}
	1996	6.7	6.4	-3.4×10^{-3}	-2.6×10^{-3}	-2.6×10^{-2}
	1997	7.4	7.6	-1.7×10^{-3}	-1.4×10^{-3}	0.17
	1998	5.9	7.0	-3.0×10^{-3}	-1.4×10^{-3}	7.8×10^{-2}
	1999	7.4	6.7	-4.2×10^{-3}	-2.2×10^{-3}	NA
	2000	5.93	7.02	7.5×10^{-3}	-1.2×10^{-3}	-1.0×10^{-2}
	2001	7.03	4.25	6.37×10^{-3}	NA	0.42
	2002	8.81	7.84	-1.1×10^{-3}	2.13×10^{-3}	-1.07×10^{-2}
	2003	5.06	6.06	NA	NA	NA
HTH#1 (Area 17)	2000	11.6	9.12	6.5×10^{-3}	-1.1×10^{-3}	0.337
	2001	0.77	1.25	1.84×10^{-3}	-2.27×10^{-3}	NA
	2002	1.15	0.95	4.79×10^{-3}	7.69×10^{-3}	NA
	2003	1.49	1.06	NA	NA	NA
Water Well 8 (Area 18)	1990	0.76	3.9	-3.0×10^{-3}	3.1×10^{-2}	3.4×10^{-2}
	1991	0.7	3.3	6.5×10^{-3}	2.2×10^{-3}	-5.6×10^{-2}
	1992	5.8	3.6	7.0×10^{-3}	-1.2×10^{-2}	-1.5×10^{-2}
	1993	0.62	3.2	-8.2×10^{-3}	-4.8×10^{-3}	7.8×10^{-2}
	1994	0.61	3.4	2.5×10^{-3}	-2.1×10^{-3}	2.0×10^{-2}
	1995	0.76	4.1	-1.1×10^{-3}	1.7×10^{-3}	0.19
	1996	0.77	3.6	-3.5×10^{-3}	-3.0×10^{-3}	-4.5×10^{-2}
	1997	0.8	3.2	-1.2×10^{-3}	1.2×10^{-2}	1.5×10^{-2}

Table 3-16
Average Annual Groundwater Activity Data for the Nevada Test Site Environmental Monitoring Program
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Well	Date	Gross Alpha (pCi/L)	Gross Beta (pCi/L)	Plutonium-239/240 (pCi/L)	Plutonium-238 (pCi/L)	Strontium-90 (pCi/L)
Water Well 8 (Area 18) (Cont.)	1998	0.82	3.5	-2.8×10^{-3}	7.0×10^{-5}	8.5×10^{-2}
	1999	0.70	2.6	-3.9×10^{-3}	2.1×10^{-3}	NA
	2000	0.58	2.77	1.7×10^{-2}	1.1×10^{-3}	-7.45×10^{-2}
	2001	-0.22	3.17	2.46×10^{-3}	0	0.19
	2002	0.74	3.36	-8.6×10^{-4}	-2.58×10^{-3}	5.17×10^{-2}
	2003	0.44	2.38	NA	NA	NA
ER-19-1 (Area 19)	2000	NA	NA	NA	NA	NA
	2001	NA	NA	2.39×10^{-3}	NA	NA
	2002	4.63	79.9	1.71-03	1.61-02	NA
Water Well 2 (Area 2)	1989	NA	6.2	1.90×10^{-3}	6.60×10^{-3}	NA
	1990	3	6.7	7.00×10^{-3}	3.40×10^{-2}	-0.13
	2001	11	8.2	4.3×10^{-3}	1.1×10^{-2}	NA
	2002	NA	NA	NA	NA	NA
Water Well C (Area 6)	1989	NA	14	1.00×10^{-3}	-4.10×10^{-2}	NA
	1990	13	14	6.90×10^{-3}	5.40×10^{-2}	-3.80×10^{-2}
	1991	19	18	1.00×10^{-4}	1.00×10^{-4}	-0.12
	1992	1.1	14	-1.30×10^{-5}	4.30×10^{-3}	0.11
	1993	9.3	13	-1.10×10^{-2}	-8.60×10^{-3}	0.14
	1994	5.7	6.9	4.90×10^{-4}	-5.90×10^{-3}	6.10×10^{-2}
	1995	16	21	3.30×10^{-3}	-8.30×10^{-4}	0.17
Water Well C-1 (Area 6)	1989	NA	15	-3.00×10^{-3}	-1.10×10^{-2}	NA
	1990	11	15	2.10×10^{-2}	-1.70×10^{-3}	-6.40×10^{-3}
	1991	17	16	2.60×10^{-2}	6.40×10^{-2}	0.16
	1992	9.3	14	-7.70×10^{-4}	-1.30×10^{-2}	0.71
	1993	8.3	12	-5.80×10^{-3}	3.50×10^{-3}	0.1
	1994	8.2	10	1.50×10^{-3}	-7.70×10^{-4}	5.40×10^{-2}
	1995	13	16	-1.40×10^{-3}	-6.60×10^{-4}	0.14
	1996	8.3	14	-2.70×10^{-3}	1.50×10^{-3}	-6.40×10^{-3}
	1997	11	9.8	-1.80×10^{-3}	-3.30×10^{-3}	4.90×10^{-2}

Table 3-16
Average Annual Groundwater Activity Data for the Nevada Test Site Environmental Monitoring Program
(Page 3 of 3)

Well	Date	Gross Alpha (pCi/L)	Gross Beta (pCi/L)	Plutonium-239/240 (pCi/L)	Plutonium-238 (pCi/L)	Strontium-90 (pCi/L)
Water Well C-1 (Area 6) (Cont.)	1998	12	14	3.40×10^{-3}	-2.70×10^{-3}	0.22
	1999	10.5	13.2	1.20×10^{-3}	-2.30×10^{-3}	NA
	2000	11.54	14.5	1.73×10^{-2}	-1.10×10^{-3}	2.70×10^{-2}
	2001	14.2	11.79	NA	NA	1.21×10^{-2}
	2002	14	15.16	1.24×10^{-3}	2.12×10^{-3}	-8.59×10^{-2}
	2003	9.05	11.35	NA	NA	NA
Median MDA	1992	1.2	0.85	1.70×10^{-2}	3.80×10^{-2}	0.13
	1993	0.86	0.76	1.10×10^{-2}	1.10×10^{-2}	0.14
	1994	0.86	0.16	1.30×10^{-2}	1.30×10^{-2}	0.12
	1995	1.5	1.4	2.40×10^{-2}	2.40×10^{-2}	0.32
	1996	1.4	1.2	2.00×10^{-2}	1.90×10^{-2}	0.29
	1997	1.4	1.2	1.70×10^{-2}	2.10×10^{-2}	0.34
	1998	1.7	1.2	1.70×10^{-2}	2.00×10^{-2}	0.28
	1999	1.8	1.24	2.7×10^{-3}	2.7×10^{-3}	NA
	2000	1.47	1.42	1.52×10^{-2}	1.4×10^{-2}	0.49
	2001	1.92	2.28	2.73×10^{-2}	2.58×10^{-2}	0.70
	2002	1.84	1.76	2.20×10^{-2}	2.57×10^{-2}	0.67
	2003	1.46	1.87	NA	NA	NA

Sources: REECo and EPA, 1990; REECo, 1991, 1992, 1993, 1994, 1995; BN, 1996a, 1996b, 1997a, 1997b, 1998a, 1999, 2000a, 2001a, 2002c, 2003a, 2004
Variability in tritium data due to two different analytical methods, the conventional method and the enrichment method.
MDAs were not reported prior to 1992.
NA = Data were not available

observation. Detected gross alpha and gross beta activities were due to the presence of naturally occurring radionuclides (e.g., ^{226}Ra, ^{228}Ra) in the groundwater.

Radioactivity was also measured in surface water within the Rainier Mesa/Shoshone Mountain CAU and reported in the annual site environmental reports. Three natural springs in Area 12 (Captain Jack Spring, Gold Meadows Spring, and White Rock Spring) and one spring in Area 16 (Tippipah Spring) were sampled on an annual basis. Tunnel discharge and tunnel effluent contained in the tunnel containment ponds for N-Tunnel, T-Tunnel, and E-Tunnel were sampled and analyzed in the early 1990s, but only effluent contained in the ponds was sampled after 1993. Surface water from the tunnel discharge and containment ponds were analyzed for gross alpha and beta radioactivity, tritium, ^{90}Sr, ^{137}Cs, ^{238}Pu, and $^{239+240}$Pu, but the springs were analyzed only for gross beta radioactivity. Gross beta results for surface water in the natural springs and in the containment ponds are reported in Table 3-17. Although the gross beta values reported for the Gold Meadows Spring tend to be slightly higher than the values reported for the other three springs, none of the values from any of the springs were determined to be statistically different from the network average at the five-percent significance level (REECo, 1991). However, T-Tunnel containment pond samples, and to a lesser extent E-Tunnel containment pond samples, reported elevated concentrations of gross beta, reflecting the contamination of perched water discharging from these tunnels due to underground testing. A comparison of the results from the natural springs with results from the tunnels indicates that contamination from the underground testing within the tunnels has not affected the portion of the perched groundwater system at Rainier Mesa that discharges at the springs. Tunnel discharge has been mitigated by the construction of engineered barriers within N- and T-Tunnels that prevent effluent discharging from the tunnels to the surface environment. Engineered barriers constructed in E-Tunnel were not successful, and water discharges from the tunnel to the surface. This discharge is permitted under the terms of Nevada Water Pollution Control Permit, NEV 96021 (NDEP, 2002). At Shoshone Mountain, sample results from Tippipah Spring suggest that the discharge from springs fed by perched water have not been impacted by contamination from the underground tests.

3.4.8.2 Environmental Restoration Program

As part of the Environmental Restoration Program (UGTA Project and the predecessor Groundwater Characterization Program), DOE contractors have collected groundwater samples for radionuclide

Table 3-17
Gross Beta Concentrations (pCi/L) in Surface Ponds and Springs at Rainier Mesa and Shoshone Mountain

	1990	1991	1992	1993	1994	1995	1996
T-Tunnel Pond	383	15.9	580	260	NA	NA	NA
N-Tunnel Pond	56.2	2.46	26	5.3	NA	NA	NA
E-Tunnel Pond	161	8.13	56	83	55	85	140
Captain Jack Spring	8.26	9.0	6.8	9.1	12	7.8	7.8
Gold Meadows Spring	57.9	29.0	17	14	28	13	NA
White Rock Spring	14.7	13.7	12	9.9	8.2	8.7	9.0
Tippipah Spring	7.94	4.8	4.7	4.6	5.8	6.3	6.3
Topopah Spring	24.9	8.37	6.7	4.2	8.6	19	7.9

Data from REECo, 1991, 1992, 1993, 1994, 1995; BN, 1996b, 1997b
Annual averages in pCi/L
NA = No Analysis

analysis from three wells (ER-12-1, ER-12-2, and ER-19-1) within the Rainier Mesa/Shoshone Mountain investigation area during well completion activities. Radiological data are also available for E-, N-, and T-Tunnels. Well ER-12-1 groundwater samples were collected and analyzed for a suite of radionuclides during drilling and well development. Groundwater was sampled for tritium whenever fluids were introduced to, or removed from, the well. All of the radionuclides measured in the groundwater of Well ER-12-1 were below the detection limit with the exception of tritium (Russell et al., 1993; Smith, 1993b). Tritium was measured at 361 pCi/L. The source of tritium within this groundwater was thought to have originated from drilling fluids (Smith, 1993b). The tritium concentration reported for a more recent sample, collected from ER-12-1 on April 10, 2003, was less than the MDC of 350 pCi/L. LLNL reported a small but measurable amount of tritium in the groundwater at ER-12-2 (Rose, 2003). The reported concentration, 4.3 pCi/L, should be considered the upper limit since post-sampling contamination was suspected (Rose, 2003). No tritium was detected in a groundwater sample collected in July 1996 from Well ER-19-1. All tritium measurements performed on groundwater of ER-12-1, ER-12-2, and ER-19-1 were well below the 20,000 pCi/L SDWA standard (SDWA, 1996).

Tritium concentrations in E-Tunnel remained fairly constant at about 2.00 x 10^6 pCi/L during the characterization period of June 17, 1991, to May 12, 1992 (Russell et al., 1993). These concentrations are 100 times greater than the SDWA standard and reflect the nature of the perched groundwater after it had entered E-Tunnel. Tritium concentrations were also fairly constant in effluent tested from N-Tunnel during the characterization period of June 17, 1991 to July 28, 1992. Here, the mean tritium concentration was 3.12 x 10^5 pCi/L, or about 15 times greater than the SDWA standard. A grab sample from the effluent from the N-Tunnel collected in 1986 had a concentration of 7.83 x 10^5 pCi/L, more than twice the level measured during the later characterization period (Russell et al., 1993). T-Tunnel had fairly constant concentrations of tritium that averaged 6.46 x 10^6 pCi/L during the first half of the characterization period (June 17, 1991 to May 12, 1992). However, during the second half of the characterization period following the decrease in tunnel discharge, concentrations increased five-fold, with a final concentration of 3.76 x 10^7 pCi/L. The grab sample of tunnel discharge collected from T-Tunnel in 1986 had a concentration of 2.61 x 10^8 pCi/L (Russell et al., 1993). The high tritium concentrations exhibited in all the 1986 tunnel grab samples relative to the values observed during the later characterization period might result from diminishing concentrations of tritium within the tunnels due to natural radioactive decay, or it might reflect the mobilization of underground test-generated tritium contamination away from the test tunnel complex by the passage of the perched groundwater. In 1993, the concentrations of tritium from E-Tunnel averaged 1.8 x 10^6 pCi/L (REECo, 1994). In 1994, E-Tunnel effluent was reported at 1.83 x 10^6 pCi/L (DNA, 1996). Since then, concentrations have decreased at an average rate that is roughly consistent with radioactive decay, with the tritium concentration reported for DTRA's permit (NDEP, 2002) for 2003 at 8.2 x 10^5 pCi/L. The lowest concentration reported during this interval was 7.76 x 10^5 pCi/L, which was measured in February 2001. Fluctuations in concentration are probably due to variations in climatic conditions that affect the volume of water available for transport.

Gross alpha radiation varied by no more than a factor or two during the characterization period in E-Tunnel. Here concentrations of gross alpha measured in the effluent averaged 24.4 pCi/L, whereas a sample collected in 1986 measured 46.0 pCi/L. Gross alpha concentrations were also fairly constant in N-Tunnel, averaging 27.9 pCi/L, but with two notable exceptions. There were two sampling intervals during the characterization period where gross alpha concentrations were approximately two orders of magnitude higher. Gross alpha values averaged 11.0 pCi/L for T-Tunnel effluent during the characterization period, with a value of 1.4 x 10^2 pCi/L observed during the 1986 sampling event (Russell et al., 1993).

In E-Tunnel, gross beta radiation concentrations varied by almost an order of magnitude during the characterization period, averaging 70.3 pCi/L, but attaining concentrations as high as 1.1 x 10^2 pCi/L. During the 1986 sampling event gross beta concentrations in the E-Tunnel were 2.82 x 10^2 pCi/L, or more than twice as high as during the 1991 to 1992 characterization period. In the N-Tunnel, gross beta concentrations were fairly consistent, averaging 33.1 pCi/L. However, there were three sample episodes during the characterization period when concentrations increased by almost an order of magnitude. The 1986 sample of N-Tunnel effluent had a gross beta value of 4.20 x 10^2 pCi/L, more than an order of magnitude greater than the average during the characterization period, and higher than any of the peak concentrations during that same period. For T-Tunnel, gross beta values varied by almost an order of magnitude during the characterization period, with an average value of 3.33 x 10^2 pCi/L. The highest values encountered in T-Tunnel, 1.41 x 10^3 pCi/L, were observed after the discharge from the tunnel had diminished. Gross beta values in T-Tunnel were 1.54 x 10^6 pCi/L during the 1986 sampling event (Russell et al., 1993).

3.4.8.3 Radionuclide Migration Program

Since the mid 1970s, the radiochemistry of NTS groundwater has been investigated as part of the RNM Program. As reported in 1987 the RNM Program was merged with the LTHMP. These merged programs were designated as the HRMP. The HRMP is sponsored by the NNSA/NSO and program participants have included DRI, LANL, LLNL, and USGS. The objective of the HRMP is to investigate the movement of radionuclides away from nuclear explosion cavities and chimneys (Finnegan et al., 2004). Radiochemistry data have been collected for groundwater in several underground test locations where a satellite well was installed near a test cavity and pumped to induce transport of radionuclides from the test cavity, or periodically tested to monitor natural radionuclide transport. Although no such HRMP tests have been conducted at Rainier Mesa or Shoshone Mountain, HRMP studies conducted at Frenchman Flat (CAMBRIC) and Pahute Mesa (CHESHIRE) provide useful data as analog studies.

3.4.8.3.1 CHESHIRE (U20n and UE20n#1)

CHESHIRE was conducted at Central Pahute Mesa (Area 20) in February 1976 at a depth of 1,174 m bgs, 544 m below the water table, with an announced yield in the range of 250 to 500 kt. The working point was in a brecciated rhyolite lava flow within a stratigraphic sequence that includes permeable fractured welded tuff and lava flows as well as impermeable zeolitized nonwelded tuff. The CHESHIRE site was originally chosen for HRMP characterization because of the complex volcanic stratigraphy of the site, the higher hydraulic gradients relative to sites located in Frenchman Flat and Yucca Flat, and the potential for fracture-controlled groundwater flow through lavas and welded tuff.

A re-entry hole (renamed as U-20n PS1 DD-H) was drilled and sampled in 1976, soon after the CHESHIRE test. This hole has been modified several times since 1976 while providing periodic access to the CHESHIRE cavity and/or chimney region (Sawyer et al., 1999; Rose et al., 2004). In 1985, a bridge plug was installed in U-20n PS1 DD-H to isolate the cavity region and samples were collected from within and also above the cavity. Sawyer et al. (1999) report that the concentration of non-sorbing radionuclides above the CHESHIRE cavity region were similar to those measured in the cavity region, whereas lower concentrations of the sorbing radionuclides were observed above the cavity. Samples have been collected periodically from U-20n PS1 DD-H. The concentrations of tritium and ^{85}Kr in the chimney region decreased by a factor of 3 to 4 over the period of 1985 to 1998, whereas the concentrations of ^{125}Sb and ^{137}Cs decreased by factors of 20 and 88, respectively (Thompson, 2000). Tritium concentrations within the cavity region decreased by a factor of two over the period of 1985 to 1998. Gamma emitting radionuclides (^{60}Co, ^{125}Sb, ^{137}Cs, ^{152}Eu, and ^{154}Eu) slightly increased in concentration within the cavity region during the same time period, suggesting the leaching of melt glass or desorption from rock surfaces in the cavity region (Thompson, 2000). Measurement of radionuclide concentrations in samples, pumped in 1998, from lower and upper cavity intervals of U-20n PS1 DD-H, show the ascent of radionuclides from the test cavity over approximately 300 m (Smith et al., 1999). The transport was attributed to hydraulic communication between a lower and upper aquifer. Results from the more recent (1999 and 2003) samples collected from U-20n PS1 DD-H suggest a continued small decrease in tritium concentrations over time (Rose et al., 2004). Plutonium was present at detectable concentrations in the 1999 and 2003 samples. Filtration experiments performed on the 2003 samples showed that greater than 90 percent of the plutonium is associated with mineral colloids in the water (Rose et al., 2004).

In 1987, a satellite well, UE-20 n#1, was drilled 300 m southwest of the CHESHIRE emplacement hole and completed in fractured lavas thought to intercept radionuclides moving downgradient from the CHESHIRE chimney. Samples taken from UE-20 n#1 contained concentrations of tritium, ^{99}Tc, and ^{129}I similar to those measured in groundwater above the cavity region in U-20n PS1 DD-H (Sawyer et al., 1999). This is consistent with conservative down-gradient movement of the non-sorbing radionuclides through a laterally transmissive aquifer. The concentrations of sorbing radionuclides were strongly depleted in the groundwater of UE-20 n#1 (Sawyer et al., 1999). Sampling was discontinued in UE-20 n#1 in mid 1980 due to high concentrations of iron hydroxide in the water. The iron hydroxide was assumed to result from iron parts rubbing within the Moyno pump (Sawyer et al., 1999).

The cumulative data set produced from the CHESHIRE site provides valuable information on the evolution of the hydrologic source term (HST) over time. This data set was used in the calibration of an HST model for the CHESHIRE test (Pawloski et al., 2001).

The CHESHIRE data can, to a first order, be used to understand the transport of radionuclides at the underground test locations at Rainier Mesa and Shoshone Mountain. Whereas the lithologies present at CHESHIRE (fractured welded tuff and lava flows) are dissimilar to the nonwelded tuff characteristic of Rainier Mesa and Shoshone Mountain, the movement of radionuclides through fractured rhyolite lava and welded tuff provides a useful analog for the potential transport of contamination away from Rainier Mesa/Shoshone Mountain in volcanic rocks.

3.4.8.3.2 CAMBRIC (RNM-1 & RNM-2S)

CAMBRIC was conducted in 1965 at a depth of 294 m bgs, 73 m below the water table. The working point was in the tuffaceous alluvium and valley fill deposits of Frenchman Flat. Although the working point was located 73 m below the static water table, there appears to be little ambient groundwater flow sufficient to cause the migration of radionuclides. For example, during the early hours of pump tests at RNM-2S, the tritium concentration increases until it reaches a steady-state value equal to that measured at previous pumping campaigns (Thompson et al., 2000). The cavity was re-entered in 1974 with the drilling of the RNM-1 monitoring well, which was drilled through the test cavity and into the alluvial strata beneath it. Sampling of groundwater from intervals within and beneath the cavity confirmed that tritium and fission products associated with the test were still present (Thompson, 1987). Detectable amounts of tritium, chlorine-36 (^{36}Cl), cobalt (^{60}Co), ^{85}Kr, ^{90}Sr, ^{99}Tc, ^{106}Ru, antimony-125 (^{125}Sb), iodine-129 (^{129}I), ^{137}Cs, and ^{239}Pu were found in sampled waters believed to be most representative of the cavity fluids (Tompson et al., 1999). In 1974, a sixteen-year pump test was started in a satellite well (RNM-2S), located 91 m from the test cavity, to determine if radionuclide contamination would be transported away from the test cavity in moving groundwater. Over the years, tritium, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{106}Ru, and ^{129}I were detected, although concentrations of these radionuclides were significantly below those collected from RNM-1 (Tompson et al., 1999). Tritium concentrations in RNM-2S water peaked about 5 years after the start of the pump test, slowly declined for about 1.4 years, and then steadily declined. Concentrations of ^{85}Kr in RNM-2S water followed a similar pattern but peaked later. The ^{85}Kr/tritium ratio in RNM-2S water has been slowly rising, but remains significantly less than the source term in the test cavity, reflecting the fact that ^{85}Kr has not moved out of the cavity region as readily as tritium has (Thompson, 1987). Pumping from RNM-2S was terminated in 1991. Tritium and ^{85}Kr concentrations decreased by several orders of magnitude over the period of pumping; to a lesser extent, the concentrations of ^{137}Cs and ^{90}Sr also decreased. Subsequent sampling of RNM-1 indicates that the concentrations of tritium and ^{85}Kr are now near or below the analytical detection limit (Finnegan and Thompson, 2001). The concentrations of tritium and ^{85}Kr in RNM-2S have continued to decline over the course of 20 years (Rose et al., 2004, Finnegan and Thompson, 2003; Finnegan et al., 2004). Results from the periodic sampling of water from RNM-2S have shown that, in the absence of a hydraulic gradient imposed by pumping from adjacent wells, there is little dispersion of tritium from the test cavity region (Thompson, 1995). Over the years, water from RNM-2S has indicated radionuclide anions such as ^{129}I and ^{36}Cl in small amounts, but cations such as ^{137}Cs and ^{90}Sr have never been detected (Thompson, 1989a). These field results confirm laboratory observations that ^{137}Cs and ^{90}Sr are strongly sorbed on nonwelded tuffaceous rocks (Daniels et al., 1982).

Although the mineralogy and texture of the nonwelded tuffs in the test intervals at Rainier Mesa and Shoshone Mountain are dissimilar to the alluvial sediments of CAMBRIC, the mobility of radionuclides in potential down-gradient pathways through alluvium in the discharge areas may be similar.

3.4.9 Transport Parameters

Data on contaminant transport parameters, including porosity, dispersivity, matrix diffusion coefficient, distribution coefficient (K_d), and colloidal transport are discussed in this section. Data gathered and evaluated during the regional evaluation may be found in Sections 3.0 through 5.0 of Volume V of the regional evaluation documentation package (IT, 1996g), and in Section 8.0 of the regional evaluation report (DOE/NV, 1997a).

3.4.9.1 Porosity

In fractured geologic materials, both effective and matrix porosities are needed to simulate contaminant transport. Effective porosity is best measured via a tracer migration test. However, because effective porosity values from tracer experiments are scarce for the HSUs present on the NTS, data on bulk fracture porosity are used to estimate the effective porosity of the HSUs. Matrix and bulk porosity values are also used to constrain the value of the effective porosity in fractured media. A summary of the porosity data gathered during the regional evaluation (DOE/NV, 1997a), including measured matrix, bulk, and fracture porosities, as well as effective porosities from tracer tests, is provided in this section. The details can be found in Section 3.0 of Volume V of the regional evaluation documentation package (IT, 1996g).

During the regional evaluation, a database of measured porosity values for geologic units found in the NTS region was developed using data from the literature. The contents of this database are found in Appendix A, and additional porosity data as reported in the literature are found in Appendix B, of Volume V of the regional evaluation documentation package (IT, 1996g). Multiple porosity values exist for discrete locations because of the different methods used to calculate porosity for a variety of drill-hole tests and geophysical logs. Therefore, the data set was statistically reduced to provide an estimate of the mean and variance of the porosity for each HSU. The results of this analysis are found in Appendix C of Volume V of the regional evaluation documentation package (IT, 1996g). Alluvial and volcanic aquifers have significantly larger porosities than the Paleozoic carbonate and clastic units. The differences in volcanic unit porosity are due to the large variations in lithology, both laterally and vertically, that are inherent to these rocks. A statistical summary of the porosity data is provided in Table 3-18.

Table 3-18
Statistical Summary of Porosity Data

Hydrostratigraphic Unit	Porosity Type	Mean (percent of bulk volume)	Variance	Range Min/Max	Number of Points
Alluvial Aquifer	Bulk	36.3	79.8	10 to 35	126
Alluvial Aquifer	Matrix	25.2	32.3	13.4 to 38.6	18
Lower Carbonate Aquifer	Bulk	11.7	0.3	11 to 12	3
Lower Carbonate Aquifer	Matrix	3.8	7.5	0.3 to 9.9	18
Lower Clastic Confining Unit	Matrix	3.3	6.5	0.2 to 10	31
Tuff Confining Unit	Matrix	28.1	64	7.3 to 47.5	75
Topopah Spring Tuff Aquifer	Matrix	23.7	NA	NA	1
Upper Clastic Confining Unit	Matrix	8.8	20.6	1.3 to 22.6	34
Vitric Tuff Aquifer	Matrix	34	84.3	19.9 to 44	17
Welded Tuff Aquifer	Matrix	20	138.1	1.4 to 65	639
Volcanic Confining Unit	Matrix	16	13	9.2 to 23.5	28

Source: IT, 1996g
NA = Not Available

Estimates of effective porosity for geologic units of the NTS region are also derived from existing tracer test data, which is reported in Section 3.4.3 of Volume V of the regional evaluation data package (IT, 1996g) and from the BULLION tracer test (Reimus and Haga, 1999). Leap and Belmonte (1992) examined data from the USGS Amargosa Tracer Calibration Site (south of the NTS) and determined an effective porosity of 10 percent for a fractured 10 m thick interval of the Bonanza King dolomite within the LCA. The 10 percent value may be accurate for the Amargosa site, but it is unlikely to be representative of the NTS as a whole. The Amargosa Tracer Site has a thin aquifer (less than 10 m) about 200 m bgs, and these conditions are not representative of the study area as a whole. Burbey and Wheatcraft (1986) used an effective porosity of 32 to 36 percent for the alluvium at the CAMBRIC site in Frenchman Flat. A preliminary assessment of the tracer experiment at Wells C and C-1 (Winograd and West, 1962) yielded an effective porosity between 0.064 and 0.5 percent for the LCA. Effective porosity was calculated from the BULLION tracer test, with results ranging from 1.8 to 2.3 percent (IT, 1998a). The ER-6-1 tracer test will be analyzed to provide additional effective porosity values. Effective porosity estimates from tracer tests are presented in Table 3-19.

To supplement the tracer studies, data from core fractures were used to calculate fracture porosity values on the NTS during the regional evaluation. Details are provided in Section 3.4.4 of Volume V of the regional evaluation documentation (IT, 1996g). Drill-core samples of carbonate rock

Table 3-19
Effective Porosity Estimates from Tracer Tests Conducted at or near the Nevada Test Site

Site Location	Test Site Geology	Test Scale (feet)	Test Method	Effective Porosity (percent)	Sources
Amargosa Desert, south of the NTS	Cambrian Bonanza King Dolomite (fractured)	403	Doublet recirculation (tritium, sulfur-35, bromide)	10	Leap and Belmonte, 1992
Yucca Flat	Fractured Limestone	96	Radial converging test at Water Wells C and C-1	0.064 to 0.5	Winograd and West, 1962
Frenchman Flat	Tuffaceous Alluvium	298	Radial converging with monitoring the elutions of tritium and chlorine-36 at pumping well RNM-2S	31 to 35	Burbey and Wheatcraft, 1986
BULLION Site Pahute Mesa	Fractured Lava	971	Cross-hole tracer test (equivalent porous media)	1.8 to 2.3	IT, 1998a

Source: IT, 1996g; IT, 1998a

(IT, 1996g) and volcanic rock (Drellack et al., 1997) provide insights into fracture porosity, as follows:

- Carbonate Rock – Core from Well ER-6-2 was examined and fracture aperture, fracture density, and fracture orientation data were collected. Fracture porosity was calculated as 0.4 percent by dividing the aperture by the fracture spacing. This value compares well with larger values obtained from the tracer test in Water Wells C and C-1, and with results published by Schoff and Winograd (1961) of 0.5 to 1.6 percent for carbonate rocks in northern Yucca Flat.

- Volcanic Rock – A study was conducted to characterize fractures in volcanic rock units of Pahute Mesa (Drellack et al., 1997). Open fractures found within the cored intervals of seven boreholes were analyzed. A range of fracture porosity values were calculated from the measurements of aperture, density, orientation, and percent open area. These data are presented in Table 3-20. The data from Drellack et al. (1997) compares favorably with results obtained at Yucca Mountain (Klavetter and Peters, 1986).

Borehole fracture log data are also used to estimate fracture porosity through incorporation of the cubic law into the definition of fracture porosity. In general, the cubic law (Domenico and Schwartz, 1990) is used to calculate the discharge through fractures of definite aperture over a finite

Table 3-20
Fracture Porosity Obtained from the Study of Volcanic Core

Hydrostratigraphic Unit	Fracture Porosity Range (percent)
Uppermost Welded Tuff (Timber Mountain Aquifer)	0.0022 to 0.0056
Tuff Cones	0.00026 to 0.013
Welded Tuffs Above Basal Confining Unit	0.0012 to 0.012
Basal Aquifer	0.00061 to 0.0061

Source: IT, 1996g

test (borehole) interval. In the case that fracture apertures are unknown, apertures can be estimated if the test-interval hydraulic conductivity and fracture spacing are known. This analysis would require, respectively, well-test data and borehole fracture log data (location, aperture measured at the borehole, and orientation) over that interval. Although borehole fracture logs include fracture aperture measurement, the surveys consider fractures that are open only at the borehole and do not denote those that are proximally closed in the formation. Given the data requirements, there are presently no coincident well-test and fracture-log data for boreholes in the Rainier Mesa/Shoshone Mountain CAU. Well-test (pumping-test and drill-stem test) data are available for Well ER-12-1 (Russell et al., 1996). Data that are to be collected at Rainier Mesa and Shoshone Mountain at three ER wells in the fiscal year (FY) 2005 (see Section 6.1.1) may permit fracture porosity to be estimated using the cubic law method.

For the entire NTS, several published sources of fracture porosity data were evaluated. Lee and Farmer (1993) showed that fracture porosity typically ranges from 5 x 10^{-4} to 5 x 10^{-2} percent for clastic, metavolcanic, and crystalline rocks, which is similar to data presented in Table 3-20. Fractured basalt in eastern Washington is reported to have a fracture porosity of 4.3 x 10^{-2} percent from tracer tests (Gelhar, 1982). The Culebra Dolomite in eastern New Mexico has a range of fracture porosity values from 0.05 to 0.15 percent (Jones et al., 1992). NTS-derived and literature values of fracture porosity for various rock types provide initial estimates to constrain expected ranges for this parameter.

3.4.9.2 Dispersion

A comprehensive summary and discussion of dispersivity is included in the dispersion technical basis document by Shaw (2003). The data presented in this section predominantly summarize longitudinal, horizontal, and vertical transverse dispersivity data assessed during the regional evaluation (DOE/NV, 1997a). Details are found in Section 4.0 of Volume V of the regional evaluation documentation package (IT, 1996g), and in Section 8.6 of the regional evaluation report (DOE/NV, 1997a). Additional sources of dispersivity data current beyond 1997 are presented below.

NTS-specific and near-vicinity data for longitudinal dispersion were obtained from one contaminant migration experiment and several tracer tests. 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 were not available at the time this document was prepared. A summary of dispersivities derived from the tracer test and transport model analyses is presented in Table 3-21.

Additional data related to the NTS are reported by Borg et al. (1976), who calculated longitudinal dispersivity from the calibration of numerical solute transport models against hydraulic head and concentration data. Longitudinal dispersivities ranged from 11.6 to 91 m for a wide variety of lithologies, including glacial outwash sand and gravel, basalt lava, 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).

The most current summaries of non-NTS dispersivity data are presented by Gelhar et al. (1992), who analyzed dispersivity observations from 59 different field sites for reliability and for trends. These

Table 3-21
Longitudinal Dispersivity Information Summary from Tracer Tests Conducted on and Near the Nevada Test Site

Site Location	NTS Regional HSU/Geology	Scale of Test (meters)	Analysis Method	Longitudinal Dispersivity (meters)	Sources
Amargosa Tracer Calibration Site, Amargosa Desert, NV (near NTS)	LCA/Cambrian Bonanaza King Dolomite (fractured)	122.8	1-D quasi-uniform fitting of Grove's curves	15 to 30.5	Leap and Belmonte, 1992
C-Well Site, Yucca Flat	LCA/Fractured Limestone	29.3	2-D Analytical Welty & Gelhar (1994)	0.6 to 1.4	Winograd and West, 1962
CAMBRIC Test, Frenchman Flat	AA/Tuffaceous Alluvium	91.0	Welty & Gelhar (1994)	9.6	Thompson, 1991
			Sauty's method	2.0	Burbey and Wheatcraft, 1986
			Sauty's method	9.1	Travis et al., 1983
			Sauty's method	15.1	Thompson, 1988; Ogard et al., 1988
BULLION Test, Pahute Mesa	VA/Fractured Lava-Flow Aquifer, Calico Hills Formation	42.3 to 131.5	Calibration of numerical 3-D transport and 2-D analytic models	10 (horiz. trans. 3) (vert. trans. 2)	IT, 1998a; Reimus and Haga, 1999
C-Well Complex, Yucca Mountain	VA/Bull Frog and Tram Tuffs	90	1-D and 2-D analytical models	3.3 to 59	Winterle and La Femina, 1999

LCA = Lower Carbonate Aquifer
AA = Alluvial Aquifer
VA = Volcanic Aquifer

data were classified into three reliability classes. The analysis indicated a trend of systematic increase of longitudinal dispersivity with observation scale, from 10^{-2} to 10^{4} m for travel distance 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. Fewer data on horizontal dispersivity were available. The two high-reliability points available show that horizontal dispersivity is one order of magnitude less than longitudinal dispersivity. Even fewer vertical dispersivity data were available. Gelhar et al. (1992) found that in all cases where transverse dispersivity were also measured, the values of the vertical dispersivity were one to two orders of magnitude less than the horizontal transverse dispersivity. They concluded from the data that overall dispersivity values did not appear to differ with lithology (i.e., porous versus fractured media).

3.4.9.3 Matrix Diffusion Coefficient

This section includes descriptions of the available matrix diffusion data for tritium compiled during the regional evaluation (DOE/NV, 1997a), as well as a brief summary of matrix diffusion data for other constituents. Details are found in Section 5.0 of Volume V of the regional evaluation documentation package (IT, 1996g), and in Section 8.7 of the regional evaluation report (DOE/NV, 1997a).

Available data on matrix diffusion of tritium into volcanic rocks of Yucca Mountain have been reported by Triay et al. (1996). A summary of these data is presented in Table 3-22. The effective diffusion coefficient for tritium in the welded tuff aquifer (WTA) is on the order of 1.0 x 10^{-6} to 3.5 x 10^{-6} square centimeters per second (cm^2/s).

Table 3-22
Diffusion Coefficients for Tritium

Well or Location	Sample	Porosity (percent)	Diffusion Coefficient (x 10^{-6} cm^2/s)	Hydrostratigraphic Unit
USW G-4	737	7	2.2	WTA
USW GU-3	304#1	6	1.5	WTA
USW GU-3	304#2	6	1.6	WTA
USW GU-3	433	10	3.5	WTA
USW GU-3	1119	10	2.0	WTA
Topopah Spring Tuff Outcrop	NA	7	1.0	WTA

Source: Triay et al., 1996
WTA = Welded Tuff Aquifer
NA = Not Available

However, the data summarized in Table 3-22 are limited. First, these data represent a small set of information for only one HSU. Additionally, the range of porosity values is narrow compared to the range of porosity values manifested by all the rocks on the NTS. Finally, these tests were performed on fresh rock surfaces, whereas most *in situ* fractures have some mineral coating, especially in the saturated zone. The testing of fresh surfaces provides the most direct access for tritium to diffuse into the rock matrix. If the fracture surface is coated with mineralization, the diffusion could be reduced. The small data set limits the extrapolation of the results to the other HSUs at the NTS. This is especially true for the LCA, which will have characteristics that differ significantly from the tuffs at Yucca Mountain.

Other NTS matrix diffusion data are available from Reimus et al. (2002), Walter (1982), Papelis and Um (2003), Reimus et al. (1999), and Hershey et al. (2003). Reimus et al. (2002) 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, using three different radioactive tracers: tritiated water $NaH^{14}CO_3$, and $Na^{99}TcO_4$. Matrix diffusion coefficients ranged from 5×10^{-12} to 2×10^{-9} m^2/sec. Walter (1982) derived matrix diffusion coefficients by diffusion cell experiments with fractured tuff samples from Yucca Mountain and also determined constrictivity and tortuosity from conductive experiments. Matrix diffusion coefficients ranged from 2×10^{-11} to 2×10^{-10} m^2/sec. Papelis and Um (2003) studied adsorption and diffusion and also conducted spectroscopic analysis of Frenchman Flat rock samples (welded ash flow and zeolitic volcanic tuffs) using pulverized, sieved particles. The matrix diffusion values were determined by batch experiments, measuring the change in tracer concentration over time for a test tube containing spherical volcanic tuff particles in a tracer solution, using three different tracers: strontium (Sr), cesium (Cs), and lead (Pb). Matrix diffusion coefficients ranged from 2×10^{-14} to 9×10^{-9} m^2/sec. Reimus et al. (1999) derived matrix diffusion coefficients by diffusion cell experiments on 57 zeolitic tuff samples from Pahute Mesa using two different tracers, iodide and PFBA, with matrix diffusion coefficients ranging from 1×10^{-11} to 2×10^{-9} m^2/sec. Hershey et al. (2003) evaluated diffusion of ^{14}C through LCA cores obtained from two NTS wells and also determined tortuosities. The effective diffusion coefficient ranged from 3.0×10^{-10} to 3.9×10^{-10} m^2/sec.

3.4.9.4 Distribution Coefficients

Distribution coefficients (K_d) are a factor that is used in contaminant transport models to account for a variety of chemical interactions between dissolved contaminants and the solid substrate through which the contaminants are transported. Measured K_d values are typically a function of the mineralogy of the substrate, the chemical composition of the water, and a variety of experimental variables, including water-to-rock ratios, batch versus column testing, and particle size in the substrate. In some cases, measured K_d values reflect processes other than sorption. No information was gathered on K_ds during the regional evaluation because the only radionuclide considered at that time was tritium ($K_d = 0$).

Researchers at the DRI have conducted several relevant studies involving primarily Pb and Sr sorption on various Rainier Mesa rock samples. Bernot (1999) investigated various mechanisms for Pb and Sr sorption on zeolitized tuff from Rainier Mesa. Although her research primarily focuses on specific mechanisms affecting the sorption rates of these two metals, she found that Pb has a much greater affinity for zeolitized tuff than Sr, but that both are much greater than 100 mL/g.

Um and Papelis (2001) have also investigated sorption and desorption behavior of Pb and Sr on NTS/Rainier Mesa zeolitized tuffs using batch and column experiments (Table 3-23). Again, Pb sorption is found to be stronger than Sr, and showed a greater pH dependence. For typical NTS groundwater compositions, both Sr and Pb are expected to sorb nearly irreversibly on zeolitized tuff.

Table 3-23
Sr and Pb K_ds for Zeolitized Tuff from Rainier Mesa

Metal	Ionic Strength (Molar)	K_d (Sorption) (mL/g)	K_d (Desorption) (mL/g)
Sr	0.01	3,900	4,900
Sr	0.1	420	810
Pb	0.01	94,000	640,000
Pb	0.1	87,000	320,000
Pb	1	1,600	4,700
Pb	1	260	710

Source: Um and Papelis (2001)

Sloop (1998) also investigated the equilibrium sorption of Pb and Sr on zeolitized tuff from Rainier Mesa (Table 3-24). He investigated ionic uptake of these elements for varying pH and ionic strength conditions. As with the other DRI studies, Pb (II) is found to have a greater affinity for zeolitized tuff from Rainier Mesa than Sr (II) for all geochemical conditions considered, and both have a very large affinity for zeolitized tuff. Linear sorption K_ds consistent with standard solute transport models are provided by Sloop (1998), with the caveat that the non-linear Freundlich isotherm is actually a more accurate descriptor of solute uptake for this system. Sloop (1998) reports sorption K_ds for Pb with a background electrolyte concentration of 1.0 mole (M) sodium nitrate ($NaNO_3$), and for Sr with background electrolyte concentrations of 0.1 and 0.01 M $NaNO_3$. Table 3-24 summarizes the Pb and Sr K_ds for zeolitic tuff reported by Sloop (1998, Tables 9, 12, and 14).

Table 3-24
Sr and Pb K_ds Reported for Zeolitized Tuff from Rainier Mesa

Metal	Ionic Strength (Molar)	pH	K_d (Sorption) (mL/g)
Pb	1	7	1.24×10^3
Pb	1	8	3.87×10^3
Pb	1	9	8.06×10^3
Sr	0.1	7, 8, 9	1.92×10^3
Sr	0.01	7, 8, 9	2.5×10^3

Source: Sloop (1998)

K_d data from Rainier tuff samples from several authors are reported in Borg et al. (1976) (Table 3-25). Sr and Cs K_ds from ground tuff samples in the presence of Rainier Mesa groundwater or the Rainier Mesa Spring water varied from 260 to 4,300 and 1,020 to 17,800 milliliters per gram (mL/g), respectively (Borg et al., 1976). The range of strontium K_ds encompass the range reported by Sloop (1998) and Um and Papelis (2001). Additional distribution coefficient measurements are reported for Cs, ruthenium (Ru), antimony (Sb), pranethium (Pm), europium (Eu), and iodine (I).

The K_d values in Table 3-26 from Conca (2000) and Kelkar et al. (2003) are the most current data recommended for use in the Yucca Mountain performance assessment. The K_d values shown are based on data obtained from studies using groundwater from both volcanic aquifers and carbonate aquifers. For most of the potential contaminants, Conca (2000) and Kelkar et al. (2003) reported K_d

Table 3-25
Distribution Coefficients Reported for Rainier Mesa Tuff Samples

Radionuclide	Distribution Coefficient (K_d) (mL/g)		Data Source as Reported by Borg et al. (1976)
	Minimum	Maximum	
Sr	---	260[a]	Nork and Fenske (1970)
	2,070	3,480	Goldberg et al. (1962)
	1,700	4,300	Kaufman (1963)
Cs	---	1,020[a]	Nork and Fenske (1970)
	12,100	17,800	Goldberg et al. (1962)
Ru	---	7.5[a]	Essington and Nork (1969)
Sb	---	1.4[a]	
Ce	---	400[a]	
Pm	---	400[a]	
Eu	---	400[a]	
I	---	1.1[a]	Goldberg et al. (1962)

Source: Borg et al., 1976

[a]Only one value is reported, this should be taken as a maximum value to ensure conservative estimates of transport.

values for devitrified, vitric, and zeolitic tuff, and for alluvium. Although the K_d range may vary by orders of magnitude for a given contaminant, several generalities can be garnered from the data provided in Table 3-26:

- Sorption depends on volcanic rock type.
- Uranium is not sorbed to an appreciable degree.
- Americium, cesium, lead, plutonium, and strontium sorption is appreciable, regardless of substrate.
- Cesium and strontium sorption is high in zeolitic tuff.
- Sorption of all radionuclides tends to be lowest on vitric tuffs.

The presence of natural zeolites tends to increase sorption of radionuclides. However, cation exchange reactions in natural zeolites favor elements with similar ionic size and charge (cesium and

Table 3-26
Summary of K_d (mL/g) Distributions for YMP

Species	Unit	Kelkar et al. (2003)		Conca (2000)	
		Minimum	Maximum	Minimum	Maximum
U	Vitric Tuff	---	---	0	4
	Zeolitic Tuff	5	20	5	20
	Devitrified Tuff	0	4	0	5
	Alluvium	---	---	0	8
Np	Vitric Tuff	---	---	0	2
	Zeolitic Tuff	0	6	0	5
	Devitrified Tuff	0	2	0	2
	Alluvium	---	---	0	100
Pu	Vitric Tuff	---	---	50	300
	Zeolitic Tuff	50	300	50	400
	Devitrified Tuff	50	300	5	100
	Alluvium	50	300	---	---
Cs	Vitric Tuff	---	---	10	100
	Zeolitic Tuff	4,000	42,000	500	5,000
	Devitrified Tuff	100	1,000	20	1,000
	Alluvium	100	1,000	---	---
Am	Vitric Tuff	---	---	100	1,000
	Zeolitic Tuff	1,000	10,000	100	1,000
	Devitrified Tuff	1,000	10,000	100	2,000
	Alluvium	1,000	10,000	---	---
Pa	Vitric Tuff	---	---	0	100
	Zeolitic Tuff	1,000	10,000	0	100
	Devitrified Tuff	1,000	10,000	0	100
	Alluvium	1,000	10,000	---	---
Sr	Vitric Tuff	---	---	20	50
	Zeolitic Tuff	---	---	2,000	5,000
	Devitrified Tuff	20	400	10	200
	Alluvium	20	400	---	---
Th	Vitric Tuff	---	---	100	1,000
	Zeolitic Tuff	1,000	10,000	100	1,000
	Devitrified Tuff	1,000	10,000	100	2,000
	Alluvium (same as devitrified)	1,000	10,000	---	---
Ra	Vitric Tuff	---	---	100	500
	Zeolitic Tuff	1,000	250,000	1,000	5,000
	Devitrified Tuff	100	1,000	100	500
	Alluvium	100	1,000	---	---
C/Tc/I	Volcanic/Alluvium	0	0	---	---

Source: YMP DTNs: LA0310AM831341.002, LA0003AM831341.001

strontium, in this case) as the major element cations within the zeolite structure (usually sodium, potassium, and calcium) (Pabalan and Bertetti, 2001).

3.4.9.5 Colloidal Transport

Colloids are small particles (less than 1 micrometer) that may facilitate the migration of contaminants in groundwater flow systems. Groundwater transport is strongly dependent on colloidal transport mechanisms. Colloids are composed of either organic matter or inorganic mineral material from the host rock. Oxides and hydroxides of actinide elements (e.g., plutonium) can also form as colloids (Kersting et al., 1998). Dissolved solids can be removed from solution and attached to colloids by ion exchange or by adsorption. Ramsay (1988) described three general cases for colloidal-facilitated contaminant transport:

- Uncharged colloid particles that migrate without retardation.
- Charged colloids that have the same charge as the surface charge of the aquifer medium, are thus repelled by the medium walls, resulting in a net increase in colloid flow velocity.
- Charged colloids that have the opposite charge as the surface charge of the aquifer medium, are thus attracted to the medium walls, resulting in a net retardation in colloid transport.

In the Rainier Mesa/Shoshone Mountain CAU, there are few wells presently available for the monitoring of geochemical data pertaining to colloidal transport (e.g., ER-12-1, Hagestad #1, ER-19-1, HTH #1). No information was gathered on colloidal transport during the regional evaluation (DOE/NV, 1997a). The only radionuclide considered at that time was tritium, which is not subject to colloidal transport. The E-, N-, and T-Tunnel systems have provided access to *in situ*, subsurface radionuclide contaminated water without the use of pumps. In 1998, LLNL and the Defense Threat Reduction Agency (DTRA) sampled unsaturated zone water from fractured volcanic tuffs in all three tunnels. Samples were analyzed for colloid content (as well as for groundwater composition, gamma-emitting radionuclides, plutonium, americium, and ^{90}Sr). It was found that low-solubility radionuclides detected in the unsaturated zone water strongly sorbed to the colloidal fraction of the groundwater and were not present in the dissolved phase (Kersting and Reimus, 2003). Specifically, the Pu detected in the groundwater is associated with the colloidal fraction, as was observed in the saturated fracture flow system at Pahute Mesa. Kersting and Reimus (2003) also report that the colloidal minerals identified in T-Tunnel are the same as those, with the exception of calcite, identified in the CHESHIRE and ER-20-5 groundwater samples. At present, no other documented sampling/analysis of groundwater at the Rainier Mesa/Shoshone Mountain CAU has been performed for colloidal transport.

At Pahute Mesa, colloids containing radionuclides have been detected in groundwater (DOE/NV, 1999). The mass concentration of colloids in groundwater from the CHESHIRE location was 10 milligrams per liter (mg/L) in a sample from the cavity region and 4 mg/L in a sample from the formation above the cavity (Buddemeier, 1988). The fraction of total radioactivity associated with colloids varied by radionuclide; some radionuclides were present in groundwater entirely as dissolved species (e.g., tritium), while others were predominantly associated with colloids (e.g., europium).

Water samples from Wells ER-20-5#1 and ER-20-5#3 near the TYBO location were analyzed for tritium, gamma emitters, and plutonium isotopes. A large fraction of the total activity from ^{60}Co, ^{137}Cs, $^{152,154,155}Eu$, and $^{239,240}Pu$ was shown to be associated with colloidal material. ^{241}Am is likely to be associated with colloids, and ^{90}Sr and ^{214}Pb may also be. The colloids examined were composed of clay, zeolites, cristobalite, and glass. This mineralogy is consistent with the host-rock mineralogy. Tritium moves unretarded with groundwater (Wolfsberg et al., 2002).

It was originally assumed that the radioactivity found in these water samples originated from TYBO, but evaluation of the isotopic data indicated the source was BENHAM, located about 1,300 m north of the ER-20-5 well complex. These results imply that plutonium had migrated an appreciable distance from the test location site (Kersting et al., 1998).

Additional information on the nature and behavior of colloids in groundwater at the NTS and the Yucca Mountain region are presented in Bryant (1992), Buddemeier and Hunt (1988), Kingston and Whitbeck (1991), Thompson (1989b), and Triay et al. (1997). Other colloid research and modeling activities that can be applied to the Rainier Mesa/Shoshone Mountain CAIP include Grindrod and Lee (1997), Mills et al. (1991), Penrose et al. (1990), Puls et al. (1991), Toran and Palumbo (1992), and Vilks et al. (1997).

3.5 Contaminants

This section includes descriptions of all known and/or inferred radioactive and hazardous substances present in the Rainier Mesa/Shoshone Mountain CAU. In addition, a description is also included of those substances that are considered potential contaminants based on the risks they pose to human health and the environment. Information on tritium is available in Section 6.0 of Volume V of the regional evaluation documentation package (IT, 1996g), and in Section 8.8 of the regional evaluation report (DOE/NV, 1997a).

3.5.1 Radioactive and Hazardous Substances Present

Three predominant types of substances are associated with the radiological source term. These include *in situ* materials, direct nuclear reaction products, and activation products. *In situ* materials are those contained within the device that have not undergone fission or fusion. Nuclear reaction products include the radioactive atomic nuclei that result from the fission of special nuclear material within the test package. Activation products result from the creation of radioactive isotopes from pre-existing stable isotopes due to neutron bombardment and neutron capture of materials used within the test and of the surrounding geologic media.

Table 3-27 lists materials commonly used in, or produced by, an underground nuclear test. During a given underground nuclear test, large quantities of materials used to support the test were introduced into the tunnels. These materials included steel used to support the device, lead and magnetite used as shielding material, and cement and gravel used to backfill the opening. Additionally, nuclear devices contain fissionable and fusionable radioactive elements in the critical mass used for detonation. These elements include uranium, plutonium, tritium, and lithium. Small amounts of radioactive detectors were also used. Incomplete consumption of these radioactive materials during detonation from testing would leave them within the subsurface for potential leaching to groundwater (Bryant and Fabryka-Martin, 1991).

3.5.1.1 Release Mechanisms

Radionuclides and other contaminants enter the groundwater system through a variety of mechanisms starting with the explosion of the nuclear device. To support the understanding of release mechanisms associated with underground nuclear tests, this section includes a generalized description

Table 3-27
Materials Involved in Underground Nuclear Testing

Fuels, Detectors, Tracers	Rack/Canister Materials	Organics	Drilling Stemming Materials
Americium	Aluminum	Alcohol	Bentonite
Curium	Arsenic	Anionic Polyacrylamide	Cement
Neptunium	Barite	Coal-Tar Epoxy	Gel
Plutonium	Beryllium	Complex Fluorescing Compounds[a]	Gravel
Tritium	Boron	Galacto-Mannans $(C_6 H_{10} O_5)_n$	Modified Starch
Uranium	Cadmium	Laser Dyes[a]	Neoprene®
Lithium	Chrome Lignosulfate	Liquid Anionic Polyelectrolyte	Polyethylene
Yttrium	Chromium	Paraformaldehyde	Pregelatinized Starch
Zirconium	Copper	Phenolic	Sand
Thallium	Gold	Polystyrene	Sepiolite
Lutetium	Iron	Polyvinyl Chloride	Soda Ash[b]
	Lead[c]	Two-Part Epoxy	Sodium Polyacrylate
	Lithium		Sodium Montmorillonite
	Magnetite[d]		Surfactant TF Foamer
	Nickel		Teflon™
	Osmium		
	Potassium Chloride		
	Sodium Hydroxide		
	Tantalum		
	Tungsten		
	Zinc		

Source: Bryant and Fabryka-Martin, 1991

[a]Fluorescing compounds and laser dyes used in some detector packages may contain potentially hazardous organic constituents.
[b]Contains theophylline, ethylenediamine, carbonic acid disodium salt.
[c]Extensive quantities of lead (57.2 metric tons) are typically used as shielding material for device canisters and racks.
[d]Magnetite is a naturally occurring iron oxide (Fe_3O_4) containing thorium and other heavy rare earth elements.

of nuclear explosion phenomenology. The early-time phenomenology describes initial explosive affects, test cavity void formation, and lithostatic rebound. The late-time phenomenology describes thermal and mechanical mechanisms that result in cavity collapse and breccia chimney formation. The distribution of contaminants in the subsurface during nuclear testing and their availability to transport in the groundwater are included in the discussion of late-time phenomenology.

Early Time Phenomenology

Sufficient energy is released during nuclear detonation to instantaneously vaporize the experiment canister and the rock surrounding the experimental package. Within microseconds of detonation the initial temperature rises to several million degrees Kelvin and the initial pressure rises to about 1 megabar. Within a few milliseconds the resulting shockwave crushes and fractures rock out to a distance of about two to three cavity radii beyond the initial cavity. Within tenths of a second the energy of the shockwave attenuates to equal and below the elastic limit of the rock, at which point the surrounding rock mass rebounds without permanent damage.

Rock material immediately adjacent to the explosion is vaporized and melted by the thermal and mechanical energy of the explosion. As the shockwave moves out radially, cavity growth slows. The size of the resultant cavity is dependant on the explosive yield of the nuclear device and on the strength of the surrounding rock. The cavity reaches its maximum size from 80 and 500 milliseconds after the detonation, depending on the yield. The surrounding rock mass rebounds radially about the circumference of the cavity in response to the passage of the shock wave. A compressive tangential hoop stress is formed when the stress field in the rebounded rock is greater than the cavity pressure.

The shock wave initially results in brittle rock failure which transitions into plastic rock deformation, and finally into elastic rebound. At about one third of the distance from the working point of the detonation and the ground surface, the shock wave becomes elastic and travels at the speed of sound through rock, reaching the surface within 100 to 500 milliseconds. The upward acceleration of material from the detonation point to the ground surface can cause surface bulges of 1 to 3 m, although the one test at Rainier Mesa (BLANCA) actually resulted in a 9 m surface bulge and the venting of radioactive gasses (Flangas and Rabb, 1961).

The final cavity pressure is not dependent on overburden pressure, but rather on the strength of the overlying rock. The cavity growth ceases when ambient hydrostatic overpressure within the cavity is equal to lithostatic pressure. The cavity stabilizes and dynamic motion ceases within a few seconds of the explosion.

Late Stage Phenomenology

Rock vapor begins to condense and forms a puddle of melted material at the bottom of the cavity after the shock wave and elastic rebound waves have dissipated. Water vapor and incondensable gases, such as carbon dioxide and hydrogen, are still present in the cavity. Thermal energy from the fireball is radiated into the rock walls and high thermal gradients are created in the rock mass surrounding the cavity by thermal conduction. Pressure within the cavity decreases due to condensation of vapor. Within minutes after the explosion, the high thermal gradient and the drop in cavity pressure causes ablation and spalling of wall material into the cavity. Clasts of wall rock fall into the puddle of melted rock in the bottom of the cavity, causing it to cool and quenching the liquid to glass. Cavity collapse starts within minutes to hours as the shattered rock in the roof falls into the cavity. Collapse propagates upward forming a breccia-filled chimney. If the material strength of the overlying rock is insufficient and the bulking factor of the resulting breccia is small, then collapse proceeds to the surface and a subsidence crater is formed.

Other Phenomena

Other phenomena related to underground nuclear testing have occurred, including hydrofracturing, prompt injection of radionuclides, mounding and pressurization of groundwater, reflection and refraction of seismic energy, and movement on preexisting faults. These phenomena may affect cavity growth, residual stress, collapse, and crater formation. However, reentry studies at Rainier Mesa indicate that true hydrofracturing is rare to nonexistent, and that prompt injection mostly occurs along preexisting planes of weakness, such as weak bedding planes, faults or fractures, or along the edges of blocks of rock moving due to block motion (BN, 2002a).

3.5.2 Potential Contaminants for the CAI

The potential contaminants for the CAI are defined as that set of contaminants that would cause risk to human health and the environment within the time frame of interest (1,000 years). A systematic approach was used to select the potential contaminants for the CAI.

A list of radioactive contaminants was established based on knowledge of radionuclides that are residual from underground nuclear testing. The list, shown in Table 3-28, includes 43 radiological contaminants (Bowen et al., 2001).

This list was used to derive a preliminary list of potential contaminants that are relevant to UGTA corrective action activities, as presented in Table 3-29.

Three criteria were used in formulating the preliminary list of potential radioactive contaminants shown in Table 3-29: (1) the number of atoms in the unclassified inventory, (2) the relative mobility of the radionuclide determined from historical field observations, and (3) the health effect of a radionuclide relative to a total body or organ dose. The health effects were obtained from a ranking

Table 3-28
List of Radionuclides Related to Underground Testing

Aluminum-26	Palladium-107
Americium-241	Plutonium-238
Americium-243	Plutonium-239
Argon-39	Plutonium-240
Cadmium-113m	Plutonium-241
Calcium-41	Plutonium-242
Carbon-14	Potassium-40
Cesium-135	Samarium-151
Cesium-137	Strontium-90
Chlorine-36	Technetium-99
Curium-244	Thorium-232
Europium-150	Tin-121m
Europium-152	Tin-126
Europium-154[a]	Tritium
Holmium-166m	Uranium-232
Iodine-129	Uranium-233
Krypton-85	Uranium-234
Neptunium-237	Uranium-235
Nickel-59	Uranium-236
Nickel-63	Uranium-238
Niobium-93m	Zirconium-93
Niobium-94	

Source: Bowen et al., 2001

[a]Short-lived radionuclide, half-life less than ten years

of radionuclides related to DOE and proposed EPA drinking standards. The preliminary list reflects an evaluation of each radionuclide against the above criteria, and represents radionuclides potentially of concern at sites contaminated by underground nuclear testing.

For the value of information analysis (VOIA) conducted for the Rainier Mesa/Shoshone Mountain CAU (SNJV, 2004b), a list of potential contaminants for the 1,000-year CAI time period was derived from the preliminary list. Table 3-30 lists the ten radioactive contaminants that were selected based on inventory estimates, health effects, and fate and transport information. This group of radionuclides was considered to be the most significant for predicting the contaminant boundary over

Table 3-29
Preliminary List of Potential Radioactive Contaminants for UGTA

Contaminant	Abbreviation	Half-Life (years)	Criteria
Americium-241	^{241}Am	432.7	Health
Carbon-14	^{14}C	5,730	Production, mobility
Cesium-137	^{137}Cs	30.17	Production, mobility
Chlorine-36	^{36}Cl	3.01×10^5	Mobility
Europium-152	^{152}Eu	13.48	Production
Europium-154	^{154}Eu	8.59	Production
Iodine-129	^{129}I	1.57×10^7	Mobility, health
Krypton-85	^{85}Kr	10.73	Mobility
Neptunium-237	^{237}Np	2.14×10^6	Mobility, health
Plutonium-239	^{239}Pu	2.41×10^4	Production, health
Plutonium-240	^{240}Pu	6.56×10^3	Production, health
Samarium-151	^{151}Sm	90	Production
Strontium-90	^{90}Sr	29.1	Production, health
Technetium-99	^{99}Tc	2.13×10^5	Mobility
Tritium	^{3}H	12.3	Production, mobility
Uranium-234	^{234}U	2.46×10^5	Production, health
Uranium-235	^{235}U	7.04×10^8	Production, health

Source: Smith, 1997

a 1,000 year time period. For this reason, the ten radionuclides were included in the simulations performed for the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b).

In addition to the ten radionuclides discussed above, other radioactive contaminants listed in Table 3-29 may be of potential concern to the Rainier Mesa/Shoshone Mountain CAU. The list of potential radioactive contaminants that will be included in simulations of the contaminant boundary for the Rainier Mesa/Shoshone Mountain CAU may be modified based on the findings of the CAI.

Lead is also a potential contaminant because it is known to be used in significant quantities in underground nuclear tests. In addition, lead is a contaminant cited in the *Resource Conservation and Recovery Act* (RCRA) (1996). It was assumed that any RCRA regulated volatile or semivolatile

Table 3-30
Estimated Concentration Range of Potential Radioactive Contaminants in Nuclear Test Cavity Groundwater

Isotope	Activity (Ci)	Minimum Concentration (Ci/m^3)	Maximum Concentration (Ci/m^3)	Half-Life (year)	Dose Conversion Factor (Sv/Bq)
tritium	764,500	0	2.15×10^{8}	12.32	1.73×10^{-11}
^{14}C	110.2	0	8.51×10^{4}	5,715	5.64×10^{-10}
^{36}Cl	11.3	0	873	3.01×10^{5}	8.36×10^{-10}
^{99}Tc	7.817	76.8	143	2.13×10^{5}	6.72×10^{-10}
^{137}Cs	37,730	1.48×10^{6}	2.75×10^{6}	30.07	1.34×10^{-8}
^{154}Eu	909	2.23×10^{3}	4.15×10^{3}	8.593	3.15×10^{-9}
^{235}U	0.1717	0.964	1.45	7.04×10^{8}	2.72×10^{-8}
^{237}Np	0.06027	0.169	0.254	2.14×10^{6}	6.38×10^{-7}
^{238}Pu	2,659	7.47×10^{3}	1.12×10^{4}	87.7	5.10×10^{-7}
^{241}Am	2,555	7.17×10^{3}	1.08×10^{4}	4.33×10^{2}	5.79×10^{-7}

Source: Modified from SNJV, 2004b

Ci/m^3 = curies per cubic meter
yr = years
Sv/Bq = sieverts per becquerel

organic compound would be consumed during the explosion, leaving only metals as potential contaminants.

Table 3-30 presents estimated concentration ranges for the potential radioactive contaminants evaluated in the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b). The residual radionuclide inventory remaining from the underground tests, which is expressed as curie activities for the six principal geographic test centers (including the Rainier Mesa/Shoshone Mountain CAU) can be found in Table V of Bowen et al. (2001). The radiological source term is assumed to be dissolved in a volume of water equal to the sum of the volumes of spheres defined by one cavity radius for each Rainier Mesa/Shoshone Mountain test. The estimated yield-based cavity radius for individual tests ranges from 5 to 71 m with a mean value of 34 m and a median value of 35 m. The mass sequestered in melt glass is assumed to be unavailable for dissolution and mobilization, and there is no reduction of volume for rubble or other cavity filling. Only those nuclides for which the concentration in microcuries per milliliter would be greater than 10 percent of the Maximum Permissible Concentration (MPC) proposed for drinking water by the EPA are retained for detailed transport calculations.

Further uncertainty into these calculations is introduced by the varying levels of accuracy in estimating residual activities. Bowen et al. (2001) states that the accuracies range from approximately 10 to 30 percent for fission products (i.e., ^{99}Tc, ^{137}Cs, ^{154}Eu), 20 percent or better for unspent fuel materials (i.e., ^{235}U, ^{237}Np, ^{238}Pu, ^{241}Am), 300 percent or better for residual tritium, and a factor of 10 for activation products (i.e., ^{14}C, ^{36}Cl). Based on these estimates, the minimum and maximum values for the concentrations of the nuclides of interest are calculated and shown in Table 3-30. Also shown are the dose conversion factors for an ingestion pathway. Note that the uncertainty estimates are conservatively applied using an arithmetic scale, which means that a 300 percent uncertainty translates to a range between ***x-3x*** and ***x+3x***, where ***x*** is the mean estimate.

3.6 Conceptual Model of the CAU

The conceptual model for the CAU is described in this section. Additional descriptions are provided in Section A.1.2.1.2 of Appendix A.

The conceptual model for UGTA CAUs is an interpretation or working description of the characteristics and dynamics of the physical system. For the UGTA investigations, the conceptual model is a simplified representation of important factors affecting the availability, release and discharge, and migration of contaminants. Central to the conceptual model, in terms of constructing a computer model, is a clear illustration of the fundamental elements of the groundwater flow system. As such, the conceptual model for the Rainier Mesa/Shoshone Mountain CAU includes descriptions of the contaminated media and of the release and discharge mechanisms from the underground test cavities and testing tunnels, descriptions of the potential migration routes from the Tuff Confining Unit (TCU) at Rainier Mesa and at Shoshone Mountain into the regional groundwater aquifer, and descriptions of exposure pathways associated with the contamination. While the groundwater flow system at Rainier Mesa and Shoshone Mountain contains many elements common to Yucca Flat and to Pahute Mesa, other parts of the flow system are unique. Elements of the Rainier Mesa/Shoshone Mountain CAU conceptual model are shown in Table 3-31. A schematic representation is shown in Figure 3-18.

Table 3-31
Summary Conceptual Model of the Rainier Mesa/Shoshone Mountain CAU

Conceptual Model Element	Description	Source
Groundwater Flow System	The groundwater flow system and down-gradient areas include groundwater below the water table from northern boundary of NTS south to Jackass Flats, and include Rainier Mesa, Shoshone Mountain, western Yucca Flat, and eastern Timber Mountain. Geologic units include bedded tuffs, welded tuffs, lava flows, Paleozoic carbonates, and Paleozoic clastic units. Aquifers include VA, BAQ, LCA, and LCA3, and confining units include TCU and UCCU.	Regional modeling results (DOE/NV, 1997a)
Contamination	Source terms from 67 underground nuclear tests constitute the sources of contamination for groundwater at Rainier Mesa and Shoshone Mountain. Potential contaminants include tritium, cesium-137, carbon-14, chlorine-36, technetium-99, europium-154 plutonium-238, uranium-235, americium-241, and neptunium-237.	Value of Information Analysis (SNJV, 2004b)
Current Extent of Contamination	The contamination is currently located within the test cavities. Vertical extent of the contamination is not believed to reach the LCA or LCA3.	HRMP reports Regional modeling results (DOE/NV, 1997a)
Future Extent of Contamination	The potential contaminants are predicted to dwell within the UZ, then infiltrate into groundwater and migrate south, southwest, and southeast. Lateral migration of contamination is not expected to reach NTS boundary within the 1,000 year time-frame. The direction and rate of contaminant migration will vary due to geologic variability and recharge variability.	Regional modeling results (DOE/NV, 1997a) Value of Information Analysis (SNJV, 2004b)
Current and Future Land Use	Rainier Mesa and Shoshone Mountain are reserved as nuclear test zones. The area down-gradient includes the southern part of NTS.	Environmental Impact Statement (DOE/NV, 1996a)
Potential Receptors	Off-site and on-site users of groundwater are potential receptors.	Environmental Impact Statement (DOE/NV, 1996a)
Potential Exposure Routes	Exposure routes include ingestion, dermal contact, and irradiation. For purposes of the CAI, the drinking water scenario is used in the definition of the contaminant boundary.	Regional evaluation (DOE/NV, 1997a)

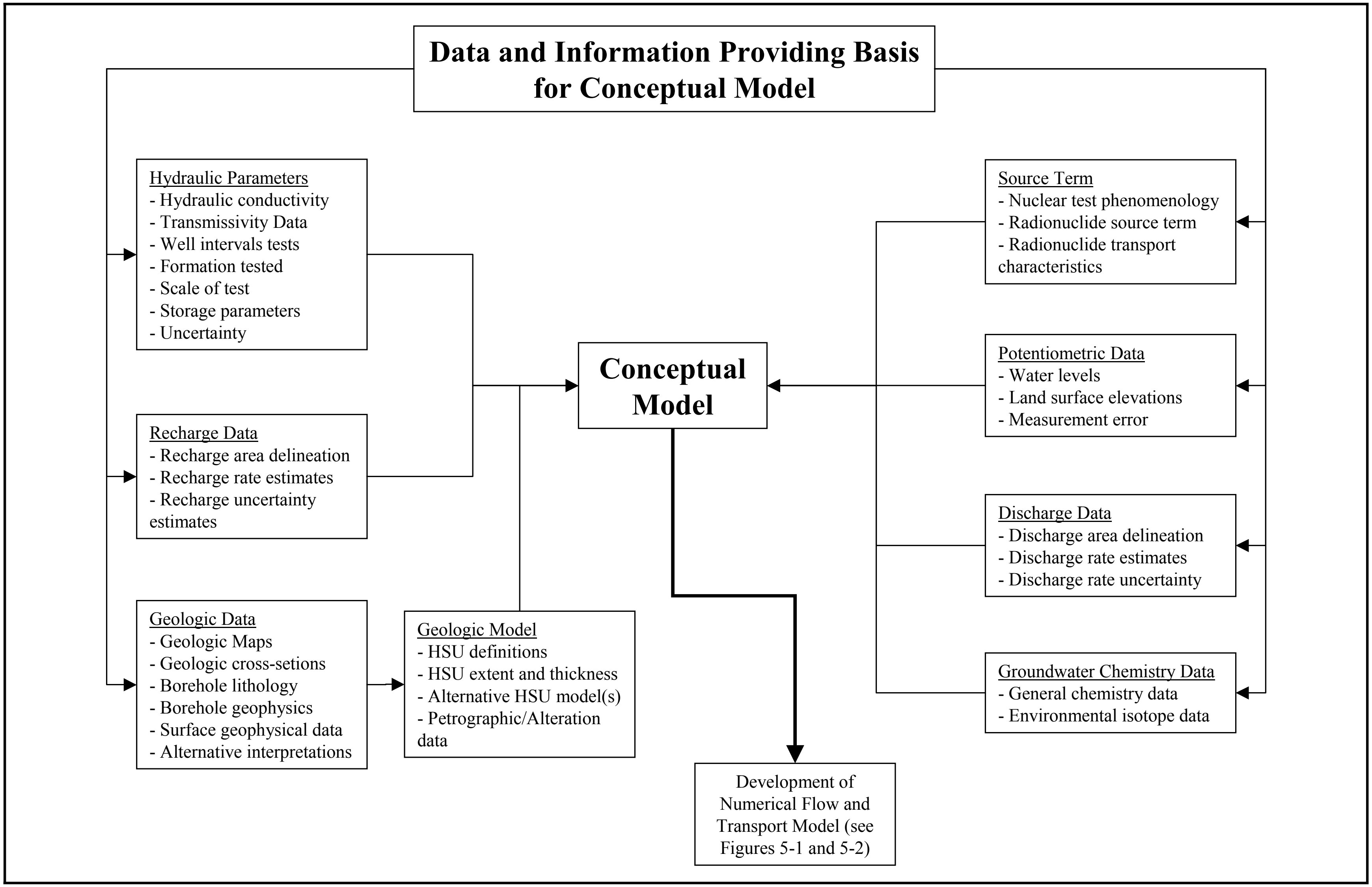


Figure 3-18
Elements of the Rainier Mesa/Shoshone Mountain CAU Conceptual Model

Many types of data are required to conceptualize groundwater flow and contaminant transport within a given site, including precipitation and recharge data, topographic data, groundwater chemistry and radiochemistry data, transport parameters, information on surface water, geology, hydrogeology, and the contaminant source. The current conceptual model of the Rainier Mesa/Shoshone Mountain CAU was developed during the DQO process described in Appendix A. The groundwater flow and contaminant transport component of the Rainier Mesa/Shoshone Mountain conceptual model was adapted from the regional model (IT, 1996b through h; IT, 1997; DOE/NV, 1997a) and developed for the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b). Specific sources of data for the conceptual model are presented in Table 3-32 and in Section A.2.0 of this document. Details of the climate and precipitation are discussed in Section 3.4.1. The topography and surface water are discussed in greater detail in Section 3.4.2 and Section 3.4.3, respectively. The details of the geology are addressed in Section 3.4.4, and hydrology is discussed in Section 3.4.6. Groundwater chemistry is discussed at length in Section 3.4.6 and groundwater radiochemistry in Section 3.4.8. Transport parameters are discussed in Section 3.4.9, and contaminants are discussed in Section 3.5. The salient features of the conceptual model are discussed below in the remainder of this section. However, the reader is referred to the previous sections of this chapter if additional details of the components of the conceptual model are required.

3.6.1 Release and Discharge

The nuclear test radionuclide release mechanism was described in Section 3.5.1.1. There are a variety of processes that contribute to the migration of radionuclides and other contaminants into the groundwater system from test cavities. Figure 3-19 presents a schematic diagram of the processes that result in radionuclides potentially entering the groundwater flow system from underground nuclear testing. These mechanisms are presented in the following sections.

3.6.1.1 Distribution and Release of Materials Related to Testing

The nuclear explosion phenomenology previously described is responsible for the observed distribution of materials that were introduced into the subsurface environment during testing. Radionuclides are not uniformly distributed in the chimney/cavity region, but are partitioned based on their physical and chemical characteristics. Smith (1993a) indicates that the partitioning can be described in terms of a three-stage condensation process. The refractory radionuclides (actinides),

Table 3-32
Sources of Information for Rainier Mesa/Shoshone Mountain Conceptual Model of Groundwater Flow and Contaminant Transport

Data Type	Location within CAIP	Reference within Regional Evaluation Documentation Package	Reference within Regional Model Report and VOIA Report
Precipitation	Sect. 3.1 (pg. 29) and Sect. 3.4.1 (pg. 38)	Sect. 3.0 through 11.00 (pg. 3-1 to 11-6); Specific to precipitation: Sect. 7.3.1 (pg. 7-5 to 7-12) of Volume III (IT, 1996c)	Sect. 5.7.1.2.1 (pg. 5-24 to 5-25) of the regional evaluation report (DOE/NV, 1997a)
Topography	Sect. 3.1 (pg. 29) and Sect. 3.4.2 (pg. 46)	Map F20 in Appendix F of Volume I (IT, 1996f)	Sect. 2.2 (pg. 2-1 to 2-4) of the regional evaluation report (DOE/NV, 1997a) and
Surface Water	Sect. 3.4.3 (pg. 47)	Sect. 5.0 (pg. 5-1 to 5-2), Sect. 8.0 (pg. 8-1 to 8-7), and Appendix A (pg. A-1 to A-26) of Volume III (IT, 1996c)	Sect. 5.7.2.1 (pg. 5-30 to 5-37) of the regional evaluation report (DOE/NV, 1997a)
Geology	Sect. 3.1 (pg. 30) and Sect. 3.4.4 (pg. 48)	Appendices C5 through C9 (pg. C5-1 to C9-15), and C15 (pg. C15-1 to C15-10) of Volume I (IT, 1996f); and Appendix B of Volume II (pg. B-1 to B-73) (IT, 1996e)	Sect. 4.0 (pg. 4-1 to 4-15) of the regional evaluation report (DOE/NV, 1997a)
Hydrostratigraphy	Sect. 3.4.5.1.1 (pg. 62) and Sect. 3.4.5.2.1 (pg. 70)	Appendices C5 through C9 (pg. C5-1 to C9-15), C15 (pg. C15-1 to C15-10), E2, and F of Volume I (IT, 1996f)	Sect. 4.0 (pg. 4-1 to 4-15), and Sect. 6.2.1 (pg. 6-2 to 6-11) of the regional evaluation report (DOE/NV, 1997a)
Hydraulic Conductivity	Sect. 3.4.5.1.1 (pg. 62) and Sect. 3.4.5.2.1 (pg. 70)	Sect. 3.0 to 8.0 (pg. 3-1 to 8-3), Appendices A and C of Volume IV (IT, 1996d)	Sect. 5.5 (pg. 5-4 to 5-12) of the regional evaluation report (DOE/NV, 1997a)
Hydraulic Conductivity Versus Depth	Sect. 3.4.5.1.1 (pg. 62)	Sect. 6.2 (pg. 6-3 to 6-12) of Volume IV (IT, 1996d)	Sect. 5.5.1.5 (pg. 5-9 to 5-12) of the regional evaluation report (DOE/NV, 1997a)
Water Levels	Sect. 3.4.5.1.2 (pg. 66) and Sect. 3.4.5.2.2 (pg. 76)	Sect. 3.0 through 10.0 (pg. 3-1 to 10-4), Appendix A (pg. A-1 to A-69), and Appendix C (pg. C-1 to C-54) of Volume II (IT, 1996e)	Sect. 5.6 (pg. 5-15 to 5-21) of the regional evaluation report (DOE/NV, 1997a)
Recharge	Sect. 3.4.5.1.2 (pg. 66) and Sect. 3.4.5.2.2 (pg. 76)	Sect. 3.0 through 11.00 (pg. 3-1 through 11-6) of Volume III (IT, 1996c) - Recharge-specific discussion in Sect. 7.3.2 (pg. 7-12 to 7-18)	Sect. 5.7.1 (pg. 5-22 to 5-30) of the regional evaluation report (DOE/NV, 1997a)
Groundwater Flow	Sect. 3.4.5.1.2 (pg. 66) and Sect. 3.4.5.2.2 (pg. 76)	Sect. 9.3.2 (pg. 9-6 to 9-8) of Volume II (IT, 1996e), and Volume VI of the regional evaluation (IT, 1996b)	Sect. 6.2.2 (pg. 6-12 to 6-32), Sect. 7.0 (pg. 7-1 to 7-99), Appendix B, and Appendix C of the regional evaluation report (DOE/NV, 1997a) and Sect. 1.1.2 of the VOIA report (SNJV, 2004b)
Porosity	Sect. 3.4.5.2.1 (pg. 70) and Sect. 3.4.9.1 (pg. 111)	Sect. 3.0 (pg. 3-1 to 3-12), Appendix A, Appendix B, and Appendix C of Volume V (IT, 1996g)	Sect. 8.5 (pg. 8-3 to 8-6) of regional evaluation report (DOE/NV, 1997a); and Sect. 3.2.4 of the VOIA report (SNJV, 2004b)
Dispersion Coefficient	Sect. 3.4.9.2 (pg. 115)	Sect. 4.0 (pg. 4-1 to 4-22) of Volume V (IT, 1996g)	Sect. 8.6 (pg. 8-6 to 8-9) of regional evaluation report (DOE/NV, 1997a) and Sect. 3.2.4 of the VOIA report (SNJV, 2004b)
Matrix Diffusion Coefficient	Sect. 3.4.9.3 (pg. 117)	Sect. 5.0 (pg. 5-1 to 5-3) of Volume V (IT, 1996g)	Sect. 8.7 (pg. 8-9 to 8-10) of regional evaluation report (DOE/NV, 1997a); and Sect. 3.2.4 of the VOIA report (SNJV, 2004b)
Contaminants	Sect. 3.5 (pg. 125)	Sect. 6.0 of Volume V (pg. 6-1 to 6-2) (IT, 1996g)	Sect. 8.8 (pg. 8-10 to 8-12) of regional evaluation report (DOE/NV, 1997a); Sect. 3.2.3 of the VOIA report (SNJV, 2004)
Contaminant Transport	Sect. 3.6.2 (pg. 140)	Volume VI of the regional evaluation (IT, 1996b)	Sect. 9.0 (pg. 9-1 to 9-54) of regional report (DOE/NV, 1997a); Sect. 4.5, 4.6, and 4.7 in the VOIA report (SNJV, 2004b)

Sect. = Section(s)   pg. = Page(s)

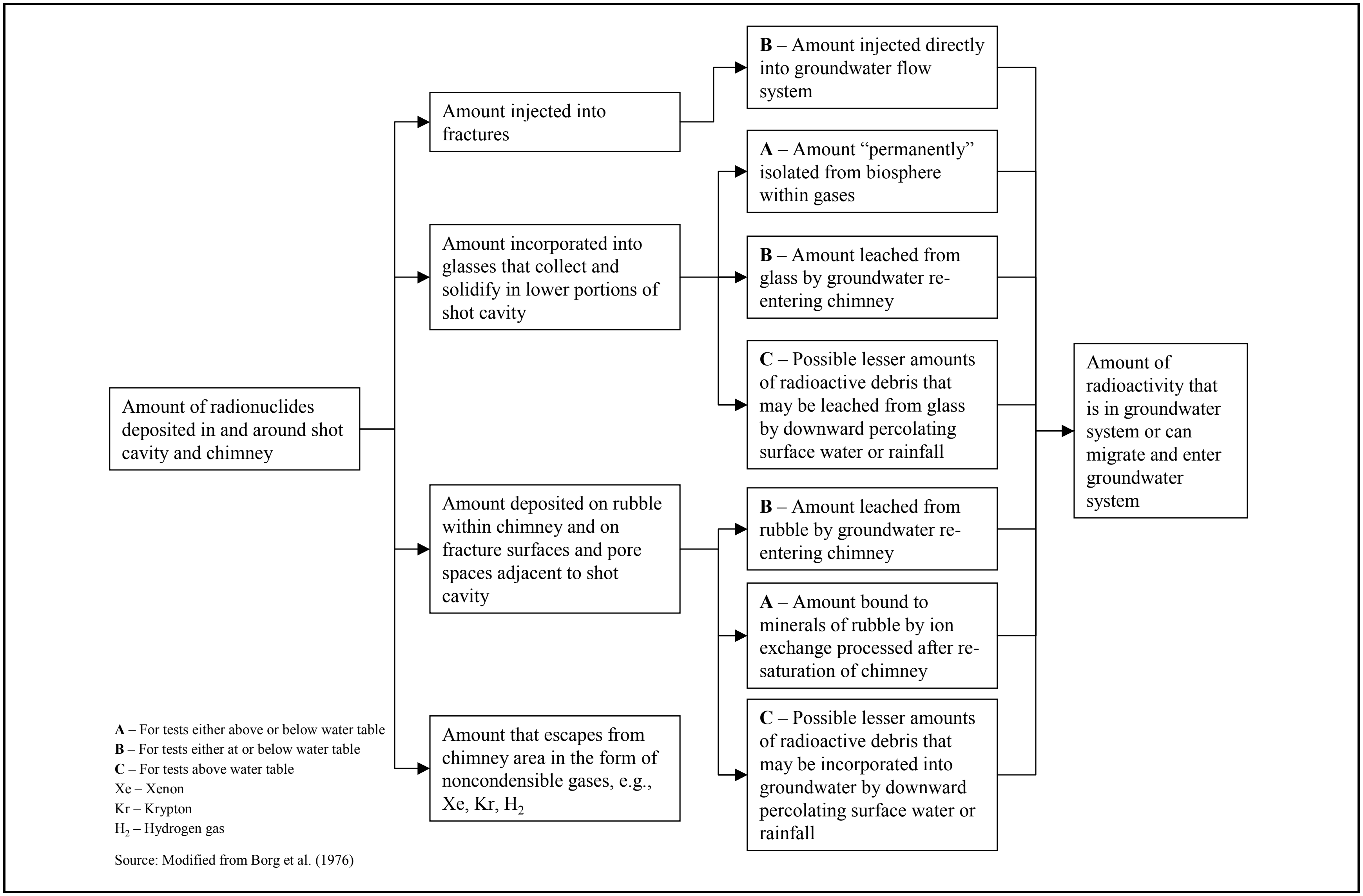


Figure 3-19
Contribution of Radionuclides from Underground Tests to Hydrologic Source Term and Groundwater Flow System

whose melting points are significantly greater than the melting temperature of the adjacent geologic media, are scavenged by the molten material that lines the cavity. These radionuclides are deposited within the melt glass that puddles in the bottom of the cavity. Further condensation occurs as cavity gas moves into the crushed rubble and fractured rock surrounding the test cavity. During this stage, the radionuclides of intermediate volatility, often with gaseous precursors (e.g., ^{137}Cs), condense and deposit on rubble and fracture surfaces. Final condensation occurs as residual gas ascends toward the ground surface. Condensation occurs during this stage, depositing radionuclides on rubble surfaces and on fracture walls. These processes fractionate the radionuclides such that heavier elements are concentrated within the melt glass at the base of the rubble chimney and the lighter elements are concentrated higher up within the chimney and within the fractured rock network enveloping the upper portions of the breccia chimney (Smith, 1993a). Tritium initially is distributed within the gas phase, and later forms tritium oxide steam (Smith, 1995).

During tests conducted at or below the water table, groundwater is evacuated from the test cavity and then slowly seeps back into the cavity after the detonation (Borg et al., 1976). Although all underground tests performed at Rainier Mesa and Shoshone Mountain were well above the static water table, perched groundwater typically seeped back into the test cavities and tunnels, potentially leaching radionuclides back into these areas. Where detonations were near or below the static water level, groundwater is impacted due to prompt injection of radionuclides into surrounding fractures. However, recent work indicates that prompt injection likely was not a factor in the underground tests at Rainier Mesa (BN, 2002a).

The distribution of radionuclides in the cavity/breccia chimney greatly influences the availability of potential contaminants for transport by groundwater. Radionuclides incorporated into the melt glass matrix are accessible to groundwater only through slow processes such as devitrification and glass dissolution. Other radionuclides are predominantly associated with surfaces and are accessible to groundwater through relatively fast processes such as ion exchange (Smith, 1995). Additionally, metals, drilling mud, and organic compounds may be left within or in close proximity to the test cavity/breccia chimney due to reentry operations. Non-radiological contaminants from these sources can also be leached into groundwater.

3.6.1.2 Discharge Mechanisms

Contaminants resulting from underground nuclear testing at Rainier Mesa and Shoshone Mountain may potentially migrate to the surface in groundwater. All underground nuclear tests at Rainier Mesa and Shoshone Mountain were conducted above the regional groundwater table. E-, N-, and T-Tunnels at Rainier Mesa encountered significant perched groundwater, which was initially discharged to holding ponds below the tunnels. This groundwater was contaminated with radionuclides. The engineered barriers were emplaced to seal the tunnels when operations ceased. Effluent no longer discharges from N- and T-Tunnels, and subsequent studies have monitored the impounded water within these tunnels (Russell et al., 2003). At E-Tunnel, the barriers were not successful in stopping the discharge. The E-Tunnel discharge, which flows into ponds below the muckpile, is permitted under Nevada Water Pollution Control Permit, NEV 96021 (NDEP, 2002). E-Tunnel discharge water quality is monitored in accordance with the permit.

No regional groundwater discharge occurs within the Rainier Mesa/Shoshone Mountain vicinity, but several springs and seeps are present that discharge perched water. The perched groundwater from the springs in the Rainier Mesa and the Shoshone Mountain area have been sampled for radionuclides that might have originated from the underground nuclear testing activities. Annual sampling of Captain Jack Spring, Gold Meadows Spring, White Rock Spring, and Tippipah Spring for the NTS Annual Site Environmental Report have failed to detect radiation values above natural background concentrations (REECo, 1991, 1992, 1993, 1994, 1995; BN, 1996b, 1997b, 1998a).

Perched groundwater might potentially percolate into the regional groundwater and eventually travel to discharge sites located in the Amargosa Desert and in Death Valley (DOE/NV, 1997a). All underground tests at Rainier Mesa and Shoshone Mountain were conducted within the nonwelded zeolitized tuffs of the TCU in the unsaturated zone. Groundwater flow within these rocks is restricted to perched groundwater percolating through fractures in the tuff (BN, 2002a). Although both infiltration through the TCU is believed to be slow and secondary minerals that form along fractures can potentially retard radionuclide migration, the conceptual model assumes all radionuclide contaminant migration commences at the static water table below the TCU. This boundary condition of the conceptual model results in travel times that are likely to be faster than the actual travel times, and yields contaminant concentrations that are likely to be higher than the actual concentrations.

3.6.2 Migration of Contaminants

In order for human receptors to be exposed to radionuclides leached or injected into groundwater near the underground nuclear test locations, a transport or migration mechanism must be present. For contaminants generated by underground nuclear testing at Rainier Mesa and Shoshone Mountain, the most probable migration pathway is the regional groundwater flow system. A summary of the current understanding of the groundwater flow paths and travel times is presented in this section. The fundamental elements of the groundwater flow system as it relates to the conceptual model of contaminant transport at Rainier Mesa and Shoshone Mountain include the groundwater flow paths, contaminant concentrations and contaminant travel times, contaminated media, and exposure pathways. Each of these elements is discussed in greater detail below.

3.6.2.1 Groundwater Flow Paths

In the regional modeling simulation (DOE/NV, 1997a), groundwater flow paths passing through the Rainier Mesa/Shoshone Mountain underground nuclear test sites are predicted to cross the southern NTS boundary in the vicinity of Jackass Flats and enter the Amargosa Desert (Figure 3-20). Based on particle-tracking simulations conducted during the VOIA (SNJV, 2004b), themselves based on the calibrated regional groundwater flow model (DOE/NV, 1997a), most of the groundwater flow paths reach the AA of the Amargosa Desert on their way to Death Valley discharge areas. Because the hydrostratigraphy at the water table at Rainier Mesa and Shoshone Mountain is highly uncertain, the estimated flow paths or pathlines are also uncertain. Pathlines at Rainier Mesa bifurcate, with the eastern-most pathlines diverting to the east into Yucca Flat, while the western-most pathlines go into the Timber Mountain Caldera Complex, then go south in the Fortymile Canyon area. A smaller number of the pathlines go to the south, parallel to and east of the Fortymile Canyon pathlines. The pathlines originating from Shoshone Mountain (e.g., GUM DROP) make a short jog to the northeast before resuming a southwesterly direction (Figure 3-21).

As an example of a flow path from Rainier Mesa, a particle-tracking simulation was completed for a particle originating at the regional water table beneath CLEARWATER at Rainier Mesa (DOE/NV, 1997a). The particle traveled through the LCCU, nonwelded tuffs of the BCU, and welded tuffs of the BAQ before entering the TMA within the Timber Mountain Caldera moat. There the particle traveled south within the moat, crossed the LCCU in the upper plate of the Belted Range

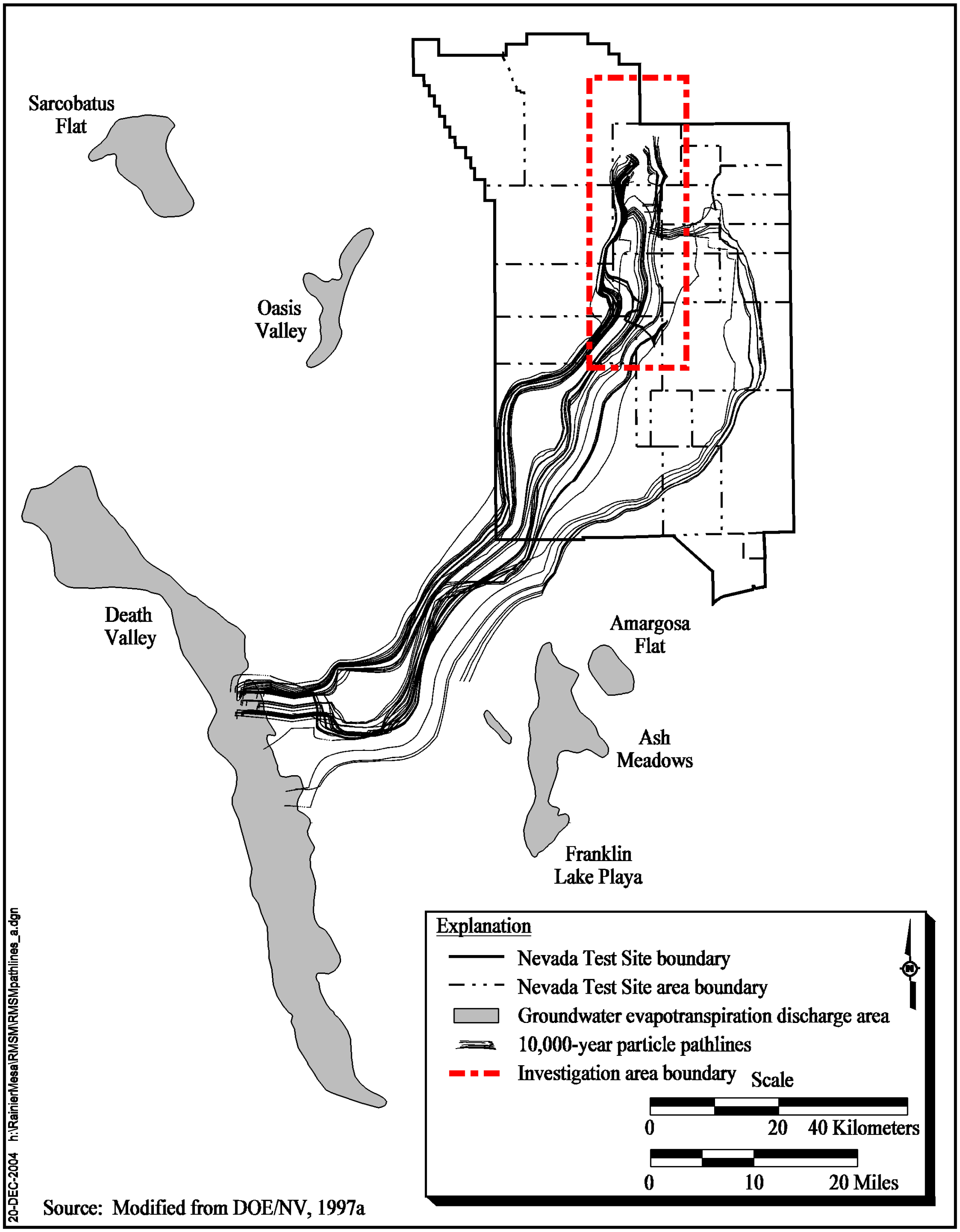
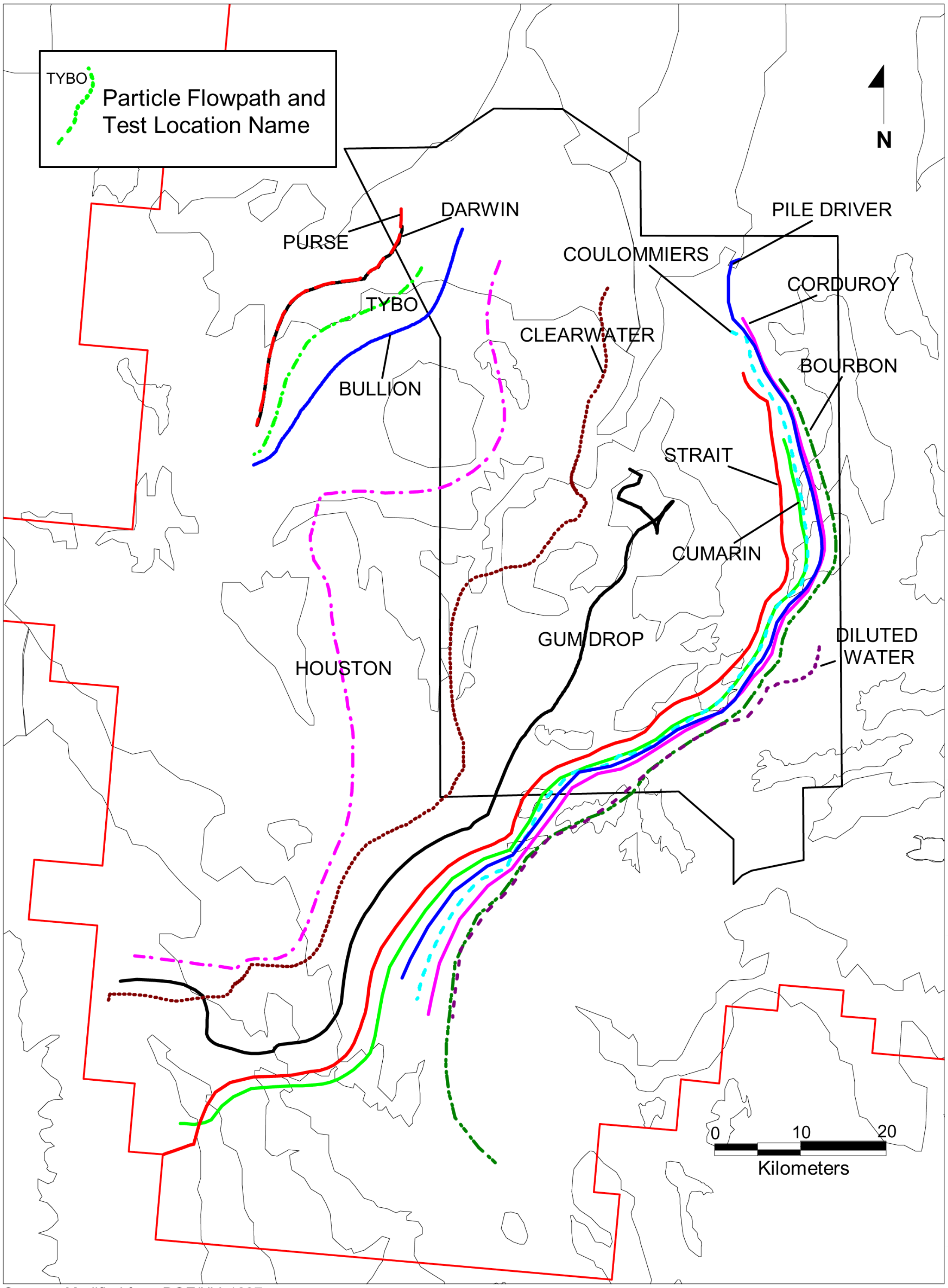


Figure 3-20
Pathlines from Rainier Mesa and Shoshone Mountain Test Locations Based on Regional Flow Model



Source: Modified from DOE/NV, 1997a

Figure 3-21
Pathlines for Particles Originating at CLEARWATER on Rainier Mesa and GUM DROP on Shoshone Mountain

thrust and into the LCA just north of the Calico Hills. It then passed through the UCCU and back into the LCA just east of Yucca Mountain where it remained until reaching the Funeral Mountains. At the Funeral Mountains it passed through the LCCU and the Tertiary Sedimentary Death Valley (TSDV) unit before discharging in the AA (DOE/NV, 1997a) (Figure 3-21).

3.6.2.2 Contaminant Concentrations and Travel Times

Tritium transport simulations (one-dimensional) were performed along one pathline relating to CLEARWATER at Rainier Mesa using the regional contaminant transport model (DOE/NV, 1997a; IT, 1996h). The source of contamination originating from the test was assumed to correspond to finite volumes of tritiated water occupying spherical volumes calculated using the cavity radii. Average tritium concentrations based on unclassified data were assumed for these sources. Simulations included the effects of parameter uncertainty via a Monte Carlo approach. Parameters that varied during the Monte Carlo simulations include groundwater flux, effective porosity, dispersion coefficient, matrix diffusion, and initial tritium concentration at the source. This test was representative of a transport path from Rainier Mesa. The tritium transport simulation was begun at the water table and did not simulate a delay based on passage of contaminants through the UZ. As such, this simulation represented a conservative scenario, based on the model parameters, rather than a realistic representation of actual travel time. During this simulation the tritium particle traveled 1.55 km down gradient from the point of origin in 100 years. The time frame of 100 years was chosen for this simulation based on the time frame in which tritium remains in the groundwater. Beyond 100 years, radioactive decay of the relatively short half-lived tritium will have largely eliminated itself as a contaminant.

Transport simulations for other radionuclides were performed in support of the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b). All radionuclides of concern listed in Table 3-30 were initially considered, but six of them were ultimately used to define the predicted contaminant boundary. These radionuclide contaminants include tritium, ^{14}C, ^{99}Tc, ^{36}Cl, ^{137}Cs, and ^{238}Pu. These elements represent unspent weapons fuel, activation products, fission/fusion products, as well as heavy refractory elements, light volatile elements, and intermediate-mass elements. Sensitivity analysis revealed that the key uncertain parameters are Darcy flux and path length in the BCU (the LCCU contained in the upper plate of the Belted Range thrust). Marginally important parameters include the UZ delay time, initial contaminant concentration, dispersivity in the BCU, fracture porosity and path length in the LCA3, and the probability of fracture porosity in the BCU.

3.6.2.3 Contaminated Media

Contaminated media include subsurface rock, and groundwater within perched aquifers in the UZ. Contamination within the UZ may be transported vertically (downward) to the saturated zone with infiltrated water from precipitation. In general, the rate of contaminant migration relative to the net infiltration rate of precipitation in the UZ is expected to be comparatively slow as a result of retardation effects (e.g., sorption/diffusion of contaminants onto/into host rock, colloidal suspension of contaminants, and gradual leaching of contaminated rock). At the NTS in general, UZ flow and transport processes have not been sufficiently characterized to permit the accurate estimate of contaminant transport pathlines and travel times through the UZ at Rainier Mesa. For example, the Rainier Mesa/Shoshone Mountain VOIA applies a probabilistic delay time for contaminants to reach the saturated zone from the UZ source to capture the large uncertainty associated with UZ contaminant transport (SNJV, 2004b). Because contaminant transport within the saturated zone both has the potential for more rapid transport than in the UZ and is well characterized relative to the UZ, saturated zone groundwater transport is the primary focus of this CAI.

The portion of the perched groundwater flow system that has flooded the test tunnel complexes is contaminated. Any portion of the UZ below the flooded tunnels and below other test cavities is potentially contaminated. The regional groundwater is potentially contaminated at test locations where the zone of fractured rock resulting from the underground nuclear test overlaps with the regional groundwater table. The portion of the groundwater flow system down-gradient of the test areas that potentially is contaminated includes the groundwater below Rainier Mesa, Shoshone Mountain, and Yucca Flat. Geologic units within this area include bedded tuffs, nonwelded ash-flow tuffs, fractured welded tuffs and lava flows, fractured Paleozoic carbonate and siliciclastic rocks, and Precambrian siliciclastic rocks. Details of the geology and hydrogeology are discussed in Section 3.4.4 and Section 3.4.5 of this document.

Lateral and vertical extent of groundwater contamination was estimated using the regional model (DOE/NV, 1997a). The contaminants are currently located within the vicinity of the test cavities and tunnels at Rainier Mesa and Shoshone Mountain. Within a 100 year time frame the contamination is modeled to travel no more than 1.5 km from the test location, assuming that the contamination starts from within the regional groundwater table. A detailed discussion of the contaminants is provided in Section 3.5 of this document.

3.6.2.4 Exposure Pathways

Rainier Mesa and Shoshone Mountain are two of the six nuclear test areas on the NTS, and access to the NTS is restricted. The Nevada Test and Training Range (formerly the Nellis Air Force Range) lies to the east, north, and northwest of the NTS, and is used for military training for which public access is also restricted. U.S. Department of the Interior, Bureau of Land Management (BLM) land borders the NTS to the south and west, where public access is available and recreation, mining, and grazing activities occur.

On-site and off-site users of groundwater are the potential receptors. On-site workers and site visitors are potential receptors from on-site water supply wells. On-site receptors are potentially exposed to radionuclides and other hazardous materials in groundwater through ingestion, dermal contact, irradiation, and inhalation of volatile radionuclides. The existing monitoring program of the on-site water supply wells limits the potential for this exposure scenario. Environmental receptors potentially are exposed to pumped groundwater at on-site surface impoundments. This potential exposure is likely localized and limited in time. Receptors associated with off-site springs and wells include plants, animals, and area residents. Off-site human receptors may be exposed to the potential contaminants from ingestion, dermal contact, irradiation, and inhalation of volatile radionuclides. For the purpose of this CAI, the worst-case scenario of drinking water ingestion is considered in the definition of the contaminant boundary as explained in Section 2.1.2.2.1.

3.6.3 Uncertainties

The current conceptual model of the Rainier Mesa/Shoshone Mountain CAU has several areas of uncertainty. These are:

- A lack of subsurface geologic characterization for the entire Rainier Mesa/Shoshone Mountain area, and a lack of hydrologic characterization in many specific areas
- Insufficient characterization of the hydrochemical framework of the Rainier Mesa/Shoshone Mountain area

- Limited knowledge of the contaminant transport and associated parameters
- Limited understanding of the contamination sources

3.7 Preliminary Corrective Action Levels

Regulatory and health-based PALs for the potential contaminants are provided in this section. The PALs are provided for groundwater because groundwater is the sole transport medium and exposure route for the contamination resulting from underground nuclear testing.

A PAL is the concentration of a contaminant in drinking water that will result in an acceptable dose level to a member of the public. The PALs for the potential contaminants evaluated in the Rainier Mesa/Shoshone Mountain VOIA are presented in Table 3-33 (SNJV, 2004b). The PAL for lead is also included. The PALs for tritium, uranium, and lead are the Maximum Contaminant Levels (MCLs) explicitly stated in Title 40 Code of Federal Regulations (CFR) Part 141 (CFR, 2004d). The PALs for the other (eight) potential contaminants are calculated as a fraction of the their respective MCLs. The 4 mrem/year MCL standard applies to a combined dose of the eight remaining potential contaminants. The isotopic combination in the dose is unknown; therefore, the PAL for each contaminant is conservatively assumed to be ten percent of its MCL. The isotope-specific MCLs for the beta- and photon-emitting isotopes are calculated using the 168 hour work week data list in “Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure,” NBS (National Bureau of Standards) Handbook 69, and Occupational Radiation Limits (ORLs) specified in EPA (1976).

Table 3-33
Preliminary Action Levels for Potential Contaminants

Contaminant	Maximum Contaminant Level[a]	Preliminary Action Level
Americium-241	15 pCi/L	1.5 pCi/L[c]
Carbon-14	2,000 pCi/L	200 pCi/L[c]
Cesium-137	200 pCi/L	20 pCi/L[c]
Chlorine-36	700 pCi/L	70 pCi/L[c]
Europium-154	60 pCi/L	6 pCi/L[c]
Lead	15 µg/L	15 µg/L[b]
Neptunium-237	15 pCi/L	1.5 pCi/L[c]
Plutonium-238	15 pCi/L	1.5 pCi/L[c]
Technetium-99	900 pCi/L	90 pCi/L[c]
Tritium	20,000 pCi/L	20,000 pCi/L[b]
Uranium-235	30 µCi/L	30 µCi/L[b]

[a]The regulatory source for all MCLs is 40 CFR Part 141 (CFR, 2004d)
[b]The PAL is equal to the MCL as explicitly stated in 40 CFR Part 141 (CFR, 2004d)
[c]The PAL is conservatively estimated as ten percent of the MCL

Note: Lead as a potential contaminant is representative of other inorganic, nonradioactive, hazardous constituents. According to Bryant and Fabryka-Martin (1991), lead was used in quantities of tens of tons in underground nuclear tests, while other inorganic, potentially hazardous substances were used in kilograms or smaller quantities. Generally, the introduced quantities are on the same scale as the quantity that would melt in the rock as a result of the detonation.

µg/L = micrograms per liter
pCi/L = picocuries per liter

4.0 Summary of Data Quality Objectives

A summary of the DQO process is presented in this section and detailed in Appendix A. The summary includes a discussion of the DQO approach and the results. In addition, a discussion of how the results of the DQO process relate to the conceptual model of the CAU and the migration routes is presented.

4.1 Data Quality Objectives Approach

The purpose of the DQO process is to define the environmental problem to be solved, identify the information needed to solve the problem, and then identify an investigation program to gather the missing information. The approach of the DQOs used for the Rainier Mesa/Shoshone Mountain CAU was a logical, orderly progression that resulted in a clear definition of the data needed and the corresponding work activities needed to achieve the ultimate objective of the Rainier Mesa/Shoshone Mountain CAI. As Section 1.1 stated, this objective is the prediction of the contaminant boundary at an acceptable level of uncertainty. A VOIA was conducted in support of the DQO process (SNJV, 2004b). The VOIA focused on the assessment of activities that could be undertaken to reduce the uncertainty in the prediction of a contaminant boundary for the Rainier Mesa/Shoshone Mountain CAU. The regional model (DOE/NV, 1997a) and the FFACO (1996) were used to support the DQO process (see Section A.1.1 of Appendix A).

The approach consists of three major steps consistent with the three-step method (EPA, 1987). Although the approach does not match the seven-step method (EPA, 1993 and 2000), it offers similarities. A comparison of the method used and its relation with other methods is presented in Figure 4-1.

The first step in the process is the *formulation of a statement of the decision to be made*, which includes the identification of the potential contaminants, a decision of the current conceptual model of the problem area including areas of uncertainty, and a statement of the decision at hand. This step corresponds to the first, second, and fourth steps of the seven-step process (i.e., state the problem, identify the decision, and define the boundaries of the study).

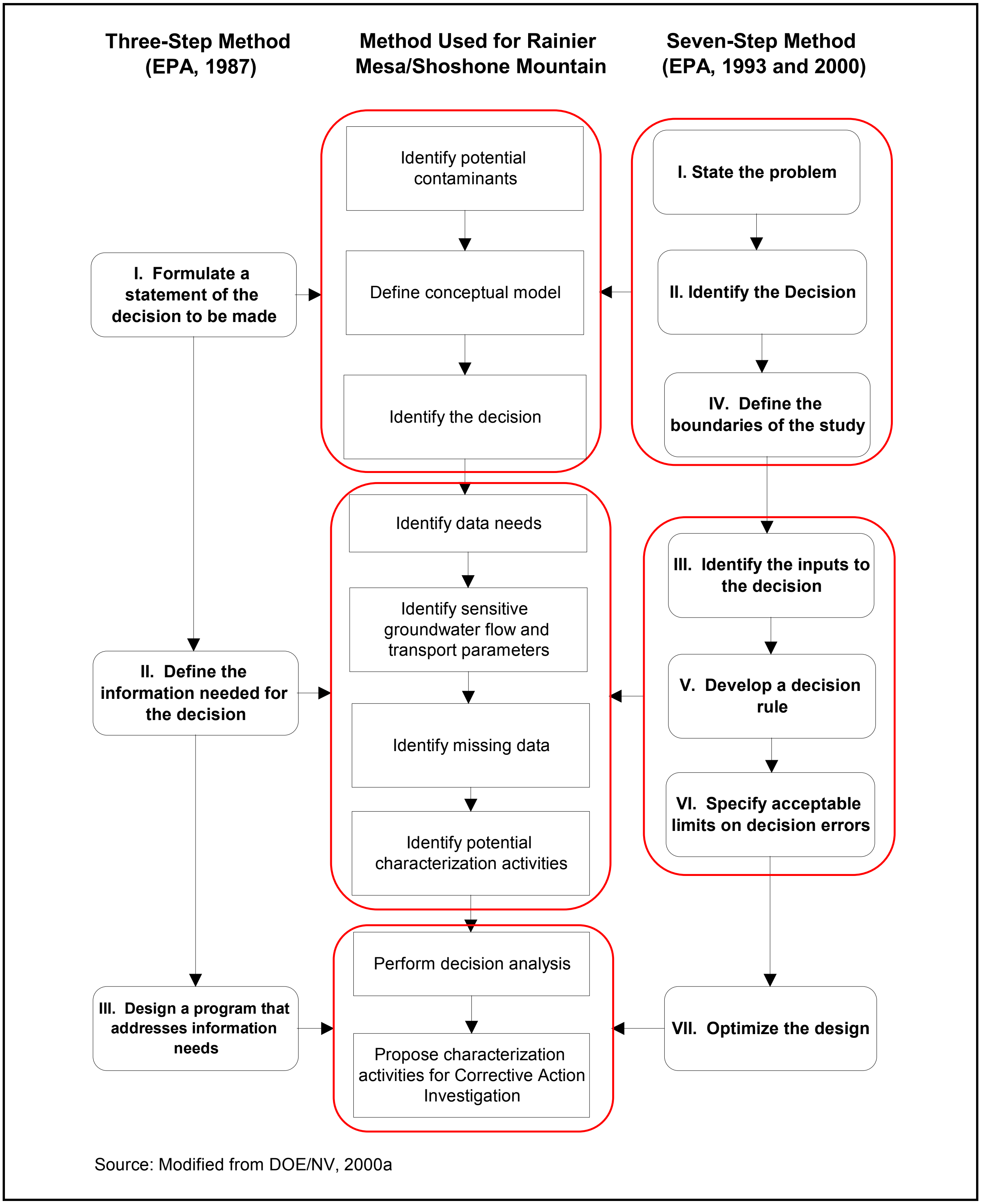


Figure 4-1
Comparison of Data Quality Objectives Process Used for Rainier Mesa/Shoshone Mountain with the EPA DQO Methods

The second step in the process is the *definition of the information needed for the decision*, which includes the identification of the necessary data, the sensitive groundwater flow and transport parameters, and the additional data needed and associated characterization activities. This step corresponds to the third, fifth, and sixth steps of the seven-step process, to identify the inputs to the decision, develop a decision rule, and specify acceptable limits on decision errors.

The third and last step in the process is the *design of a program that addresses information needs*. This step corresponds to the seventh step of the seven-step process, (i.e., optimize the design by conducting a decision analysis and selecting candidate characterization activities for the acquisition of the missing information).

4.2 Data Quality Objectives Process Results

The DQO process included several steps which were conducted to plan the CAI for the Rainier Mesa/Shoshone Mountain CAU. The results of each step are provided in this section.

4.2.1 Formulation of a Statement of the Decision to be Made

In the first step of the process, the potential contaminants were identified, the current conceptual model of the problem area was described, and a statement of the decision at hand was made.

- A list of the major potential contaminants is provided in Table A.1-2 (Appendix A).
- The current conceptual model is based on the regional model (DOE/NV, 1997a) and the VOIA (SNJV, 2004b), and is described in Section 3.6 and Appendix A of this document. Supporting information are presented in Sections 3.3, 3.4, and 3.5 of this document.

As discussed in Appendix A, the current CAU conceptual model has several uncertainties, as listed in Section 3.6.3.

- Limited understanding of the contamination sources

Based on the information on the potential contaminants and the current CAU conceptual model, a statement of the decision was made as follows: *Can an acceptable groundwater flow and transport model be formulated for the Rainier Mesa/Shoshone Mountain area using the existing data?*

4.2.2 Definition of the Information Needed for the Decision

In the second step of the DQO process, data needs, sensitive groundwater flow and transport parameters, missing data, and characterization activities were identified.

The information needed for the decision is the data necessary to develop a groundwater flow and contaminant transport model of the Rainier Mesa/Shoshone Mountain area with an acceptable level of uncertainty. The required information includes geologic data, groundwater data on contamination concentrations, contaminant source data, and information on the controlling processes of contaminant migration in groundwater. As stated before, similar information was gathered during the regional evaluation (DOE/NV, 1997a) and the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b). These data were used to define the current conceptual model described in the first step of the DQOs. The areas of uncertainty that exist in this conceptual model correspond to data gaps and information gaps identified during the regional evaluation (DOE/NV, 1997a). These include data gaps in uncharacterized portions of the study area and information gaps about contaminant sources and contaminant transport processes. Based on these areas of uncertainty, it was determined that an acceptable groundwater flow and contaminant transport model could not be formulated for the Rainier Mesa/Shoshone Mountain flow system using only the existing data. Additional data were deemed necessary to address the areas of uncertainty.

To prioritize the data needs, sensitivity analyses were conducted on the regional contaminant transport model. The sensitivity analyses were performed to determine which groundwater flow and transport parameters have the most effect on the location of the contaminant boundary.

There are several areas of uncertainty in defining the parameter values for modeling transport on flowpaths from Rainier Mesa/Shoshone Mountain. These are:

- The effective porosity of the Lower Carbonate Aquifer (LCA) is not known
- The Unsaturated Zone (UZ) delay factor is unknown
- The extent of fracture-dominated fast-pathways through confining units is unknown
- Mineral interaction and matrix diffusion in the UCCU and the LCA are poorly known

- A lack of subsurface geologic and hydrogeologic characterization for Rainier Mesa, and particularly for Shoshone Mountain

Sensitivity analysis conducted during the DQO revealed that the key uncertain parameters are Darcy flux and path length in the BCU (the LCCU contained in the upper plate of the Belted Range thrust). Marginally important parameters include the UZ delay time, initial contaminant concentration, dispersivity in the BCU, fracture porosity and path length in the LCA3, and the probability of fracture porosity in the LCCU of the hanging wall of the Belted Range thrust.

A VOIA was performed to determine what characterization options are best suited to improve the conceptual model of the Rainier Mesa/Shoshone Mountain area. Characterization options included individual activities and groups of activities designed to reduce uncertainty in sensitive parameters. A list of the individual activities is provided in Table A.1-4 (Appendix A). All characterization options are described in detail in the VOIA report (SNJV, 2004b).

All data collected during these activities for purposes of improving the CAU model of the Rainier Mesa/Shoshone Mountain areas must be collected using stringent QA procedures specified in a Quality Assurance Project Plan (QAPP).

4.2.3 Design of a Program that Addresses Information Needs

Further analyses conducted during the VOIA (SNJV, 2004b) and the results of the regional evaluation (DOE/NV, 1997a) were then used as tools to design a program that addresses the information needs.

During the VOIA (SNJV, 2004b), the characterization options identified in the second step of the DQO process were evaluated and compared with respect to their cost and potential to reduce uncertainty associated with the contaminant boundary. As part of the VOIA, the execution costs of the characterization options were compared with their usefulness in reducing uncertainty, and the options were ranked.

Characterization activities were selected for inclusion in the Rainier Mesa/Shoshone Mountain CAI based on the results of the VOIA (SNJV, 2004b) and other DOE concerns and responsibilities. All characterization data collected during these activities for purposes of developing the CAU model of the Rainier Mesa/Shoshone Mountain area will be in compliance with the UGTA QAPP

(NNSA/NSO, 2003). The selected characterization activities are listed in Table A.1-5 (Appendix A) and described in Section 6.1. Brief summary descriptions of the selected activities are described below.

Characterization Activity - Drill Holes

Two drill holes are planned for the Rainier Mesa area and one drill hole for the Shoshone Mountain area. One drill hole will be drilled in the axis of a synform in the Paleozoic rocks southwest of the N-Tunnel. This structure is probably a syncline, or less likely an overturned anticline, although this will be determined from the rock samples returned during drilling. A second drill hole will be placed southwest of T-Tunnel. These drill holes are located downgradient from the potential source of the contamination in N- and T-Tunnels, and will assist in characterizing potential flow paths within the saturated zone of the regional groundwater, as well as characterizing the tuffs between the test horizon within the Tunnel Formation and the Paleozoic rocks. The drill hole at Shoshone Mountain will be located south or southwest of the test tunnels and downgradient from the contamination, and will assist in characterizing potential flow paths in the saturated zone as well as the tuffs in the UZ.

Characterization Activity - Sample New Drill Holes and Existing Locations

Water samples from the new and existing locations will be analyzed for radionuclides in order to characterize actual contaminant migration within the perched water and within the regional groundwater. Major cations and anions will be analyzed to characterize perched water and regional groundwater beneath Rainier Mesa and Shoshone Mountain. The studies will support modeling the small-scale hydrologic source term for the CAU-scale model. Stable isotopes will be analyzed to characterize the perched water and potential recharge from Rainier Mesa and Shoshone Mountain. Stable isotopes and major element geochemistry data will assist in characterizing groundwater flow paths for both perched water and regional groundwater. Rock samples collected from the new drill holes will be used to characterize the fracture network and secondary alteration minerals in the tuffs beneath the test horizon and within the Paleozoic rocks beneath the tuffs. Determining fracture density within the siliciclastic rocks in the UCCU bears on how this unit is treated in the CAU-scale model.

Characterization Activity - Evaluate Geophysical Information

This activity includes the analysis of seismic data, gravity data, magnetic data, and down-hole geophysical logs. Analysis of down-hole geophysical logs will assist characterizing tuffs within the TCU and the VA, and the Paleozoic rocks within the UCCU, LCA3, and LCA in regard to porosity, permeability, potential fracture density, and saturation levels above and below zones of perched water. Analysis of existing seismic data will be used to characterize the 3-D extent and distribution of the surfaces formed by contacts between and within the volcanic and Paleozoic rocks. Key features such as faults, formational pinchouts, and juxtapositions will be investigated throughout the Rainier Mesa and Shoshone Mountain area. This activity entails analysis of existing data and acquisition of new data.

4.3 Relationship Between Data Collection Activities and Conceptual Model

The proposed characterization activities resulting from the DQO process will improve the conceptual model of the Rainier Mesa/Shoshone Mountain area. The activities are designed to improve the understanding of the geology and hydrology of the Rainier Mesa/Shoshone Mountain area, the contaminant transport processes at work in the area, and the sources of contamination. Improved understanding of the conceptual model of the Rainier Mesa/Shoshone Mountain area will lead to the development of a more reliable numerical groundwater flow and contaminant transport model. Contaminant transport model predictions made with such a model will lead to more reliable simulations of the migration routes and a more reliable location for the contaminant boundary.

The first characterization activity, the drilling of new boreholes, will address major uncertainties within the geologic framework of the Rainier Mesa/Shoshone Mountain area. These three drill holes will allow characterization of the Paleozoic strata comprising the LCA3 and the LCCU in the upper plate of the Belted Range thrust. Characterization of these stratigraphic units is important because they lie between the contaminated test cavities and tunnels located within the TCU, and the regional aquifer, which lies in the LCA below the thrust fault system. Such drill hole data could potentially yield valuable data on the presence and extent of fracture porosity within the LCA3 and the LCA, as well as fracture-dominated fast pathways through confining units in the upper plate of the thrust (the LCCU) and in the volcanic strata of the TCU. Such data will help to construct a more accurate geologic framework model of the CAU and help to construct more realistic groundwater flow model with better defined migration routes.

The second characterization activity, sample new drill holes and existing locations, will address specific uncertainties within the geologic framework model, as well as refining hydrochemical and contaminant information about the groundwater flow system in the vicinity of the testing areas. Refining the knowledge base of the major element chemistry and isotopic composition of groundwater in the vicinity of the testing areas will help refine the present relation between the perched water and the regional groundwater, and will address major uncertainties about the UZ delay factor. Hydrochemical data will help characterize the groundwater flow paths. Rock samples collected from new drill holes will help characterize the secondary alteration minerals in the flow paths within tuffs and Paleozoic rocks in the vicinity of the test areas. These data will potentially address uncertainties about mineral interaction and matrix diffusion in the TCU, UCCU, LCCU, and LCA3.

The third characterization activity, evaluate geophysical information, will address major uncertainties within the geologic framework of the Rainier Mesa/Shoshone Mountain area. Geophysical logs will assist characterizing the TCU, UCCU, LCCU, LCA3, and LCA. Analysis of seismic data will help characterize the 3-D geologic framework of the CAU model area, including the location and extent of HSUs and structures.

These data will support a more realistic groundwater flow model with better defined migration routes.

5.0 Corrective Action Investigation

As a part of the CAI proposed for the Rainier Mesa/Shoshone Mountain CAU, the location of the contaminant boundary (as described in Section 2.1.2.2.1) will be predicted using a numerical model that simulates groundwater flow and contaminant transport at the CAU scale. The CAU model may be supported by local models designed to simulate specific processes or small-scale features such as flow along fault zones or sub-CAU features of interest. The models will be supported by several data-collection activities. This section contains descriptions of the CAU model and other models used during the CAI. The data-collection activities, which are also a part of the CAI, are described in Section 6.0.

5.1 Groundwater Flow and Contaminant Transport Model

The CAU-scale model will be developed using existing and newly acquired data. Existing data include those described in Section 3.0 and supplemental data that will be acquired during the CAI from public and private sources, including the HRMP and the Weapons Program. The data currently planned to be acquired are described in Section 6.0. The following text provides an overview of the modeling process, while the details are discussed in Sections 5.1.2 through 5.1.5.

5.1.1 Overview of Modeling Process

A summary of the CAU modeling objectives is presented along with an overview of the modeling process used.

The objectives of the Rainier Mesa/Shoshone Mountain CAU model are as follows:

- Develop a CAU model that integrates a wide variety of data into a mass-conservative description of contaminant migration in groundwater from underground nuclear test locations in a CAU.
- Simulate, as output, the concentration of individual contaminants downgradient of underground test locations over a time period of 1,000 years. These concentrations will be used to define a contaminant boundary based on SDWA standards.

- Quantify the uncertainty in concentrations and contaminant boundary location.
- Serve as a tool to evaluate impacts of future flow system changes on the migration of contaminants in the CAU.

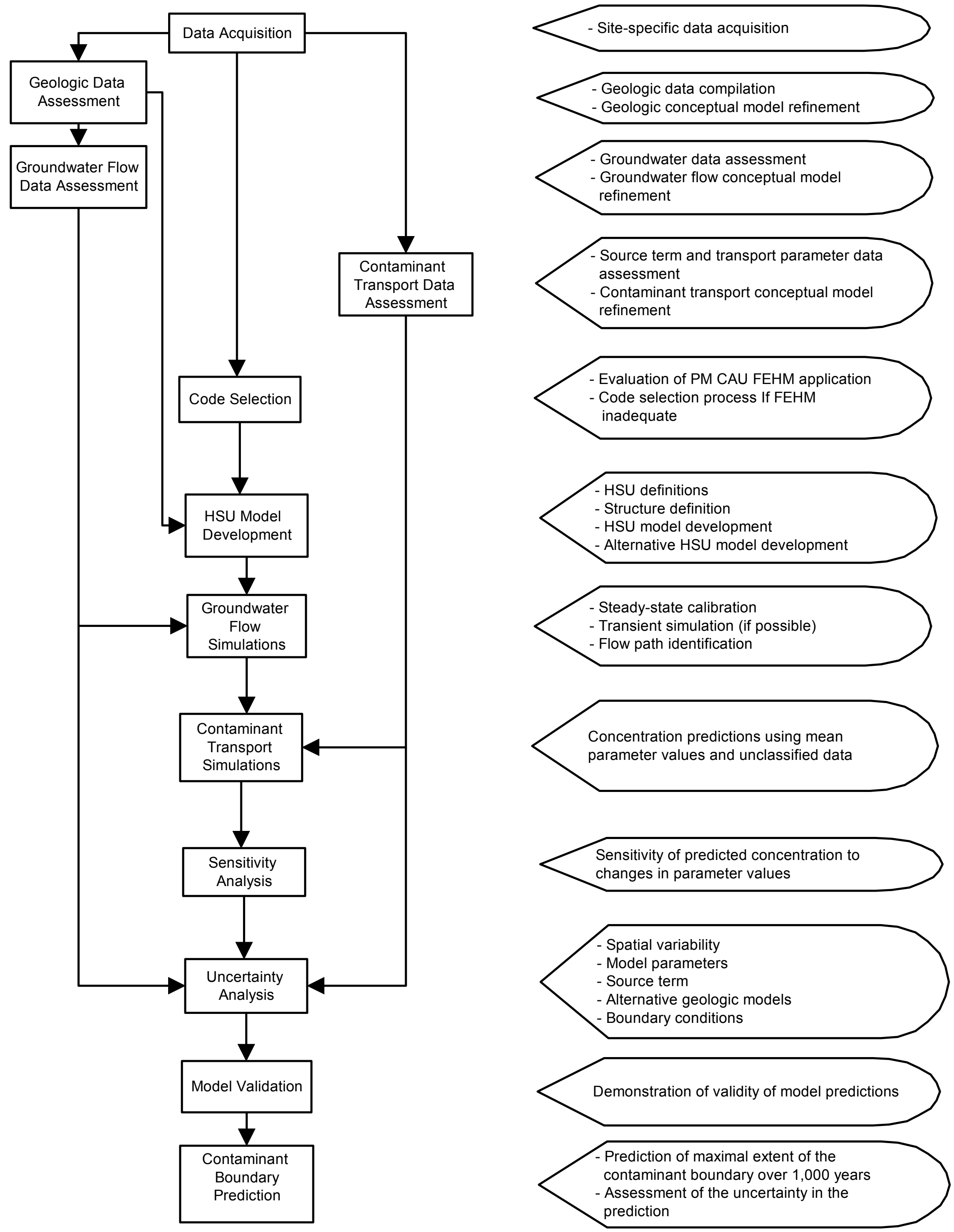
As shown in Figure 5-1, the major tasks in the modeling process for the Rainier Mesa/Shoshone Mountain CAU are data acquisition, data assessment, model (or code) selection, hydrostratigraphic framework model development, groundwater flow model development, contaminant transport model development, sensitivity analyses, uncertainty analysis, model validation, and contaminant boundary prediction.

The end of each modeling step corresponds to a major decision point during the modeling process. The findings of each modeling step are documented in a product which is either a technical report (or portion of a report), a plan, or an FFACO document (Table 5-1). These products are reviewed by the NNSA/NSO UGTA Project Manager, NDEP, modeling experts, and representatives of the TWG, as appropriate. The decisions are then made by the NNSA/NSO UGTA Project Manager based on the results of the product review for each modeling step.

The data acquisition step includes several studies designed to obtain new data needed to fill the information gaps identified for the Rainier Mesa/Shoshone Mountain CAU during the DQO process described in Section 4.0 and Appendix A. The field and laboratory data collected during these activities will be assessed along with the existing data as described in the following text. Details on the additional data to be collected are provided in Section 6.1.

The data assessment task consists of compiling and evaluating relevant data for use in the CAU model (Figure 5-2). Relevant data that are from locations outside the Rainier Mesa/Shoshone Mountain CAU will be considered on a per-datum basis as described by a transferability of data protocol (SNJV, 2004a), presented later in this section. The specific data required for the CAU model are presented in Sections 5.1.3.2.1 and 5.1.3.3.1. The relevant data for the CAU model will come from the following sources:

- Data used to prepare this CAIP (Section 3.0), including data from relevant wells and springs, as shown in Figure 3-1



Source: Modified from DOE/NV, 2000a

Figure 5-1
Modeling Process for the Rainier Mesa/Shoshone Mountain CAU

Table 5-1
Modeling Products

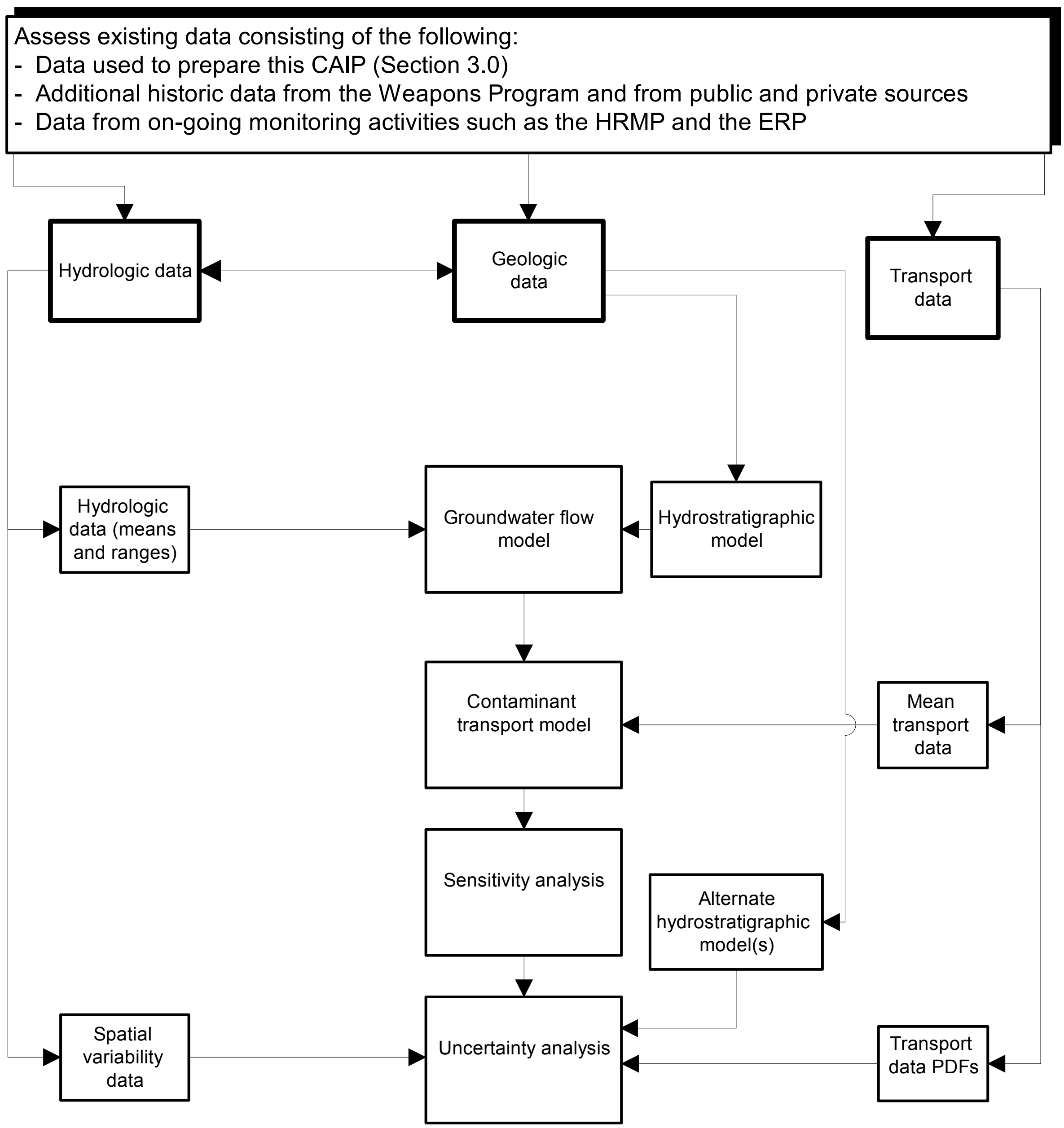
Modeling Step	Products
Geologic Data Assessment	Hydrostratigraphic Framework Model Documentation Package
Hydrogeologic Data Assessment	Hydrologic Data Documentation Package
Contaminant Transport Data Assessment	Contaminant Transport Parameter Data Documentation Package
Groundwater Flow Model	CAU Model Documentation Package
Contaminant Transport Model	
Sensitivity Analyses	
Uncertainty Analyses	
Model Review	
Model Validation	Model Validation Plan
Contaminant Boundary Prediction	CADD

Source: Modified from DOE/NV, 2000a

- Historic data from the Weapons Program, public, and private sources not used before, but identified during the data acquisition and data assessment phase of the CAI
- Data from on-going monitoring activities such as the HRMP and ERP that were collected after the information in Section 3.0 was compiled
- Newly acquired data derived from the characterization activities described in Section 6.0

Data other than the newly acquired data will be obtained from existing databases in electronic and hard-copy formats, and from published and unpublished literature and maps. All data will be compiled into a comprehensive database for the Rainier Mesa/Shoshone Mountain investigation and key data types will be qualified according to the procedure described in Section 7.0. The data will be used to refine the current Rainier Mesa/Shoshone Mountain conceptual model described in Section 3.6, and to construct the CAU numerical model as shown in Figure 5-2.

In the case that data gaps exist in those data compiled from investigations conducted within the Rainier Mesa/Shoshone Mountain CAU, related data from neighboring CAUs will be considered to fill those gaps. Relevant factors for determining whether or not material-property data collected from



PDF - probability density function

Source: Modified from DOE/NV, 2000a

Figure 5-2
Data Utilization During the CAU Modeling Process

other CAUs can be used to support groundwater flow, radionuclide transport, and other models at the CAU under investigation are identified in *Transferability of Data Related to the Underground Test Area Project, Nevada Test Site, Nye County, Nevada* (SNJV, 2004a). This document describes the protocol for the determination and application of relevant data that are derived from locations outside the CAU under investigation. When adequate data are available, statistical testing may be used to test whether two areas are sufficiently similar to directly use the data from outside the CAU; this is considered to be the most robust approach. The document also provides a procedure to determine how much emphasis or weight should be placed on data that are accepted for use.

Following data gathering and compilation, the data will be screened for quality. The screening process includes data documentation evaluation and data quality evaluation. The data documentation evaluation is described in Section 7.0. The method of data quality evaluation varies with the criteria for the data and the intended use of the data. Thus, a variety of criteria will be used to evaluate data quality. As a result of this evaluation procedure, one or more flags will be assigned to each record compiled in the database, indicating the data quality or suitability of the individual data record for a specific intended use. For data that are from locations outside the Rainier Mesa/Shoshone Mountain CAU, the documentation and quality evaluation are described by a data-specific transferability protocol (SNJV, 2004a).

Descriptions of the specific data types needed for the groundwater flow model and the contaminant transport model and their utilization during the modeling process are presented in Sections 5.1.3.2.1 and 5.1.3.3.1. A detailed discussion of the data assessment process will be presented in the documentation packages which will explain the findings of the Rainier Mesa/Shoshone Mountain CAI. The interface between the data and the model includes attributes such as scale-of-measurement and uncertainty. Some of these attributes will be addressed in the data documentation and other attributes will be presented in the model documentation.

Code selection is the process used to identify the computer code that will be used to simulate contaminant migration at the CAU-scale. Code selection is conducted in parallel with the data acquisition and assessment processes (Figure 5-2). The Rainier Mesa/Shoshone Mountain code selection process will depend on the assessment of the application of the code FEHM (Zyvoloski et al., 1997a) to the Pahute Mesa CAUs. If the FEHM application to Pahute Mesa is acceptable, FEHM will be used for the Rainier Mesa/Shoshone Mountain area. If FEHM is not acceptable, the code selection process will begin by defining a set of required and desirable code attributes, identifying a set of available codes, and selecting three of these codes for further evaluation. The process continues by defining a set of testing criteria and testing the three selected codes. The final code selection is based on the results of the testing. Details on the code selection process for the Rainier Mesa/Shoshone Mountain CAU is described in Section 5.1.2.

Following completion of the data assessment process and final code selection, the groundwater flow model and the contaminant transport models are constructed. Both the groundwater flow model and contaminant transport model construction include model setup and model calibration (at least for flow). Model setup consists of preparing the relevant data for input to the CAU model. Model calibration is the process of adjusting input parameters until the model results match the observed behavior of the groundwater flow system within predefined limits of acceptability. The construction of the two components of the CAU model are described in Sections 5.1.3.2.2, 5.1.3.2.3, 5.1.3.3.2, and 5.1.3.3.3.

Sensitivity analyses will be performed after the contaminant transport model is completed. The objective of the sensitivity analyses is to assess the response of the predicted concentration values as a result of changes in input parameter values. The results of the sensitivity analyses will be used to guide potential additional data collection efforts for model validation to ensure that meaningful data are collected. Results of the sensitivity analyses may help define monitoring locations and the type of data to be collected for the monitoring network design. Details on the sensitivity analysis procedure are presented in Section 5.1.3.4.

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 data used to build the CAU model. Model result uncertainties caused by uncertainties in the CAU hydrostratigraphic model, source term, parameter values, and boundary conditions will be evaluated as described in Section 5.1.3.5. Alternative hydrostratigraphic and conceptual hydrologic models will be evaluated as part of the uncertainty analyses.

During the validation process (detailed in Section 5.1.4), NNSA/NSO, NDEP, and a panel of peers will review the modeling approach and results following completion of the CAU model. Both NNSA/NSO and NDEP will evaluate the flow and contaminant transport model to determine if it is acceptable for defining the contaminant boundary.

Once the CAU model is validated to NNSA/NSO's and NDEP's satisfaction, the location of the contaminant boundary will be calculated. The maximal extent of contamination as defined by SDWA standards above background over 1,000 years and the uncertainty in the prediction will be calculated using the concentrations simulated by the CAU model as explained in Section 5.1.5.

The modeling steps described in this overview are discussed in detail in the following four major subsections: Model Selection, Model Discussion, Model Validation, and Contaminant Boundary Prediction.

5.1.2 Model Selection

The selection of the model (code) to use for the CAU simulations is an important decision because the selected code will be used to predict the migration of contaminants within the CAU-scale model boundary. To establish confidence in the CAU model, the process to select the code will be outlined and justified. The selection process will ensure that the selected code will simulate the migration of the potential contaminants in groundwater and allow for an assessment of the uncertainty in the predictions.

The selection process will follow one of two tracks depending on the acceptability of the code FEHM, which was chosen to simulate the Pahute Mesa groundwater flow system (DOE/NV, 1999). Figure 5-3 outlines the code selection process for the Rainier Mesa/Shoshone Mountain area. The first step (in the upper left hand corner of Figure 5-3) is an assessment of how well FEHM performed in the simulation of radionuclide transport in groundwater of the Pahute Mesa CAUs. If the FEHM performance is deemed acceptable, FEHM will be used for the Rainier Mesa/Shoshone Mountain CAU. However, if FEHM is deemed unacceptable, the code selection process will begin with the identification of candidate codes and the selection of the three best-qualified codes based on the set of

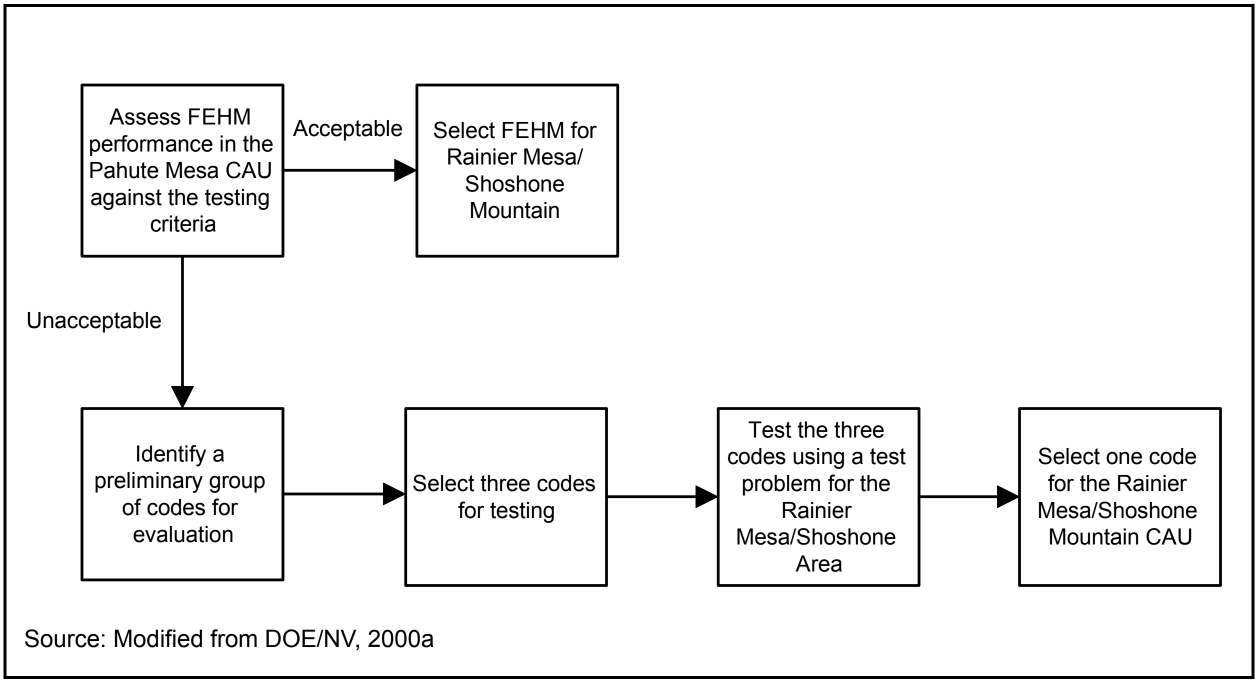


Figure 5-3
Code Selection Process for the Rainier Mesa/Shoshone Mountain CAU Model

code attributes identified in Section 5.1.2.2. These three codes will be tested by application to an example problem designed to simulate conditions in the Rainier Mesa/Shoshone Mountain area and the final code selection will be made.

5.1.2.1 Assessment of FEHM Acceptability

As presented in the Pahute Mesa CAIP (DOE/NV, 1999), the code FEHM (Zyvoloski et al., 1997a) was chosen to simulate the groundwater flow and radionuclide transport for the Pahute Mesa CAUs. The processes of interest for the Rainier Mesa/Shoshone Mountain area are the same as those for the Pahute Mesa area (i.e., groundwater flow and transport in porous and fractured rock). Therefore, it is expected that if FEHM is acceptable for the Pahute Mesa CAUs, it will be acceptable for the Rainier Mesa/Shoshone Mountain CAU also.

The first step is to evaluate the application of FEHM to the Pahute Mesa CAUs to determine if the application is acceptable. Acceptability will be defined by comparison to code testing criteria (defined in Section 5.1.2.4.1), with particular emphasis on the ability to represent CAU hydrogeology and speed of simulation. Current Pahute Mesa CAU flow model simulation results indicate that FEHM is acceptable for Pahute Mesa.

If the FEHM is found to be unacceptable for application to the Rainier Mesa/Shoshone Mountain area, the code selection process begins with the process identified below. The code attributes identified in Section 5.1.2.2 will be used to screen a list of candidate codes and to rank the codes in order of preference. The list of candidate codes will not be presented at this time because the code selection is planned for the future and advances in existing codes and development of new codes may make any current list obsolete at the time the code evaluation is performed.

5.1.2.2 Code Attributes

A number of attributes or capabilities of the CAU model were defined to satisfy the modeling objectives presented in Section 5.1.1. The first objective requires the CAU model to have the ability to represent the important physical and chemical features of the CAU groundwater flow system. The features will include faulting, stratigraphy, sources and sinks of water, the distribution of contaminants and their rates of introduction into the groundwater flow system, and other physical or chemical features unique to the CAU. The second objective requires the CAU model to simulate the movement of a variety of contaminants for which their distribution and abundance serve to define the contaminant boundary. The third and fourth objectives require flexibility in the CAU model to allow grid changes, parameter value changes, placement of additional wells, and boundary condition variations. The required code attributes that were defined to meet the modeling objectives were categorized under “general,” “flow model,” and “transport model” (Table 5-2). Each of these attributes will be described and assessed with respect to importance for the CAU modeling. In addition, six non-essential but desirable attributes were identified. These include finite element formulation, steady-state capability, double porosity/double-permeability formulation, the ability to simulate the transport of multiple solutes and daughter products, and established pre- and postprocessors.

Table 5-2
Required Hydrologic Code Attributes

General Attributes[a]	Flow Model Attributes[a]	Transport Model Attributes[a]
Fully 3-D Large number of nodes (500,000 or more) capability Multiple boundary condition options Transient capability Efficient solver Acceptable numerical accuracy Minimal numerical dispersion Acceptable verification and validation Access to source code	Saturated groundwater flow Heterogeneous and anisotropic hydraulic conductivity Point and distributed sources and sinks of water Temperature dependence Complex geology	Advection, dispersion, sorption, and matrix diffusion Radioactive decay

Source: DOE/NV, 2000a
[a]Order of attributes does not indicate order of importance.

5.1.2.2.1 General Attributes

The general attributes are defined with the goal of using a code that can closely represent a large modeling domain, in addition to being flexible, user-friendly, and efficient.

Fully Three-Dimensional

The groundwater flow system is controlled by the distribution of geologic units as well as the location of sources and sinks of water. Additionally, transport properties including source location and strength, porosity, and diffusion may vary in space. The 3-D nature of the groundwater flow system requires that the CAU model be 3-D to adequately simulate migration of the potential contaminants within the CAU model area.

Large Numbers of Nodes Capability

The greater the number of nodes in the CAU model, the greater the detail that can be included. Given the anticipated large geographic area of the Rainier Mesa/Shoshone Mountain CAU model, the ability of the CAU model to simulate many nodes will control the amount of detail that can be included and reduce errors caused by source dilution.

Multiple Boundary Condition Options

Options to allow for specified pressure and specified flux boundary conditions for fluids, as well as specified temperature or specified heat flow, may be required in implementing the CAU model.

Transient Capability

The initial flow simulations for the CAU model will be steady-state with possible transient runs to follow. The contaminant transport simulations will all be performed under transient transport conditions, but may utilize a steady-state groundwater flow system.

Efficient Solver

To simulate in sufficient detail, the CAU model will require a large number of nodes as mentioned above. To make a large model practical, the codes must run efficiently. Generally, a code has a selection of solvers available. The solvers must be efficient enough to allow for more than one run per day. A code that requires more than six hours per simulation would be eliminated. A six-hour run time allows two runs per day on a single computer.

Acceptable Numerical Accuracy

The numerical solution of the transport equation is typically more difficult than the solution of the flow equation. This attribute requires verification of the results of the code for a given test problem against analytical solutions and against the results of other numerical codes for the same problem. Documentation of the numerical accuracy must be available.

Minimal Numerical Dispersion

Under certain circumstances, the error in the numerical approximation of a value can become as large as the value being approximated. When this occurs, the numerical solution combines an exclusively numerical dispersion with the real hydrodynamic dispersion producing an overestimate of the actual dispersion. Solution techniques that minimize numerical dispersion are required.

Acceptable Verification and Validation

The degree of computer code verification and validation varies widely depending on the code being considered. The extent to which this process has been documented for a particular code varies even more. Thoroughly documented testing is required to ensure that the code satisfies requirements specified for its options and features.

Access to Source Code

Computer codes are initially written by humans in a high-level language such as FORTRAN and then translated into machine language for execution on the computer. The high-level version of the code is called the "source code," and can be read and modified by humans. The machine-language version is called the "executable code" and can only be deciphered by the computer. Many distributors of computer codes provide only the executable version of the code to the user. During the course of the development or application of the CAU model, it may be necessary to examine or modify the step-by-step procedures implemented in the computer code. To accomplish this, access to the source code will be required.

5.1.2.2.2 Groundwater Flow Model Attributes

The attributes for the groundwater flow model are defined with the goal of simulating the flow paths and groundwater fluxes.

Saturated Groundwater Flow

The focus of this CAI is solely on the saturated zone. Although many of these codes will simulate variably-saturated conditions, the codes must be able to simulate saturated conditions.

Heterogeneous and Anisotropic Hydraulic Conductivity

Aquifer heterogeneity reflects the natural variability in the subsurface. The CAU model must be capable of simulating flow through aquifers in which the hydraulic conductivity may vary from location to location. Anisotropy is a directional dependence of the hydraulic conductivity. In fractured aquifers, it is common for hydraulic conductivity to be larger in a direction parallel to fracturing and smaller perpendicular to fracturing.

Point and Distributed Sources and Sinks of Water

Recharge may occur over a large spatial area due to precipitation or may be concentrated into washes or craters. Discharge may occur at wells or individual springs or may occur over larger areas such as playas. The CAU model should have the capability to simulate these various cases.

Temperature Dependence

The flow of groundwater may be influenced by water temperature variations. Warm water is more buoyant than colder water and tends to rise. Additionally, warm water is less viscous and tends to move more easily than cold water. These processes may be important in some portions of the CAU where naturally occurring sources of heat have caused elevated groundwater temperatures. An additional source of warm water may be the underground test cavities. It may be important to account for these temperature effects in the simulations.

Simulate Complex Geology

As described in Section 3.0 of this report, the geology of the Rainier Mesa/Shoshone Mountain area is very complex. It consists of multiple stratigraphic units, some of which are truncated by faults and other structural features. Even within units, changes in facies result in spatial variations in material properties. The flow of groundwater (amount and direction) is governed, in large part, by the distribution of hydrogeologic units. The code must be able to include important features of the hydrogeology such as lateral and vertical changes in material properties. Much of this attribute is similar to earlier general attributes related to number of grid nodes and simulation speed. The greater the number of nodes, the more detail that can be incorporated into the CAU model.

5.1.2.2.3 Transport Model Attributes

This section discusses the contaminant transport model attributes that will be necessary to simulate the migration of the potential contaminants.

Advection, Dispersion, Sorption, and Matrix Diffusion

The primary processes of interest in the Rainier Mesa/Shoshone Mountain groundwater flow system that are expected to influence the concentration of radionuclides in groundwater are listed in this section. The regional contaminant transport model (IT, 1996h) simulations and the VOIA (SNJV, 2004b) showed that advection (via the groundwater flux) and matrix diffusion were the primary factors influencing tritium transport in fractured media. It is expected that sorption will also be important for reactive contaminants, but this may not be the dominant contributor to the location of the contaminant boundary. Longitudinal dispersion was not shown to be of primary importance in the regional simulations, but is included here because it may be more important at smaller scales.

Radioactive Decay

Most, but not all, of the potential contaminants of interest are radionuclides. The activity per volume of radionuclides decreases over time via the process of radioactive decay.

Transport of Colloids

The movement of colloids may enhance the movement of otherwise immobile contaminants. As discussed in Section 3.4.9.5, colloids are submicron size particles to which radionuclides or other solutes sorb. The colloids are transported via the groundwater flow, and the sorbed solutes move with the colloids. Currently, FEHM is the only contaminant transport code known to explicitly simulate the transport of colloids while meeting all of the code attributes.

5.1.2.2.4 Desirable Attributes

These are attributes of the computer codes that were considered valuable but not essential to satisfying the CAU modeling objectives.

Finite Element Formulation

A finite element formulation allows much more flexibility in representing the hydrogeology being modeled. Grids can be developed to represent complex structures such as faults, pinch outs and layer truncations. In addition, grid refinement allows the grid to be modified to provide more resolution in the area of interest.

Steady-State Capability

Some of the codes do not include a steady flow option, but rather reach steady-state by leaving parameters fixed in time and performing transient simulations over large periods of time until steady-state is reached. This approach is adequate, but somewhat slower than if a true steady-state option were available.

Double-Porosity/Double-Permeability Formulation

The double-porosity/double-permeability method is similar to the double-porosity method in that it allows for communication between fractures and matrix material. This feature allows for the modeling of matrix diffusion. The double-porosity/double-permeability method differs in that it allows matrix cells that communicate with fractures to also communicate with other matrix cells. While this method provides a more realistic simulation, its use is more important for unsaturated flow problems.

Multiple Solutes

Many codes are designed to provide a simulation of the migration of a single solute in a given run. Using a code with the ability to model transport for multiple solutes in a single run may be more efficient.

Daughter Products

A radionuclide may decay into one or more radionuclides (called daughter products) or into a stable isotope. More accurate estimates of dose can be obtained if the code is capable of simulating the ingrowth and transport of a radionuclide and daughter product(s).

Established Pre- and Postprocessors

Pre- and postprocessors are computer codes used to facilitate the data manipulations that are made before and after a given numerical model is used. Preprocessors are used to transform the input data into a form that is required by the model. Postprocessors are used to aid in the interpretation of the model output. Typically, postprocessors are used to create graphic images of some simulated variables such as hydraulic heads or solute concentrations. Pre- and postprocessors generally speed up the modeling task. If the processors are not available, the appropriate processors would be developed.

5.1.2.3 Code Identification and Preliminary Selection

If FEHM is deemed unacceptable at the time of the Rainier Mesa/Shoshone Mountain code selection, a list of available numerical codes capable of simulating 3-D groundwater flow and contaminant transport will be compiled. The list of codes will not be presented at this time because the code selection is planned for the future and it is expected that advances in existing codes and development of new codes could make the list obsolete by the time the code evaluation is performed. An initial comparison of the codes will be performed with respect to the attributes in Section 5.1.2.2. The results of the comparison will be presented in a table where the required code attributes are grouped into the categories of general, flow model, and transport model. Comparisons of attributes considered desirable but not required will also be shown. From the table of candidate codes, the three that best meet the desired attributes will be selected for testing.

It is important to remember that the above selection and screening process is initiated only in the case that FEHM is found unacceptable. If FEHM is acceptable, there is no reason to pursue a lengthy code selection process. However, if testing of new codes is needed, the testing and final code selection will follow the process defined below.

5.1.2.4 Testing of the Codes and Final Code Selection

The final code selection will be made following thorough testing of the three selected codes. The code-testing criteria and sample problem established to evaluate the codes are described in this section.

5.1.2.4.1 Testing Criteria

The selected code-testing criteria are portability, level of QA testing, user-friendliness, ability to represent the CAU hydrogeology, and speed of simulation.

Portability

The CAU model may be sent to independent reviewers as well as the State of Nevada for evaluation since each of these stakeholders may want to run the code themselves. Thus, the code, when complete, should require minimal special equipment or software to be usable. Additionally, the CAU model will likely need to be run on a classified computer at the DOE Nevada Support Facility or another secure location to produce a final estimate of the contaminant boundary (results based on classified data will be included in a classified DOE report). The code and associated pre- and postprocessors must be portable to the selected secure location to allow for efficient classified simulations.

QA Evaluation

The chosen code must be appropriately verified to ensure that the output is accurate. The QA evaluation refers to the level of documentation and testing for a code. The ability of the code to simulate the processes of interest is a function of the formulation of the equations and the quality of the programming. A code meets the QA requirements if its results have been verified against those of other codes as well as compared with analytical solutions. These comparisons must be documented before a code will be used for the Rainier Mesa/Shoshone Mountain model.

Ease of Use

The ease of use is a subjective judgment that assesses the modeler’s degree of difficulty in getting the model running. This is, by necessity, a value judgment of the modeler and reflects the modeler’s experience and background. A great deal of effort will be spent calibrating the CAU model and setting up sensitivity and uncertainty analyses. A code that is difficult to use makes the calibration process more difficult and reduces the code’s portability. Ease of use includes factors such as the structure of the input datasets and the units used in the model. The earlier in the modeling process that the code selection and testing occur, the greater the likelihood that the modelers will become proficient with any of the codes. In that case, ease of use will not be a major deciding factor.

Ability to Represent the CAU Hydrogeology

The primary geologic features that control flow need to be represented in the CAU model. These features include the hydrostratigraphy, physical boundaries, and structural features such as faults. In addition, the ability to model physical processes of concern (advection, dispersion, dual porosity, adsorption, and radioactive decay) is also important. The criteria also include an assessment of the ability of the model to include sufficient detail and stay within the memory limitations of the computer platform chosen for simulation.

Speed of Simulation

The time required for a solution is also of importance to the evaluation of the codes. The faster the code, the shorter the time to complete each model run. As calibration normally requires many model runs, the simulation time becomes a problem if it is too long. For the purposes of the CAU model, simulation times less than two hours for a steady-state flow simulation are acceptable. This length of simulation time will allow for four or five runs per day for a single machine, which provides sufficient time to perform the calibration assuming up to 600 runs to calibrate.

These five criteria are not equally important. The QA evaluation and the ability to represent CAU hydrologic conditions are most important. Then in decreasing order of importance are speed of simulation, ease of use, and portability.

5.1.2.4.2 Test Problem

In the case that FEHM is not acceptable for Rainier Mesa/Shoshone Mountain a test problem will be used to test candidate codes. This testing of the code is in addition to documented code validation and verification where the code is compared with existing solutions to test its accuracy. The test problem goes beyond code evaluation to assess the applicability of the code to the specific situation in the Rainier Mesa/Shoshone Mountain area. The goal of the test problem is to identify deficiencies, quirks, or other features of a code that may cause difficulties in applying the code to the Rainier

Mesa/Shoshone Mountain CAU. The features of the test problem will be chosen to mimic the conditions expected in the Rainier Mesa/Shoshone Mountain model area. By doing so, the effort to set up and run the problem could be evaluated as well as the assessment of the run times of the model. The features to be included in the test problem include complex geology such as lithologic and structural features, temperature-dependent flow, radionuclide migration from a cavity, and matrix diffusion.

A portion of the Rainier Mesa/Shoshone Mountain CAU hydrostratigraphic model, large enough to be representative of the CAU, will be selected for the comparison. The test model area will have the same boundary conditions along all sides as anticipated for the CAU model. The hydraulic heads along the boundaries will be obtained from observed data where available or from the regional groundwater flow model. The HSU model for the test problem will include all the hydrostratigraphic layers in the Rainier Mesa/Shoshone Mountain hydrostratigraphic model, as well as many of the faults. Each of the HSUs will be assigned a hydraulic conductivity consistent with values obtained from the regional flow model (DOE/NV, 1997a).

One or more underground nuclear tests will be chosen for consideration as sources of contamination in the test problem. The nuclear tests will be selected based on their location with respect to major geologic and/or structural features. The most recent unclassified hydrologic source term and transport parameters available at the time of the code testing will be used.

5.1.3 Model Discussion/Documentation/Data Availability

A discussion of the CAU model is presented in this section. The computer code under consideration for the Rainier Mesa/Shoshone Mountain CAU modeling and its documentation are also described. Descriptions of the groundwater flow and contaminant transport model development are provided, including descriptions of the data assessment process.

5.1.3.1 Description of the Candidate Code

Based on current information and acceptable performance to date on the Pahute Mesa CAU flow model, the only code identified for use in the Rainier Mesa/Shoshone Mountain CAU model is FEHM (Zyvoloski et al., 1997a). The FEHM code (Zyvoloski et al., 1997a), developed by LANL, simulates 3-D, time-dependent, multiphase, multicomponent, nonisothermal, reactive groundwater flow 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. Specific capabilities include:

- Three-dimensional model
- Flow of air, water, and heat
- Multiple chemically-reactive and sorbing contaminants
- Finite element/finite volume formulation
- Coupled stress module
- Saturated and unsaturated media
- Preconditioned conjugate gradient solution of coupled nonlinear equations
- Double porosity and double porosity/double permeability capabilities
- Complex geometries with unstructured grids

A number of documents supporting the FEHM code are readily available from LANL. In addition to the user's manual (Zyvoloski et al., 1997b), other documents include a description of the mathematical models and numerical methods used by FEHM (Zyvoloski et al., 1997a), documentation of the functional and performance requirements for FEHM, description of the FEHM software, the verification and validation plan, and description of the verification and validation activities (Dash et al., 1997).

5.1.3.2 Groundwater Flow Model Development

This section describes the groundwater flow model development process. The discussion of the modeling process is generic in the sense that the final code selection has not been made. The process outlined will apply to any codes. The goal of the groundwater flow model is to simulate the movement of water in and around the Rainier Mesa/Shoshone Mountain CAU. The groundwater flow model will define the pathways from the underground test locations and provide the flux input to the transport model which will be used to simulate the concentration of contaminants in the groundwater system. The model development process includes data assessment, model setup, and model calibration.

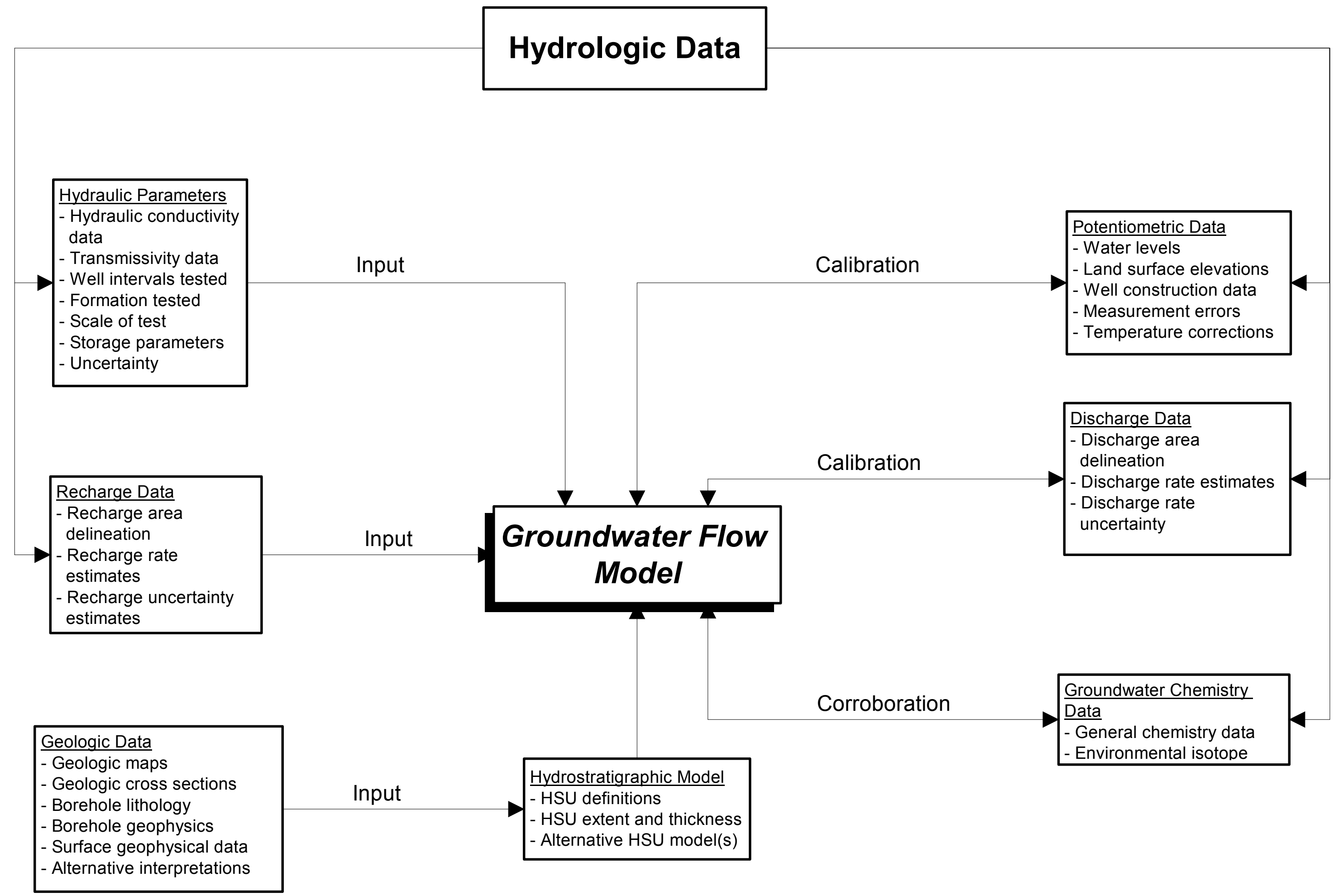
5.1.3.2.1 Groundwater Flow Data Assessment

The geology and hydrology of the CAU model area must be defined to simulate the groundwater movement within the subsurface. As discussed in Section 5.1.1 and shown in Figure 5-2, relevant existing and newly acquired groundwater data (described in Section 6.1.1 and Section 6.1.2) will be gathered and compiled into a comprehensive database. The existing and newly acquired CAU-specific data will have the highest priority. However, non-CAU specific data may be included in the development of the conceptual model, particularly to provide additional constraints on parameter uncertainty.

As shown in Figure 5-4, specific data types needed to simulate groundwater flow are geologic data, hydraulic head data, groundwater recharge estimates, discharge estimates, and hydraulic conductivity data. Geologic data are needed to set up the HSU framework within which groundwater flows. Hydraulic head data serve as a target to which the flow model is calibrated. Recharge refers to either lateral flow across the CAU model boundary into the model or recharge that enters from the land surface. Discharge is the lateral flow across the CAU model boundary out of the model or discharge to springs, seeps, or wells. The hydraulic conductivity is a measure of the water-transmitting ability of the aquifer system. Hydraulic conductivity may be heterogeneous and vary from location to location within an aquifer unit and vary across geologic units.

Geologic Data

A hydrostratigraphic model of the Rainier Mesa/Shoshone Mountain region will be constructed to define the framework of the groundwater flow system. The methodology to be used consists of geologic data compilation, conceptual hydrogeologic model development, and digital HSU model development. A process similar to the one used to create the Pahute Mesa HSU model (BN, 2002b) will be used to create the Rainier Mesa/Shoshone Mountain CAU-scale HSU model. Existing and newly acquired geologic and geophysical data (described in Section 6.1.1 and Section 6.1.3) will be compiled and evaluated. To develop the conceptual hydrostratigraphic model, detailed structural cross sections will be drawn to depict structural and stratigraphic features and will then be simplified to focus on HSU relationships. To construct these HSU cross sections, hydrologically similar geologic units will be combined into HSUs, and only the HSUs and hydrologically significant structures will be depicted. The geologic data and digitized HSU cross sections will be integrated



Source: Modified from DOE/NV, 2000a

Figure 5-4
Data Types and Utilization in the Groundwater Flow Model

into a 3-D digital HSU model. The HSU model will provide HSU thicknesses to be used in the design of the groundwater flow model layers. During this process, alternative HSU framework models will be defined to account for the range in possible framework interpretations. These alternative framework models will be used to assess uncertainty in CAU model predictions resulting from uncertainty in HSU areal extent, thickness, structural relationships, and material properties.

Hydraulic Heads

Hydraulic head data define the pressure condition in the aquifer system. Hydraulic heads are derived from measured water levels. Existing and newly acquired water-level data measured in wells and boreholes located within the investigation area (see Sections 6.1.1 and 6.1.2) will be compiled and evaluated for use in the CAU-scale groundwater flow model. This dataset will include supporting data such as measurement errors, land surface elevations, borehole deviations, groundwater temperature, and well construction information.

The hydraulic head (or fluid pressure) is the variable that a groundwater flow model calculates. For uniform density fluids, the hydraulic head is a complete description of the pressure condition. For variable density fluids, such as those where the temperature or salinity vary significantly, the fluid pressure is calculated. In this CAIP, hydraulic head is used in most cases to refer to the pressure condition; however, the reader should recognize that if variable density flow is important, fluid pressure will be used directly. Salinity variations are expected to be small and should not be a factor in determining variable density. Water temperature is known to vary within the Rainier Mesa/Shoshone Mountain groundwater flow system (see Section 3.4.5.2.2), but before variable temperature simulations are considered, preliminary analyses will be conducted to determine if isothermal simulations will be adequate.

The calibration process involves modifying input parameters such as recharge and hydraulic conductivity until the calculated hydraulic head matches the observed head, within prespecified limits. For the steady-state calibration, a set of observed average hydraulic heads will be determined from the dataset by selecting an appropriate range in which the measurements appear to be stable and approximately consistent with expected prepumping and pretesting conditions. This is the same process that was followed for the determination of target hydraulic heads for the regional groundwater flow model calibration (DOE/NV, 1997a).

The head data will be examined for trends. In addition, if possible, transient simulations will be conducted if the source and extent of the water-level changes can be represented in the model. If this analysis is conducted the simulated hydraulic head changes will be compared with the measured hydraulic head changes over time.

Boundary Fluxes and Recharge

There are two sources of water entering the Rainier Mesa/Shoshone Mountain CAU model area. The first is flow across the CAU model boundary from neighboring regions, and the second is recharge from local precipitation.

The amount of flow across the CAU model boundary will be bounded using the regional groundwater flow model. The regional model will provide the best approximation of boundary conditions for the CAU model because it integrates the entire flow system into a mass-conservative representation. However, the regional model is uncertain; therefore, the fluxes from the regional model are uncertain. To define the boundary conditions of the Rainier Mesa/Shoshone Mountain CAU model domain, uncertainty analyses will be conducted with the regional model to define the range of boundary fluxes across each boundary face of the CAU model. Uncertainty analysis will include the effects of alternative geologic and recharge models.

The current estimate of areal recharge distribution for the NTS area is derived from the regional model using a modification of the Maxey-Eakin method (Maxey and Eakin, 1949). During the Rainier Mesa/Shoshone Mountain data assessment process, this recharge distribution will be considered along with others resulting from studies of groundwater recharge. The findings of these studies may lead to refinements or modifications to the recharge distribution derived from the regional model. Recharge estimation procedures developed for the Yucca Mountain Project (Hevesi et al., 2003) will also be considered during the development of a groundwater recharge distribution for the Rainier Mesa/Shoshone Mountain area.

Uncertainty in the recharge comes from several sources. The total amount of recharge is unknown and only approximated by the Maxey-Eakin relationship. Uncertainty in discharge measurements (used to bound recharge estimates in the regional model), and estimated CAU water balance all contribute to recharge uncertainty. The spatial distribution of infiltration is unknown, thus the spatial distribution of recharge is also unknown. These sources of uncertainty will be considered during the CAU model uncertainty analyses.

Boundary Fluxes and Discharge

Groundwater discharge occurs as either outflow across the CAU model boundary, discharge to the land surface, or discharge to wells. The flow across the CAU model boundary will be handled via the determination of boundary conditions using the regional flow model as was described for recharge. Regionally, the discharge to the land surface occurs in the Amargosa Desert, Ash Meadows, and Death Valley. The current discharge estimates are uncertain, but in Ash Meadows and Oasis Valley the discharge estimates were improved by evapotranspiration measurements conducted by the USGS. The refined discharge measurements will be included in the recalibration of the regional flow model to improve the discharge fluxes. For the CAU model, the discharge from wells will be assessed as part of the water balance (although expected to be minor), and may be used in transient simulations.

Hydraulic Parameters

The hydraulic conductivity of the HSUs is a major control on the movement of groundwater. Hydraulic conductivity values were derived from measurements in numerous wells in and around the NTS (IT, 1996e). The hydraulic conductivity values will be used in two ways. First, the range of measured values provides an uncertainty range within which the calibrated values should fall. Second, the values will be used during the uncertainty analyses to generate realizations that are as realistic as possible.

In the regional flow model (DOE/NV, 1997a), the calibrated values were shown to fall within the range of measured values. During the CAU model calibration, the hydraulic conductivity data will again be used to define a range of possible values. The hydraulic conductivity will not be calibrated on a cell-by-cell basis, but rather will be defined on larger zones that represent similar hydrogeologic conditions. Estimated hydraulic conductivity (see Section 3.4.5.2) within the zones (which are not yet defined) will be used to place bounds on the range of values. As presented in Section 3.4.5.2, the field-scale hydraulic conductivity data from Rainier Mesa and Shoshone Mountain is limited to three single-well tests with tested intervals in the LCA3, UCCU, and LCA. Only core-scale measurements are available for volcanic rocks. The use of data from other study areas to enhance site-specific data can be justified by examining specific similarities that may exist between various investigation areas. SNJV (2004b) documents the data transferability approach that will be used if possible to supplement the Rainier Mesa/Shoshone Mountain data. Potential source areas for transfer include Yucca Mountain and Pahute Mesa. The available data represents relatively small-scale measurements of hydraulic conductivity, yet the CAU and local models use averaged values of hydraulic conductivity appropriate for larger spatial areas. Vanmarcke (1983, page 382) has shown that the variability of averaged parameters is often much less than the variability in the small-scale values. This scale-dependent variability will be examined as part of the data analysis and used to limit the range of variability in the hydraulic conductivity values in the local and CAU models.

An additional hydraulic parameter is the storage coefficient. As noted in Section 5.1.3.2.3, transient simulations may be conducted to add further confidence in the steady-state calibration. These simulations will require the storage coefficient as well as hydraulic conductivity. To obtain meaningful storage coefficient data, an aquifer test must be performed with two wells, one a pumped well and the other an observation well. Few such tests have been conducted on the NTS due to the cost of installing the observation well. Any data available in the literature for the NTS groundwater flow region will be included, but it is expected that few data will be available.

Geochemistry Data

Groundwater chemistry evolves or changes as groundwater moves through the subsurface environment. Groundwater will acquire a general chemical signature or fingerprint by reaction with aquifer solids along the flow path. However, under conditions at the NTS, certain constituents (e.g., stable isotopes of hydrogen and oxygen) do not change along the flow path; therefore, they provide information on recharge conditions. Other constituents, such as ^{14}C, can be used to estimate the age of groundwater. These data (see Section 6.1.2) will be assessed as part of the data analysis to determine if they are useful for providing corroborating information in support of the CAU modeling. Predicted flow paths and contaminant velocity may be compared with geochemical data to determine if the path is consistent with the chemical evolution of the water.

5.1.3.2.2 Model Setup

To simulate the hydraulic behavior of the groundwater flow system, several model setup tasks must first be completed. These include definition of the model grid, assignment of initial parameters, definition of boundary conditions, and determination of target heads for calibration.

Model Grid

The model grid itself cannot be specified at this time because it will depend on the HSU and fault complexity, and overall size of the domain that must be considered to capture the flow paths. However, several guidelines are presented that will be followed after the CAU model is selected.

The scale of the CAU model will be on the order of the Rainier Mesa/Shoshone Mountain CAU, and the downgradient area in which the contaminant boundary is likely to occur. The size of the CAU model will be the minimum necessary to simulate the flow paths of concern. The CAU-scale groundwater flow and contaminant transport model will be constructed for an area encompassing the Rainier Mesa/Shoshone Mountain CAU. The potential CAU model area encompasses the Rainier Mesa/Shoshone Mountain CAU, the western portion of Yucca Flat, the eastern portion of the Timber Mountain caldera complex, and the northern portion of Jackass Flats. The extent of the CAU model area will be finalized after the available geologic and hydrogeologic data are assessed. The area of investigation is the region where data will be collected and summarized for possible inclusion in the CAU model, and will be intentionally large enough to include all possible pathways for radionuclide migration from the Rainier Mesa/Shoshone Mountain CAU (Figure 1-1). Grid cell sizes will vary over the CAU model area. In the vicinity of the underground tests, the horizontal and vertical spacing will be smaller than on the boundaries of the model. Specific grid spacing dimensions will be defined only after the CAU model is selected.

Four modeling scales are considered to be possible: small scale, intermediate scale, large scale, and very large scale. Small-scale models, also called near-field models, refer to simulations of processes in a portion of the groundwater flow system up to 1 km (3 to 5 cavity radii) around an underground nuclear test. Typically the near-field models will be used to simulate the hydrologic system in the vicinity of the underground tests. The local models will address specific processes at scales up to about 5 km. These models will address questions of flow system interaction such as the influence of faults. One or two large-scale models of the CAU will be designed to simulate groundwater flow and contaminant migration of all the underground tests in Rainier Mesa and Shoshone Mountain. The largest scale model is the regional model. The regional model provides the regional context of the CAU flow system. The regional model will be used to provide boundary condition constraints on the CAU flow system.

It is expected that a finite-element code will be selected for the CAU model. The finite-element mesh will be a function of the particular features of each CAU. Features such as the lateral and vertical distribution of geologic layering and faults are included in the hydrostratigraphic model. To the extent possible, the physical location of layers and faults will be honored by the finite-element mesh. This will provide the maximum level of accuracy regarding contaminant movement near potentially important geologic boundaries.

The precise features of each mesh or grid can be determined only when the modeling work begins. Nonetheless, several criteria will be applied in defining the model grid:

- The external boundary of the CAU model will correspond, to the degree possible that is consistent with the CAU model heads, to appropriate cell boundaries within the regional groundwater flow model. In this way, the boundary conditions from the regional groundwater flow model will be applied to the appropriate CAU model boundary. LANL has developed an accurate head and flux interpolation method between the regional model and FEHM that will be used if necessary.

- Nodes will be placed as close as practical at each underground test location as well as at specific well locations.

- Nodes will be placed along faults that are identified as being important to the distribution of HSUs or impact the flow system.

- The grid density will be greatest in the vicinity of the underground tests, faults (if hydrologically significant), and discharge wells (if transient analysis is possible), but will decrease in density at the CAU model boundaries. The CAU model grid spacing will be no larger than the regional groundwater flow model grid.

- For a finite-element model only, nodes will be preferentially placed along HSU contacts to more precisely incorporate the hydrostratigraphic model structure in the simulations.

Local Models

Local models may need to be developed to address specific questions in the Rainier Mesa/Shoshone Mountain area. For example, a key question to be addressed is the possibility of radionuclide pathways from the VA and VCU into the LCA. The majority of the radionuclides are in the units above the LCA, which because of porosity, hydraulic conductivity, and chemical interaction properties are expected to have slower rates of radionuclide migration than for the LCA. Simulations on the local scale of up to 5 km (3 mi) on a side may need to be performed to address pathways into the LCA via faults, holes in confining units, or pathways created by structural displacement.

After the local models are completed, the CAU model(s) will be developed. The CAU flow model(s) will link the regional model flow system and the local flow system into an integrated flow system at the scale of the Rainier Mesa/Shoshone Mountain CAU.

Near-Field Models

The near-field models can be considered a subset of the local models, but with a specific purpose of simulation flow (and transport) in the vicinity of selected underground nuclear tests. The near-field models are expected to be of very limited areal extent (about 1 km) and may include a subset of all HSUs present at an underground test location. The flow field in the near-field models will be very sensitive to small-scale variations in hydraulic conductivity both within and immediately outside the underground test cavity. This small-scale variability influences the direction and magnitude of groundwater flux passing through the nuclear test cavity. Radionuclide transport along the near-field pathlines is integrated to produce the hydrologic source term for the local and CAU models.

Boundary Conditions

The boundary of the CAU-scale model(s) will correspond to a predefined portion of the regional groundwater flow model. The actual CAU model boundary will be determined after the code selection is complete. It is anticipated that the CAU HSU model will differ from the regional HSU model at the same location. In addition, the regional groundwater flow model is defined on the basis of flow model layers which often do not correspond to HSU model layers.

In plan view, the external boundaries of the CAU model will coincide with selected rows and columns of the regional finite-difference model. The nodal spacing of the CAU model will be no greater than the regional model cell size. In the vertical direction, the layer boundaries of the CAU model may not match the flow model layer elevations of the regional flow model. The external boundaries of the CAU-scale model will be specified-flux or specified-head conditions as defined by measured data and the regional groundwater flow model. In any case, the boundary conditions specified for the CAU model will be uncertain. That uncertainty will need to be accounted for in the uncertainty analyses.

It is expected that most of the CAU model boundaries will be defined via specified-head conditions. Without boundary flux constraints, this can lead to unrealistic scenarios because there are no limitations on the amount of water that can cross the model boundary. The regional groundwater flow model will be used to set bounds on the amount of water that can enter the CAU model. First, one or more sets of CAU model boundaries will be defined. Sensitivity analyses of the regional model will be performed to define the parameters that impact fluxes across CAU model boundaries or regional discharge fluxes such as at Ash Meadows or Death Valley. Uncertainty in the regional model will be incorporated in the form of alternative HSU and hydrologic conceptual models. These may be a simple as increased or decreased recharge or as complex as modifications to the regional HSU model to represent alternative geologic interpretations. In this manner the regional model provides bounds on the CAU model while allowing flexibility in alternative conceptualizations within the CAU model.

The bottom of the CAU model will be no deeper than the regional model (4,000 m below sea level). If the bottom is the same as the regional model, then the bottom of the CAU model will be treated as "no flow" as was the case in the regional model. Recent evaluations of the regional groundwater flow model have shown that little flow occurs deep in the model because of the small values of hydraulic conductivity. As noted in the regional groundwater flow model documentation (DOE/NV, 1997a) and the description of the physical setting (Section 3.4), the measured hydraulic conductivity data show a trend of decreasing values with depth. The average underground test working point elevation conducted in the P-Tunnel complex on Rainier Mesa is about 1,684 m above sea level. Working point depths for all Rainier Mesa/Shoshone Mountain tests ranged from 30 to 545 m below ground surface (bgs) (see Table 3-2 and Table 3-3). The underground tests conducted within the Rainier

Mesa/Shoshone Mountain CAU are between 212 and 890 m above the regional water table. The CAU model bottom must extend into the LCA to allow for regional migration, but the ultimate vertical extent of the model will have to be assessed as part of model design. If flow becomes very low at great depths, it may be more useful to assume a shallower extent with some estimates of flow out the bottom. If this approach is chosen, the regional flow model will be used to define bounds on the fluxes through the bottom of the CAU model.

Finally, the recharge will be initially defined as in the regional groundwater flow model with the option of modifying it to account for increased spatial resolution or results provided by ongoing work.

For the local and near-field models, the boundary conditions will be based on the variability in local hydraulic conductivity and hydraulic gradient. The uncertainty in these parameters will be used to define the uncertainty in the boundary fluxes. The flux at the local model boundary will be specified based on the range of uncertainty, or the head at the boundary may be specified, and the flux will be used as a constraint on the total flow through the model. This reliance on local variability to constrain the local and near-field models will maximize the range of conceptual models that may be examined.

Initial Flow Conditions

The initial hydraulic heads in the CAU, local, and near-field models will be determined from a combination of measured values and interpolations of the regional groundwater flow model hydraulic heads. Calibration of the CAU-scale groundwater flow model will be required to match simulated heads to measured hydraulic heads. This steady-state flow system will then become the initial condition for transient flow and transport simulations if the data to perform such analysis is available. The transient flow and transport simulations will include the effects of water well pumping.

For the local and near-field models, the initial conditions will be based primarily on the local heads, but may be supplemented with the head distributions from the CAU model.

5.1.3.2.3 Groundwater Flow Model Calibration

Calibration of the local and CAU groundwater flow models is the process of matching historical data and is a prerequisite for making predictions with the models. Calibration refines the modeled representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater flow system. A verification of the model calibration using transient simulations may also be performed as part of this task.

During the model calibration, input parameters will be adjusted until the flow simulation results match site-specific information such as measured water levels and discharge fluxes within predetermined ranges. Input parameters will be adjusted within their known ranges based on data (if sufficient data exist), or based on accepted estimated ranges (if data do not exist or are scarce). In accordance with American Society for Testing and Materials (ASTM) Standard Method D-5981-96 (ASTM, 2002a), the range of values for the calibration parameters will be presented in the data documentation packages. The calibration will produce quantitative and qualitative measures of the degree of correspondence between the simulation and site-specific information related to the physical hydrogeologic system. The degree of correspondence between the simulation and the physical hydrogeologic system can then be compared to previous simulations to ascertain the success of calibration efforts and, if needed, to identify potentially beneficial directions for further calibration efforts. Quantitative measures of correspondence will be developed based on the analysis of hydraulic head data. This will parallel the same effort that was undertaken for the regional groundwater flow modeling (DOE/NV, 1997a).

The calibration of the local and CAU models will be conducted in two steps. First, a sensitivity/ uncertainty analysis will be performed to bound ranges of flux into the models. For the local models, the range of boundary fluxes will be determined from variability in hydraulic gradient and hydraulic conductivity based on local data. For the CAU model, the range of boundary fluxes will come from the uncertainty in the regional groundwater flow model. The steady-state CAU and local models will then be calibrated to observed water levels and to the bounds of the fluxes.

After the steady-state calibration process is completed, a verification of the calibration will be implemented to verify the steady-state results. The verification test may be in the form of a transient analysis or other quantitative test (e.g., geochemistry) of the model.

The groundwater flow model for the Rainier Mesa/Shoshone Mountain area will be calibrated using ASTM standard guidance for calibrating groundwater models. The *Standard Guide for Calibrating a Ground-Water Flow Model Application* (D-5981-96) (ASTM, 2002a) is a guide for calibrating porous medium (continuum) groundwater flow models. The method can be adjusted to use on other types of groundwater models such as multiphase models, noncontinuum (karst or fracture flow) models, or mass transport models.

The ASTM standard procedures that will be used to implement the guidance cover the use of site-specific information (D-5490-93) (ASTM, 2002b), applying modeling to site-specific problems (D-5447-93) (ASTM, 1993), defining boundary conditions (D-5609-94) (ASTM, 2002e), initial conditions (D-5610-94) (ASTM, 2002f), performing sensitivity analyses (D-5611-94) (ASTM, 2002d), and documenting groundwater flow model applications (D-5718-95) (ASTM, 2000a).

5.1.3.3 Contaminant Transport Model Development

After the groundwater flow models are calibrated, the contaminant transport model portion will be constructed. The contaminant transport models build upon the groundwater flow models by simulating the movement of contaminants in the groundwater flow field calculated by the groundwater flow models. The groundwater flow models generate the hydraulic head field from which the specific discharge vectors are determined. The contaminant transport models account for a wide variety of processes including dispersion, advection, chemical interactions (sorption), radioactive decay, and matrix diffusion. The following sections discuss the data that are used to simulate the transport, explain the model setup, describe the process of evaluating the sensitivity of the transport models to parameters, and define the uncertainty analysis.

The near-field models simulate radionuclide release from the melt glass and cavity exchange volume and simulate complex chemical interactions, including aqueous complexation, surface complexation, ion exchange, precipitation and dissolutions reactions along the flow path from the point of release to several cavity radii outside the cavity. For the local models, the transport simulations will be performed as appropriate for the flow model. For example, if the local model is a simple one or is a multidimensional analytic solution of groundwater flow, the appropriate transport model may also be analytic. Other local models may be one- or multidimensional numerical flow models to assess the direction and flux of groundwater. For these models it would be appropriate to simulate transport along one-dimensional (1-D) flow lines determined from the local flow models. In some cases, simple advective transport may be sufficient and simple particle tracking would be sufficient. If radionuclide concentration is required, the one-dimensional transport models will include the important processes such as advection, dispersion, matrix diffusion, linear adsorption, and radioactive decay. These one-dimensional transport simulations could be finite-difference or finite-element models as was the case for the regional transport simulations (IT, 1996h) or may be streamline particle tracking (SPTR) as is available with the FEHM code. The SPTR approach tracks particles along 1-D streamlines and accounts for processes such as advection, dispersion, adsorption, matrix diffusion, and radioactive decay. By using large numbers of particles, the concentrations can be calculated along the pathline.

The simulation of radionuclide transport with the CAU model using the traditional solution of the 3-D advective dispersion equation (called the reactive transport model in FEHM) is likely to be very difficult to accomplish. To reduce dispersivity to small values leads to a problem that is known to be difficult to solve accurately (Zyvoloski et al., 1997a). One approach to reduce the inaccuracies is to reduce the grid size and time step. This approach quickly leads to a model that has too many nodes. For the CAU model, it is unlikely that an accurate solution can be achieved using the classical 3-D solution. Rather, the CAU model will rely on a large number of 1-D transport solutions along pathlines to define the maximum extent of the contaminant boundary. In addition, although it is not expected to produce accurate results at the CAU scale, the 3-D reactive transport model will be used to perform selected simulations to demonstrate the difference between the two methods. The reader is cautioned that this approach is untested and may not be successful. If unsuccessful, alternative approaches will be proposed.

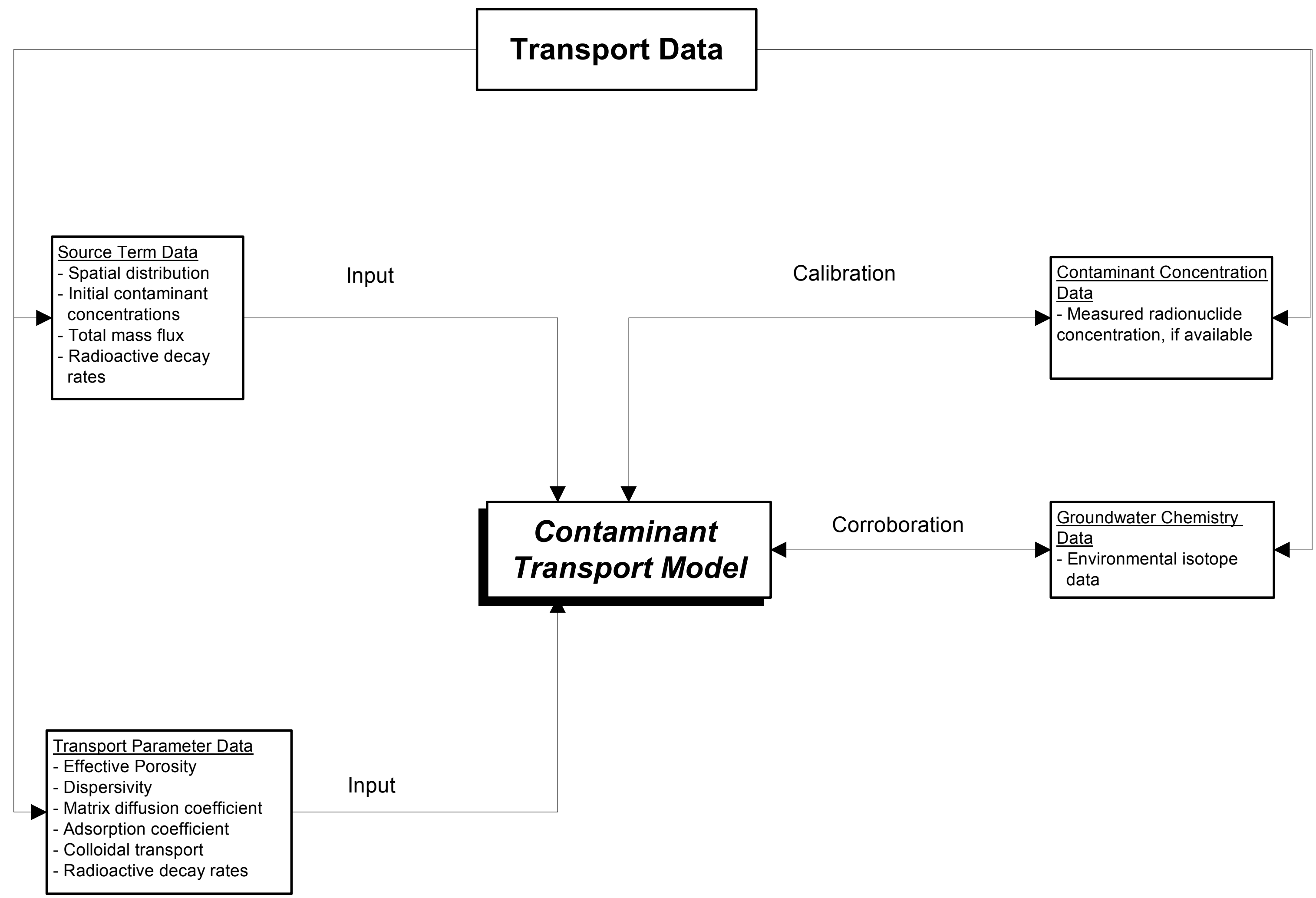
5.1.3.3.1 Contaminant Transport Data Assessment

A wide variety of data types are required to simulate contaminant transport in the groundwater system. As discussed in Section 5.1.1 and shown in Figure 5-2, relevant existing and newly acquired contaminant transport data will be gathered and compiled into a comprehensive database. The existing and newly acquired CAU-specific data will have the highest priority. However, non-CAU specific data may be included in the development of the conceptual model, particularly to provide additional constraints on parameter uncertainty.

As shown in Figure 5-5, the data types needed for input to the contaminant transport model include source term, effective porosity, radioactive decay coefficients, distribution coefficients, matrix diffusion coefficients, matrix porosity, a description of the fracture geometry, and a description of colloid-facilitated transport. Measured radionuclide and environmental isotope concentrations are also needed. Radionuclide concentrations are required for calibration of the transport model, but calibration may not be possible until the classified source is simulated, and even then there are difficulties. The unclassified source term does not represent any specific underground test. Therefore simulations using this source term may be adequate for CAU-wide calculations, but will not be expected to match local observations, even if every other parameter in the model were known with certainty. Likewise, the classified source will not be specific to every underground test in Rainier Mesa/Shoshone Mountain and again it may be possible to match local data. The environmental isotope data will be used for comparison to the conceptual models. They will not be part of the transport simulations.

Initial Source-Term Conditions

Two source-term datasets will be defined for the Rainier Mesa/Shoshone Mountain CAU Model. One source term will be based on unclassified data and will be extrapolated to all underground tests in Rainier Mesa and Shoshone Mountain. Later, a classified source-term estimate based on test-specific information will be used to calculate the final location of the contaminant boundary.



Source: Modified from DOE/NV, 2000a

Figure 5-5
Data Types and Utilization in the Contaminant Transport Model

For the unclassified data, the initial concentration data will be derived from the work conducted by LLNL. Some of the data collection tasks, described in detail in Section 6.0 of this report, may directly or indirectly contribute to improvements in the hydrologic source term. These tasks are the drilling and sampling of new wells and geophysical surveys. The source term calculated by LLNL is anticipated to provide estimates of the following source term components:

- The spatial distribution of the source term in and near an average test cavity
- The concentration of radionuclides dissolved in the groundwater for an average test cavity
- The leach rate for radionuclides currently incorporated into the melt glass
- The release rate of sorbed radionuclides in the rubble
- The mobility of radionuclides in the cavity, fracture zone, and the near-field undisturbed zone

This information will be used, in part, to update the current list of potential contaminants based on concentration, release rate, and mobility. It is anticipated that LLNL will provide the flux of radionuclides (mass per unit of time) leaving the vicinity of the test cavity and rubble chimney.

The scale of the local and CAU models will be larger than that of the source-term model. The spatial distribution of contaminants will be integrated in the larger scale transport models to preserve total mass. The release rate from the rubble zone and cavity will be summarized in terms of a total mass flux, again to preserve the total mass exiting the cavity and chimney. This contaminant mass flux will serve as the source term for the transport simulations. In all cases, the element sizes will be defined to ensure that initial concentrations are consistent with cavity observations or predictions. The researchers at LLNL are developing ways to scale the detailed calculations of the source term model into effective parameters that are appropriate for the local and CAU models. In particular, the mobility of radionuclides in the near-field undisturbed zone (i.e., outside the cavity of the test in the host rock that is undisturbed by the test) will be described by effective retardation coefficients that will be used in the larger scale models.

Effective Porosity

The advective velocity of a contaminant (assuming no chemical or diffusion interactions) is the same as the mean water velocity. The water velocity is defined as the groundwater flux (from the flow model) divided by the effective porosity which is a measure of the interconnected pore space through which water and solutes migrate. The effective porosity values for the Rainier Mesa/Shoshone Mountain CAU model will come from several sources, and will be assessed and combined using the data transferability protocol (SNJV, 2004a). First, the data from the BULLION forced-gradient tracer experiment (IT, 1996a; IT, 1998a; Reimus and Haga, 1999) will be of primary importance for the fractured VA. Additional supplemental data will come from fracture porosity estimates and an application of the cubic law to fracture data obtained from several studies of fracture characteristics in boreholes and core. For the LCA, limited additional fracture porosity data are available from tracer tests in wells WW-C and WW-C-1 as well as from the Amargosa Tracer Test Site (IT, 1996g). Interpretation of the ER 6-1 tracer test (scheduled for fiscal year 2005) should also provide additional data. Expert elicitation as part of the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b) analyses provides an estimate of the range of effective porosity values for the fractured LCA and fractured VAs. For the porous units such as the AA and the VCU, the core and geophysical log data summarized in reports by Burkhard (1989) and IT (1996g) will be used to estimate effective porosity values. Other sources of information, including Howard (1985) will be examined to compile the final data sets. It is expected that a mean value and uncertainty range will be established for each of the HSUs. For the porous units, the uncertainty ranges will be relatively narrow and well constrained by data. For fractured units, the ranges are expected to be much larger and only poorly constrained.

An additional issue related to fracture porosity is the appropriate parameterization for the effective porosity at the CAU scale. Nearly all the measurements are based on small sample areas such as cores and boreholes. At these small scales, the range of values includes very small values which lead to very rapid transport velocities. However, in fractured rock, small porosities are generally associated with small hydraulic conductivities and consequently small groundwater fluxes. At larger scales, very different tracer responses are observed depending on whether flow is parallel to fractures or perpendicular to fractures, leading to differences in effective porosity of more than an order of magnitude. Such is the case of responses obtained from NTS tracer tests such as the BULLION forced-gradient experiment, the C well test (WW C and C-1), the Amargosa Tracer test, and tracers tests associated with Yucca Mountain. The results of these tests suggest that as the size of the model areas increase, the effective porosity may also increase. All of these considerations will be taken into account when the ranges of values for the uncertainty analyses are determined.

Radioactive Decay Coefficients

For each of the potential radioactive contaminants, radioactive decay coefficients will be defined. These values will be obtained from LANL, LLNL, or published sources. These values are known with high precision and will be assumed to be constants for the duration of the transport simulations.

Distribution Coefficients

The distribution coefficients for each of the potential contaminants will be obtained from published reports of laboratory experiments. Published distribution coefficient values are typically quite variable (Triay et al., 1996 and 1997) and, therefore, have a wide range of uncertainty. For the transport simulations, an expected value for each radionuclide will be chosen from the published ranges. Published data will be assessed and combined using the data transferability protocol (SNJV, 2004a). Typically, the expected value will be chosen to be conservative (i.e., closer to the low side of the range of values). Although these values are quite uncertain, it is not expected that this will significantly impact the predicted contaminant boundary location. As observed in the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004b), the location of the contaminant boundary over a period of 1,000 years was dominated by the most mobile radionuclides. Unless the sorbed radionuclides have a small distribution coefficient, they will lag behind the more mobile radionuclides and contribute significantly to the leading edge of the contaminant boundary.

Matrix Diffusion Coefficients

Based on the regional contaminant transport modeling (IT, 1996h) and the VOIA (SNJV, 2004b), it is expected that matrix diffusion will be an important mechanism controlling the rate of radionuclide migration and, therefore, the location of the contaminant boundary, particularly in the LCA. The matrix diffusion coefficient controls, in part, the rate at which a contaminant will diffuse from a fracture into the surrounding rock matrix. All things being equal, the faster the diffusion, the slower the contaminant will appear to move relative to the movement of the groundwater. Matrix diffusion coefficient estimates for volcanic units will be available from the BULLION tracer experiment (IT, 1998a). Additional data for volcanic units are available from Reimus et al. (1999). Other measurements of the diffusion coefficient are available from the literature and will be evaluated to assess the range of uncertainty in the matrix diffusion coefficient values. The limited diffusion data available will lead to large uncertainty ranges for the diffusion coefficient. Data from these sources will be assessed and combined using the data transferability protocol (SNJV, 2004a).

Matrix Porosity

The matrix porosity defines the volume of water in the matrix into which contaminants can diffuse. The larger the volume, the more contaminant that can diffuse into the matrix and be stored there. Numerous matrix porosity values are available for the geologic units of the Rainier Mesa/Shoshone Mountain area. Many of these data are available from core and geophysical logs. The matrix porosity values are uncertain, but the range is typically much smaller than for many of the other parameters. More data are available for the shallower volcanic units than for the deep LCA. Matrix porosity will be included in the uncertainty analyses, but it is not expected to be one of the dominant parameters. Data from these sources will be assessed and combined using the data transferability protocol (SNJV, 2004a).

Description of the Fracture Geometry

The description of the fracture geometry, spacing, orientation, and fracture aperture all factor into the estimate of matrix diffusion. Much of the fracture spacing and orientation information for fractured volcanic and carbonate units was identified previously within description of effective porosity. The uncertainty in the fracture parameters will be estimated from the available analyses. The fracture spacing is a parameter that controls, in part, the rate of diffusion into the matrix. The fracture orientation was used in the past to correct the spacing values measured in vertical boreholes. The fracture aperture is not readily measurable from core or geophysical logs. One method of calculating an effective aperture is via the cubic law as was done in the Pahute Mesa Value of Information Analysis (IT, 1998b). Another method was used to calculate an effective aperture from the BULLION tracer experiment (IT, 1998a). The difficulty with any of these approximations will be the nonuniqueness of the value. The effective porosity of a fractured geologic unit made up of planar fractures is a function of the aperture and the spacing. Assumptions regarding the spacing and the appropriateness of a planar fracture model will limit the accuracy of such a calculation.

Colloid-Facilitated Transport

The transport of contaminants via colloids may be an important consideration in fractured HSUs. In previous discussions, it was stated that sorbing nuclides are not likely to impact the determination of the location of the maximum extent of the contaminant boundary because they will travel at a slower rate than non-sorbing nuclides. However, if these sorbing contaminants attach to colloidal-size particles, they can be transported much more rapidly than would otherwise be expected. Research at LANL is being conducted to define a way to measure and simulate colloid transport in groundwater flow systems. If colloid-facilitated transport is deemed an important process, it will be described in the Rainier Mesa/Shoshone Mountain CAU model report.

Contaminants

Measurements of radionuclide concentrations in water samples may be useful in evaluating the CAU model predictions. Evidence of radionuclide migration away from test locations, if available, may be compared with the range of simulated results of the CAU model and local models. These data will be evaluated to provide further confidence in the simulations.

As noted in earlier sections, comparison of model predictions to measured radionuclide values may prove problematic in many cases. Predictions made with the unclassified source term, while useful for demonstrating transport processes, are not expected to be comparable with local data because the unclassified source is unlikely to be representative of the local conditions. If any comparisons to measured radionuclide concentrations are to be successful, it will require simulations with source estimates that are appropriate to the particular test location. In general, this requires test specific data that are typically not available.

5.1.3.3.2 Transport Model Setup

The transport simulations build upon the flow paths generated by the groundwater flow model. The source data will be obtained from near-field modeling. Depending on the radionuclide, the source for each nuclear test will be simulated either as an initial concentration or as a flux of radionuclides per volume of water passing through the cavity, melt glass, and chimney as determined from the near-field modeling. The initial runs will be performed using an averaged source term derived from unclassified data. Final runs will use classified source information. The classified results, while expected to be more representative of actual conditions than the unclassified source, may not be accurate at the individual underground test scale. Other parameter values such as dispersivity, matrix porosity, matrix diffusion, and effective porosity will be determined on a HSU basis. Initially, mean parameter values will be determined for each HSU. Later, during the uncertainty analyses, the variability in parameter values will be included in the calculations.

The transport model setup may differ for the local and CAU models. The local models will be created to assess the impact of features or processes on the movement of radionuclides, but do not necessarily need to calculate radionuclide concentrations. Therefore, particle tracking methods may be employed for many of the local model simulations. If approximate concentrations are needed, the Residence Time Transfer Function (RTTF) method for the FEHM model may be used. The RTTF method allows for very fast calculation of concentrations using particles while including the retardation associated with matrix diffusion and sorption. The concentration can be determined from the RTTF method if a large number of particles are used. The RTTF method is very efficient and is capable of simulating a large number of particles, but has limitations that restrict it to advection dominated systems and suffers from numerical dispersion. Nonetheless, because of the calculation speed, it may be the best tool in cases where a comparison between two scenarios is required. The next level of simulation is the SPTR approach where the transport processes are calculated for particle that travel along a one-dimensional pathline determined from the three-dimensional flow model. The SPTR is capable of more accurately simulating concentrations than the RTTF method, but is computationally less efficient than RTTF. In selected cases, the solution to the full three-dimensional advection-dispersion equation will be calculated. These models are known to be difficult to solve accurately and typically require fine spatial and temporal resolution to be successful.

The CAU model may also use all of the techniques from simple particle tracking to the RTTF and SPTR approaches, to potentially calculate the solution of the one-dimensional transport equation along pathlines. At the scale of the CAU model, the likelihood of successful simulation of the three-dimensional reactive transport equation is doubtful because of grid and time step constraints.

5.1.3.3.3 Transport Model Calibration

Any known groundwater radionuclide concentration data will be evaluated as additional calibration targets. The amount of concentration data is generally quite limited and may not be at an appropriate scale, but every attempt will be made to include existing data. A particular difficulty in calibrating concentration data is that the actual source term for any test is classified. Therefore any comparisons that are made will involve one of two situations: (1) the source term is a generic term not representative of the test and, therefore, not appropriate for calibration or (2) the simulations and comparisons are performed in a classified environment. It is expected that the distance of radionuclide migration from any cavity at the present time is small compared with the scale of the CAU. Therefore, comparisons of model predictions to observed radionuclide concentrations would be most likely take place at the source term or local scale. It is not expected that meaningful comparisons could be made with the CAU model.

5.1.3.4 Sensitivity Analyses

The purpose of the sensitivity analyses is to determine the change in the model predictions due to changes in parameter values. A systematic process will be implemented whereby a parameter is increased and then decreased a constant factor from the calibrated value and additional simulations performed to identify the change in calibration residuals.

Sensitivity analyses are similar to the uncertainty analyses of parameter values except that each parameter is varied a fixed amount rather than over its range of uncertainty. To perform the sensitivity analysis, each parameter will be increased, then decreased by a fixed amount (for example, a factor of 2). The resulting change in the predicted contaminant concentrations will be compared for each parameter. This provides an assessment of the most sensitive parameters.

Identifying the more sensitive parameters is important for two reasons. First, the more sensitive a parameter is for calibration of the groundwater flow model, the narrower the range of acceptable values that will result in acceptable calibration. Therefore, one may conclude that the most sensitive calibration parameters are defined within the narrowest range of uncertainty.

For the transport calculations, where predictions extend well into the future, the sensitivity analyses are interpreted differently. The most sensitive parameters for contaminant transport do not have reduced uncertainty because it is not possible to calibrate to future events. The most sensitive transport parameters identify the parameters of most concern.

Second, the sensitivity analyses will serve to guide data collection as part of the validation process to ensure that meaningful data are collected. Additionally, the monitoring network design will utilize the sensitivity analyses to help define monitoring locations and the type of data to be collected.

5.1.3.5 Assessment of Uncertainty

Uncertainty in this context refers to the uncertainty in the contaminant concentration in the CAU which in turn leads to uncertainty in the location of the contaminant boundary. The location of the contaminant boundary is determined via modeling; therefore, any uncertainty in the HSU model, source term, parameter values, or boundary conditions is a potential source of contaminant boundary uncertainty.

Alternative hydrostratigraphic models reflect differences in professional judgement regarding the geology of the CAU. Often the data are insufficient to differentiate between competing geologic interpretations. The importance of the competing interpretations can be evaluated by modifying the hydrostratigraphic framework model to reflect the alternatives and simulating the resulting changes in water levels and contaminant migration. For this analysis, a limited number of alternatives will be identified. Each alternative may require more than one simulation to evaluate. One example of this analysis is the assessment of the influence of fault zones. Faults may be barriers to flow, conduits of flow, or some function in between. In the model, fault zones can be identified individually and accounted for independently of the surrounding rocks. Several simulations with faults as barriers or conduits will assess the uncertainty due to fault properties.

Another example of an alternative interpretation would be the absence or presence of an aquifer unit. After identifying the location of the geologic unit in question, a simulation will be run with the unit configured in alternative ways. The resulting impact on the water levels and contaminant transport will be observed. In this way, the impact to contaminant predictions of adding or removing an aquifer unit from the geologic interpretation can be assessed.

Source-term uncertainty may come from uncertainty in the release scenario of the source, the initial concentrations; or a wide variety of other parameters such as pH of the water, surface area of the debris, temperature history, porosity, partitioning of radionuclides, and cavity exchange radius. The source-term release scenario describes the mode of radionuclide release. For example, some radionuclides such as tritium are assumed to be nearly 100 percent released to the groundwater shortly after the test cavity resaturates. Other radionuclides are incorporated into melt glass or chimney rubble and are released at a slow rate. The range of possible release scenarios will be included in a set of simulations in which the mode of release is varied among several possibilities that will be identified by the interaction of the CAU modelers with the source-term modeling group from LLNL.

Parameter value uncertainty comes from several sources and varies with the scale of the measurement. One source of uncertainty is limited data with which to estimate parameter values. A second source of uncertainty is the spatial variability of parameters. Uncertainty due to limited data is considered reducible because additional data will provide better estimates of the mean value. Spatial variability is an irreducible uncertainty because limited data collection does not provide sufficient information to define the spatially variable parameter in much detail. Parameters that are uncertain include hydraulic conductivity, recharge, effective porosity, matrix diffusion terms, and mean groundwater flux. The uncertainty in each of these will be described by a probability density function (PDF) and included in the Monte Carlo analyses along with the source-term parameters.

Monte Carlo simulations generally require that parameter values be sampled from a probability distribution and simulated for many trials (realizations) of the parameter value. This process can be time-consuming because it involves repeated model runs. For a large 3-D flow and transport model, it may become intractable to perform the many simulations that are often required.

The uncertainty due to the unmeasured spatial variability of hydraulic conductivity was considered to be of secondary importance by the Frenchman Flat External Peer Review Group (IT, 1999). Hydraulic conductivity is known to vary both laterally and vertically, even within the same aquifer unit. At a small scale (the near-field scale), these unmeasured spatial variations may strongly influence the direction, velocity, and dispersion of transported contaminants. At larger scales, the influence of small scale variation gets averaged and can be included via effective parameters. The small-scale variability may be included in near-field simulations, but will not be included at the local or CAU scale except via effective parameters.

Boundary condition uncertainty must also be considered. Two boundary conditions will be considered in the uncertainty analysis. One is the recharge component which may vary spatially and in magnitude. A second boundary uncertainty is the flux defined by the regional model. The boundary flux can be defined directly as a flux value or it can be calculated in the CAU model by defining hydraulic head at the CAU boundary using hydraulic conductivity. The magnitude and location of the flux is a function of the parameters used in the regional model (DOE/NV, 1997a). As a result, regional model uncertainty will produce an uncertainty in the CAU model. Each boundary uncertainty will be investigated by perturbing the values within acceptable ranges and observing the impact on the simulated contaminant concentrations. For the local models, the boundary uncertainty will be estimated using local hydraulic conductivity and hydraulic gradient data.

Many sources of uncertainty were identified in the previous discussion. The approach to quantifying the uncertainty in parameter values is via a probability distribution and the use of a Monte Carlo approach with Latin Hypercube sampling to generate parameter realizations that are used in the simulation model. The probability distribution of model response (contaminant concentrations) is determined from the simulations and provides an assessment of uncertainty in the model predictions. The advantages of the Monte Carlo approach are that it is relatively straightforward to implement, it can account for correlated parameters, it can incorporate spatially-correlated random variables, and it takes full advantage of the computational rigor of the CAU model. One disadvantage of the Monte Carlo approach is the computational burden of multiple simulations. This disadvantage can be reduced by selective sampling (i.e., via a Latin Hypercube Sampling technique) to reduce the number of realizations. The Monte Carlo method can provide a quantitative measure of the uncertainty in the location of the contaminant boundary as a function of the number of realizations that produced less distant contaminant boundary locations.

Assessment of sources of uncertainty that cannot be described via a probability distribution will be included in a different manner. The alternative interpretations of the HSU or conceptual hydrologic models, for example, will be described by a limited number of interpretations, not by a probability distribution. In these cases, the simulation of contaminant concentrations for each alternative provides a quantitative change in a measure (e.g., contaminant concentration contours), but does not provide a probabilistic assessment like the Monte Carlo approach does. The amount of change in the contaminant concentration contours from an alternative HSU model will be compared with the Monte

Carlo results to identify the comparable change due to parameter uncertainty. For example, if an alternative hydrostratigraphic model resulted in a 500 m change in the location of the contaminant concentration contours, this change would be compared with the change in the location of the contaminant concentration contours in the Monte Carlo analysis. If the 500 m change corresponded to a 55-percent confidence level, it would appear the uncertainty in the contaminant concentration contours due to that alternative geologic interpretation is small. If the 500 m change corresponded to a 90-percent confidence level, the alternative geologic interpretation would be considered more important.

5.1.4 Model Validation

The process of model validation, as applied to the CAU model, involves following a modeling protocol (a series of steps which help demonstrate that a given site-specific model is capable of producing meaningful results). This process stems from a philosophy that models can never be validated in the classical sense where model predictions are proven correct. Rather, as explained in ASTM Special Technical Publication (STP) 1288 (ASTM, 1996), the adherence to modeling standards provides modelers with tools that help a model survive attempts at invalidation. This increases the confidence in the model predictions. The steps of the modeling protocol are:

1. Establishment of model purpose
2. Development of conceptual model
3. Selection of a computer code and verification of code
4. Model design
5. Model calibration
6. Sensitivity and uncertainty analyses
7. Model verification
8. Predictive simulations
9. Presentation of model results
10. Postaudit

Most of these steps are detailed in ASTM D-5447, *Standard Guide for Application of a Ground-Water Flow Model to a Site Specific Problem* (ASTM, 1993). Each of the steps will be discussed individually in the following subsections.

5.1.4.1 Model Purpose and Objectives

The objectives of a given model guide the level of detail and accuracy required of the model. The CAU-scale model will be used to integrate a wide variety of data into a mass conservative description of contaminant migration in groundwater from underground nuclear test locations in a CAU. This CAU model is then used as a decision-making tool for that CAU during the CAI. In the terms of the *Standard Guide for Subsurface Flow and Transport Modeling* (ASTM, 2000b), a hydrologic model can be termed an aquifer simulator. This means that the model is used to assess the value of unknowns at specific locations and times, which requires a high degree of correspondence between the simulations and the physical hydrogeologic system. To the extent practicable, the model is designed to honor observed data to a specified degree of confidence by following a calibration process.

The model objectives can be summarized as follows:

- Develop a CAU model that has the ability to represent the physical and chemical features of the CAU groundwater flow system important to contamination migration, using the existing and newly-collected data.
- Simulate the concentration of individual contaminants downgradient of underground test locations over a time period of 1,000 years. These concentrations will be used to define a contaminant boundary based on SDWA standards.
- Use the CAU model as a tool to evaluate impacts of future flow system changes on the migration of contaminants in the CAU.

5.1.4.2 Conceptual Model

The conceptual model of interest to the CAU model includes the groundwater flow system and contaminant transport. The conceptual model of groundwater flow defines the characteristics and dynamics of the hydrogeologic system. The elements of a groundwater flow system conceptual model are defined in ASTM D-5979, *Standard Guide of Conceptualization and Characterization of Ground-Water Systems* (ASTM, 2002c). The contaminant transport conceptual model defines the sources of groundwater contamination and the mechanisms of contaminant migration in groundwater. The data used to construct the current conceptual model of groundwater flow and contaminant transport are presented in Sections 3.1 through 3.5 of this document. This conceptual model will be refined during the data assessment phase of the CAI as described in Sections 5.1.1, 5.1.3.2.1, and 5.1.3.3.1. Non-CAU specific data may be included in the development of the conceptual model, particularly to provide additional constraints on parameter uncertainty.

5.1.4.3 Selection of a Computer Code and Code Verification

The computer code selection is the process of selecting the appropriate software that is capable of simulating the characteristics of the physical and chemical hydrogeologic system, as identified in the conceptual model to the degree required to meet the objectives. The code selection process is described in Sections 5.1.2 and 5.1.3.1 of this document. Verification of the code, defined as the process of ensuring that the code algorithms are operating properly, is an important criterion of the code selection process. Typically, code verification is accomplished by comparing the model output to analytical solutions and, in some cases, to the results of other numerical models. To fulfill this requirement, only codes that have been thoroughly evaluated through a rigorous QA process will be considered in the code selection process.

5.1.4.4 Model Design

Model design is the process of transforming the conceptual model into a mathematical form. The process typically includes the data sets and the computer code. The model design process for the CAU model is given in Sections 5.1.3.2.2, 5.1.3.3.2, and 5.2.1 of this document. The last section, 5.2.1, describes how the CAU model will be integrated with the regional model. As described in Section 5.2.1, the regional model provides boundary conditions for the CAU-scale model.

5.1.4.5 Model Calibration

As defined in ASTM D-5981, *Standard Guide for Calibrating a Ground-Water Flow Model Application* (ASTM, 2002a), model calibration is the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater system. The model calibration process was defined in Sections 5.1.3.2.3 and 5.1.3.3.3.

For the CAU model, it is expected that most of the calibration will focus on water levels because the groundwater discharge locations will fall outside the boundaries of the CAU model and, therefore, will not be direct calibration targets of the CAU model. However, because the modeling process includes the regional groundwater flow model, the constraints imposed by distant groundwater discharge calibration targets in the regional model will become indirect calibration targets at the CAU scale via the boundary conditions. The hydraulic head calibration targets of the CAU model are expected to be more restrictive (refined) than those established for the regional model. Specific calibration target ranges for the CAU model will be documented as part of the calibration analysis.

Additional calibration targets based on ranges of regional groundwater flow model derived boundary fluxes may also be imposed if specified head boundaries are utilized. These will be combined with the hydraulic head targets and will utilize constraints placed on hydraulic conductivity by observed data. This whole process may be automated via a parameter estimation approach such as the one available in the PEST code (a commercially available computer code from Watermark Numerical Computing [2004]).

5.1.4.6 Sensitivity and Uncertainty Analyses

The sensitivity and uncertainty analyses are quantitative methods of determining the effect of variations in the parameter and boundary conditions (input parameters) on model predictions (output parameters). These analyses will follow ASTM D-5611, *Standard Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application* (ASTM, 2002d). The planned sensitivity and uncertainty analyses are presented in Sections 5.1.3.4 and 5.1.3.5 of this document. The resulting uncertainty in model predictions will be summarized in several forms and will include the contaminant boundary location and particle pathlines for conservative contaminants. The uncertainty analyses will include bounding calculations that are intended to capture 90 percent of the uncertainty by choosing uncertainty ranges for input parameters that extend from the 5- to 95-percent levels.

5.1.4.7 Model Review

A thorough review of the model will be performed to verify the modeling approach and to determine if the modeling process can move forward to the verification phase. The model will be reviewed by four groups: (1) an internal group made up of the UGTA TWG/Modeling Subcommittee,

(2) NNSA/NSO management, (3) an external peer review group whose members will be prominent members of the groundwater modeling community, and (4) NDEP. These groups will be tasked with assessing model adequacy. The internal and external peer groups will be asked to review the model and identify both strengths and weaknesses. In addition, the peer reviewers will be asked to assess the ranges of parameter uncertainty incorporated into the model and to verify that the range of parameter uncertainty is inclusive. In conjunction with the results of the peer review, NNSA/NSO management and NDEP will determine if the modeling process can move into the model verification phase by not rejecting the model as presented. If either NNSA/NSO or NDEP reject the model, NNSA/NSO and NDEP will enter into discussions to determine how to proceed. If neither NNSA/NSO nor NDEP reject the model, the model verification phase will begin.

5.1.4.8 Model Verification

Model verification is defined as the testing of predictions of the calibrated model against available data not used in the model construction and calibration. For the steady-state groundwater flow model, it is expected that all the available steady-state data will be used. Transient hydraulic head response data from the water supply wells located on the NTS may be used to verify the flow model calibration. This is presented in Section 5.1.3.2.3 of this document.

It may also be necessary for additional data to be collected for purposes of model verification. However, until the CAU modeling is complete, it is not possible to state what type of data should be collected and whether new wells will need to be installed. The new data collection types and locations may be determined from the model response to the uncertainty and sensitivity analyses. Data representing both model inputs and model outputs may be collected. These new data may potentially include water levels, model parameters, geochemistry parameters, and contaminant concentrations. These data will be compared against the results of the model predictions consistent with the time period in which the verification data are collected. The data collected for model verification will be designed to provide positive comparison to model inputs and outputs, and will be compared with the range of values corresponding to the 5- and 95-percent bounds of the specific parameter.

One of several approaches may be used to determine if the new data verify the model predictions. In the case of data for which the number of values are sufficient to determine a PDF, the new data will be shown to be consistent with the previously defined PDF. If a new datum falls within two standard deviations of the mean, that parameter will be considered verified. In other cases, for which upper and lower bounds are defined, the new datum will be compared with the bounds. The parameter will be considered verified if the new datum falls within the bounds of that parameter.

If the data significantly modify the PDF, or if many of the data fall outside of the 5- and 95-percent ranges, the model will not be verified. In this case, NNSA/NSO and NDEP will initiate discussions to identify the appropriate path forward.

5.1.4.9 Predictive Simulations

The stated purpose of the CAU model is to provide predictive simulations of radionuclide migration away from underground test cavities for a period of 1,000 years. For each contaminant, the model will predict the concentration in the model at selected time steps from 0 to 1,000 years. These data will be processed to calculate a contaminant boundary location. The contaminant boundary is defined as the maximum extent of contamination based on SDWA standards. The results will be presented as a median location of the contaminant boundary along with 5- and 95-percent locations of the boundary based upon the uncertainty analyses. Additional discussion of the predictive simulations is given in Section 5.1.5 of this document.

5.1.4.10 Presentation of Model Results

The model and results will be presented in the same level of detail as in the previous regional model documentation packages (DOE/NV, 1997a; IT, 1996f). The regional model documentation package included descriptions of the numerical model, model grid, boundary conditions, aquifer parameter assignments, model calibration, sensitivity analyses and presentation of results. For the CAU model, the same information will be presented for the groundwater flow model. Additional information will be added for the transport simulations. This additional information will include the transport parameters, unclassified source term, and results which will be presented in terms of the location of the contaminant boundary based on SDWA standards. The results will be presented as a median location of the contaminant boundary along with 5- and 95-percent locations of the boundary based upon the uncertainty analyses. Additional results showing contaminant concentrations and the location of the contaminant boundary at selected times will also be presented. These times may include the verification period, the end of the five-year proof-of-concept period, as well as other times that are of specific interest.

5.1.4.11 Post Audit

The final component of the validation process is the design of a postaudit data collection effort to provide longer term verification of the model predictions. The postaudit data collection will be integrated as part of the CAP. The details of the postaudit will not be available until the CAP is written. Nonetheless, the general approach to the postaudit will be aimed at continued verification that the model output uncertainty is inclusive of actual future conditions.

The predicted contaminant boundary will be the 95^{th} percentile of the Monte Carlo realizations calculated during the uncertainty analysis. As such, the boundary does not represent a specific prediction, but instead is an expected value derived from multiple simulations of flow and transport processes. The NNSA/NSO acknowledges that the location of the contaminant boundary will be uncertain and will provide a range of possibilities to include the uncertainty. The postaudit is designed to be the final stage of a thorough model validation process which will demonstrate that the contaminant boundary location is bounded with reasonable assurance.

5.1.5 Contamination Boundary Prediction

As specified in Section 2.1.2.2.1, the contaminant boundary is the maximum extent of concentrations exceeding SDWA standards at the 95-percent confidence level within 1,000 years. In the most general case, this would require a full set of Monte Carlo runs for each nuclide and then a summation of the 95-percent confidence level concentrations to determine the contaminant boundary.

Uncertainty in the contaminant boundary location will be evaluated using the Monte Carlo simulation results for parameters and will be combined with the uncertainty from the alternative hydrostratigraphic model simulations. In all cases, the contaminant boundary location will be calculated from the contaminant concentration data generated by the contaminant transport model.

5.2 Other Models Supporting the Rainier Mesa/Shoshone Mountain CAU Model

In the preceding discussion, several models were identified as providing input to the Rainier Mesa/Shoshone Mountain CAU model. Other models will be run in support of the CAU model: the regional flow model, and the LLNL hydrologic source-term model, and local models to address the impact of faults. The regional flow model provides the boundary conditions necessary to ensure that the CAU model is consistent with the regional flow system. The near-field hydrologic source-term model provides the spatial distribution, release rates, and near-source mobility of a variety of radionuclides. In addition, there may be one or more local models developed to address specific questions or processes.

5.2.1 Regional Groundwater Flow Model

The regional groundwater flow model (DOE/NV, 1997a) was created to provide the necessary regional framework within which the CAU model operates. The Death Valley Regional Flow System model (Belcher, 2004) supersedes the 1997 model, and will be used to support the Rainier Mesa/Shoshone Mountain CAU model. The regional model balances groundwater inflows and outflows on a regional scale to ensure that a large-scale model flow is consistent with measured water levels, inflows, and outflows. For the CAU model results to be considered valid, the groundwater flow through the CAU model must be in balance with the regional model predictions.

Regional fluxes are uncertain because of uncertainty in the regional flow model. Monte Carlo analyses will be used to define ranges of permissible boundary fluxes from the regional models. These boundary flux ranges will provide bounds at the groundwater fluxes into the CAU model.

5.2.2 Near-Field Groundwater Flow and Transport Model

The purpose and methodology used in the near-field groundwater flow and transport investigation are presented in this section.

5.2.2.1 Purpose

The source term, which defines the release of radionuclides to the groundwater from underground test locations, is a complicated process. The various potential contaminants are distributed unevenly into cavity fluids, the melt glass, the chimney rubble, and the intensely fractured region surrounding the cavity (Tompson et al., 1999). Additionally, the rate at which these contaminants are released to the groundwater is a complex interaction of contaminant, rock, and water interactions. The goal of this analysis is to better define the flux of contaminants away from underground tests while accounting for leaching, geochemical interaction, and colloid transport processes.

5.2.2.2 Methodology

The methodology used to perform the geochemical modeling and the hydrologic modeling in support of the Frenchman Flat CAU model (LLNL, 1999) may also be used in support of the Rainier Mesa/Shoshone Mountain CAU model. Use of this approach is complicated by the fact that no tests in the area are at or below the water table. A summary of this methodology is provided in this section.

Geochemical Modeling

One-dimensional reactive transport simulations of radionuclide migration through puddle glass, cavity region, chimney region, and volcanic rocks will need to be made using a code(s) such as GIMRT or OS3D (Steefel and Yabusaki, 1996) or other similar application to evaluate the efficacy and controls of migration and retardation. The code(s) will need to simulate multicomponent mass transport in porous and fractured media. The code(s) must provide for aqueous speciation assuming homogeneous equilibrium, kinetically controlled mineral dissolution and precipitation, and surface complexation. Geochemical models require the use of thermodynamic data for aqueous species, gases, and solids. GEMBOCHS (Johnson and Lundeen, 1997) is an example of such a thermodynamic database.

Hydrologic Flow and Transport Modeling

A 3-D flow model must be developed to understand the flow system in the near-field area, and integrate reactive transport and glass dissolution from the geochemical modeling. Spatial resolution must permit smaller-scale variabilities of material properties such as hydraulic conductivity, porosity, or mineral abundance to be considered. In addition, a refined representation of radionuclide inventories or other chemical distributions must be considered. The spatial resolution must allow for numerical dispersion effects produced by coarser grids to be minimized, and permit more defensible simulations of real processes to be made. Numerous groundwater flow and contaminant transport codes were evaluated by the UGTA TWG/Modeling Subcommittee. It is possible that the appropriate code for the near-field model will be selected from the list evaluated by this group.

The near-field simulations, which incorporate complex geochemical reactions, will provide the basis for simplifications in the CAU modeling. It is expected that much of the detail in the near-field model can be summarized into a smaller number of simpler mathematical models to describe CAU-scale processes of importance, such as colloid transport. These mathematical models will be used in the CAU model.

5.2.3 Local Models

A number of local models may be developed to address specific questions or issues that may impact the transport of contaminants within the local groundwater system. An example is a local groundwater flow and transport model (perhaps 5 km in length on a side) that is designed to assess the migration of radionuclides along faults from the volcanic units to the underlying LCA.

The local groundwater flow and transport models will not be linked directly to the CAU model, but rather they will be used to investigate a process or phenomenon that may influence radionuclide migration in the Rainier Mesa/Shoshone Mountain area. These models will be much smaller in size than the CAU model and will not necessarily require 3-D formulations. Each local model will have a specific goal. For example, the fault modeling will have as a goal the quantification of the range of mass flux of radionuclides in the LCA. This range would then be used to bound the mass flux into the LCA in the CAU model. As necessary, the local models will be bounded by existing data.

6.0 Field Investigation

This section includes a discussion of the characterization activities for the Rainier Mesa/Shoshone Mountain CAI. The activities were designed to collect information in support of the groundwater flow and contaminant transport model described in Section 5.0 of this CAIP. The process to be followed for proposing any necessary additional characterization activities is outlined. Descriptions of related support activities involved in the Rainier Mesa/Shoshone Mountain CAI are also provided.

6.1 Investigation Activities

The Rainier Mesa/Shoshone Mountain CAI includes three major characterization activities. They are as follows:

- Drill two wells at Rainier Mesa and one at Shoshone Mountain
- Sample new wells and existing locations
- Collect and evaluate geophysical information from Rainier Mesa and Shoshone Mountain

These activities are discussed in the following subsections.

6.1.1 Drill Wells at Rainier Mesa and Shoshone Mountain

Boreholes will be drilled at Rainier Mesa and Shoshone Mountain with the objective of improving the hydrogeologic characterization of the CAU. Table 6-1 lists the proposed coordinates, planned depth relative to the predicted occurrence of groundwater for each of the boreholes. Figure 6-1 is a topographic surface view showing the locations of ER-12-3 and ER-12-4 on Rainier Mesa, and Figure 6-2 shows the location of ER-16-1 on Shoshone Mountain. Plate 2, which is a detailed geologic map of the surrounding area, shows the cross section traverses. The proposed wells and existing boreholes are also plotted on the map. Plate 3 shows a south-north cross section through the Rainier Mesa/Shoshone Mountain CAU, and west-east cross sections through Rainier Mesa and Shoshone Mountain. These cross sections are drawn through available 3-D HSU models. The cross sections were constructed from the Regional HSU model on the east and the Pahute Mesa CAU HSU model on the west. Figure 6-3 is a closer view of the HSU cross section showing ER-12-3 located on Rainier Mesa, Figure 6-4 shows ER-12-4 located on Rainier Mesa, and Figure 6-5 shows the cross-sectional view of ER-16-1 on Shoshone Mountain. Final locations will be surveyed to provide

Table 6-1
Proposed Well Locations

Well Site Name	UTMN (NAD 27) (m)	UTME (NAD 27) (m)	Surface Elevation (ft)	Planned Total Depth (ft)	Depth to Regional Water Level Depth (ft)	Depth to Perched Water (ft)
ER-12-3	4,116,592.2	569,748.3	7,389	5,000	3,189	> 1,100
ER-12-4	4,119,345.6	572,473.2	6,880	3,500	2,680	> 950
ER-16-1	4,095,916.2	570,900.3	6,563	4,000	2,563	N/A

accurate coordinates. The wells will be drilled and completed as wells to collect information concerning the following areas:

- The location and water chemistry of perched water zones in the TCU and/or in the pre-Tertiary section
- Identification of the location of the pre-Tertiary surface and identification of pre-Tertiary geologic units
- Information on the regional water table with respect to depth/elevation and water chemistry
- Hydraulic data

Several vertical exploratory boreholes were drilled on or near Rainier Mesa (Figure 6-1), and several intercept the pre-Tertiary surface. However, most of the boreholes that intercepted the pre-Tertiary surface penetrated less than 100 ft into the pre-Tertiary rocks. These boreholes encountered a variety of lithologies that underlie the Tertiary volcanic section at Rainier Mesa, including granite, dolomite, limestone, schist, quartzite, and siltstone. Only three boreholes were drilled to depths sufficient to encounter the regional water table: Well HTH-1 at the south end of Rainier Mesa, Well ER-12-1 near E-Tunnel, and Well ER-19-1 drilled just west of Rainier Mesa. The three new well locations were selected to provide new data that cannot be obtained from existing boreholes.

The following sections describe various aspects of Rainier Mesa and Shoshone Mountain hydrogeology that will be addressed by these wells.

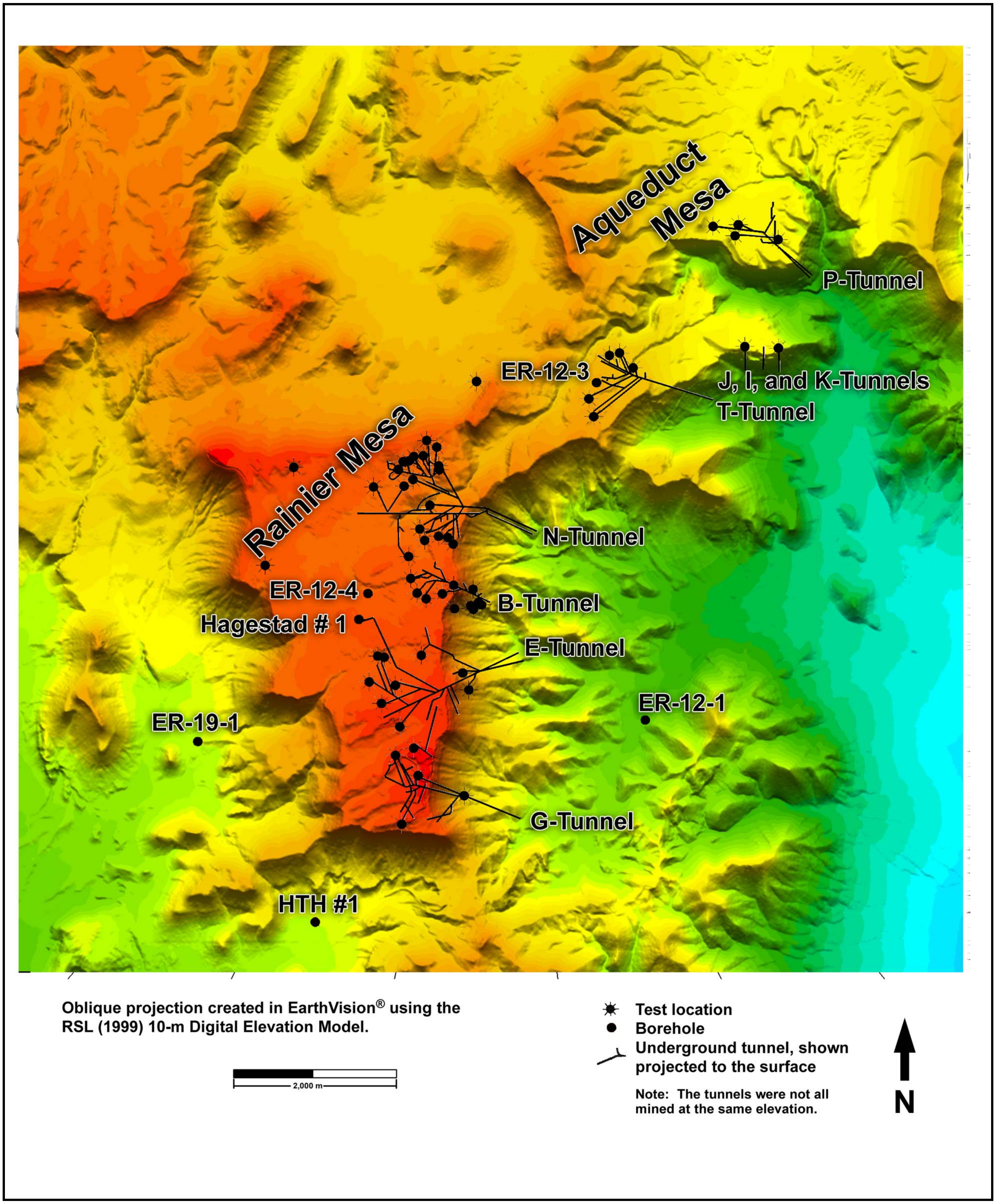


Figure 6-1
Proposed Well Locations at Rainier Mesa

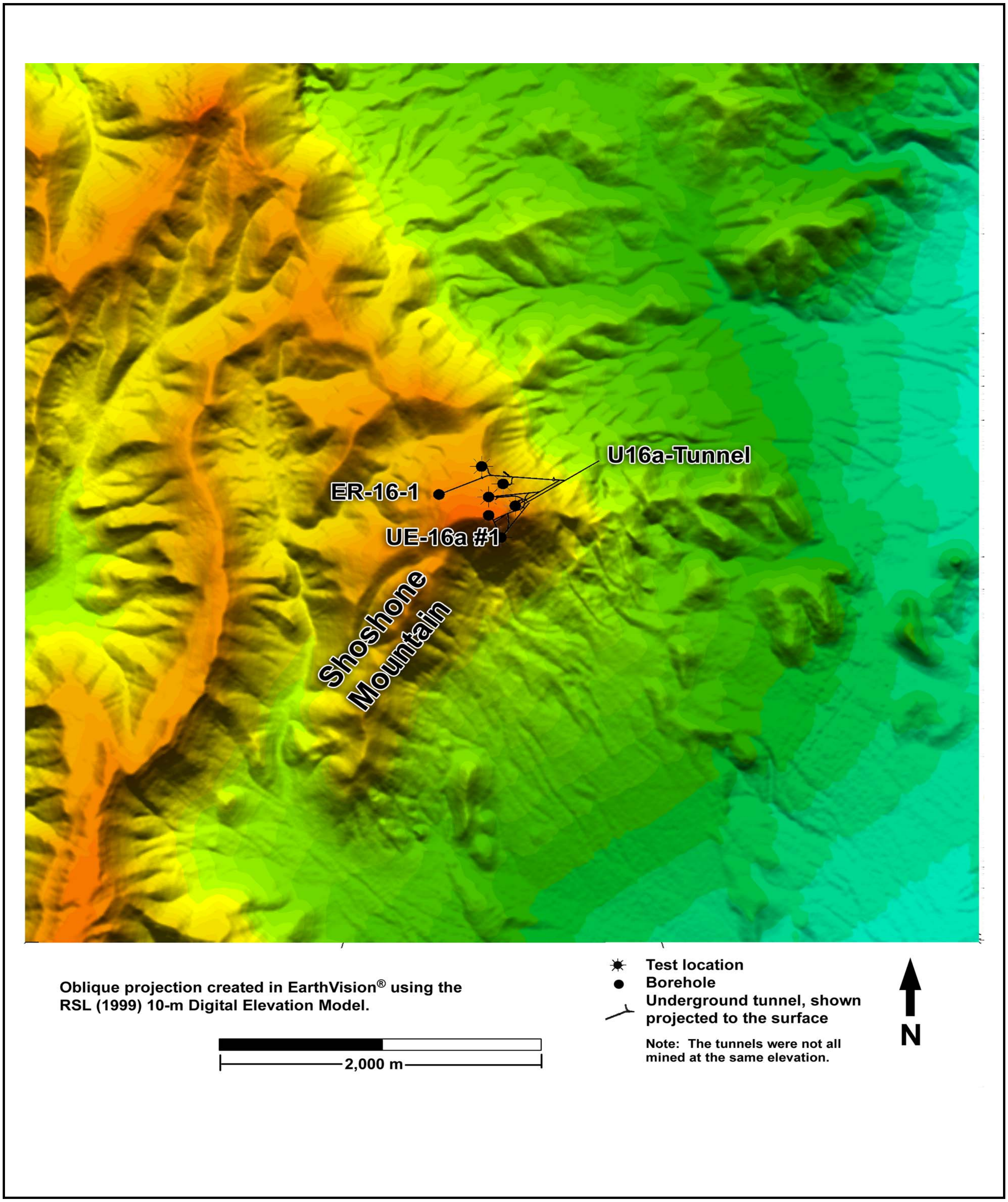


Figure 6-2
Proposed Well Location at Shoshone Mountain

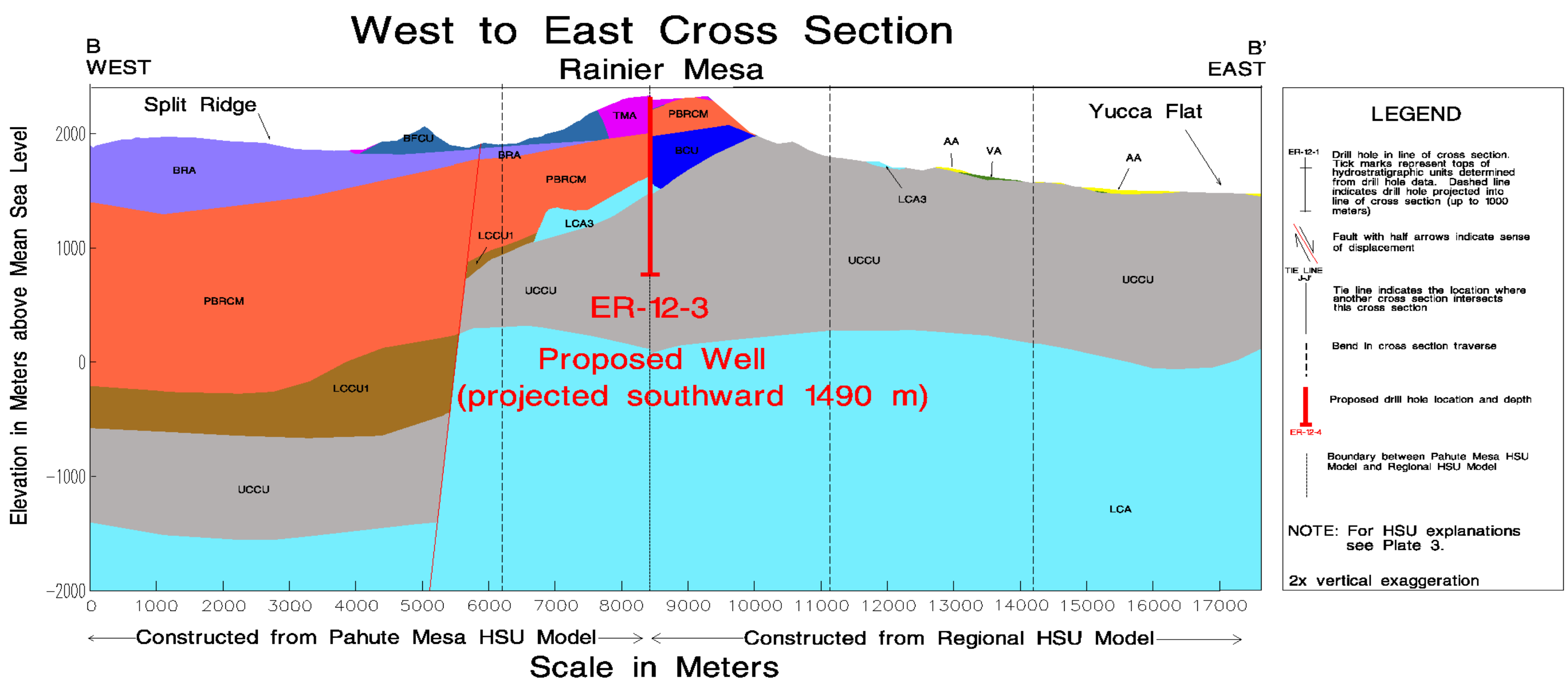


Figure 6-3
Cross Section Showing the Proposed Location of Well ER-12-3

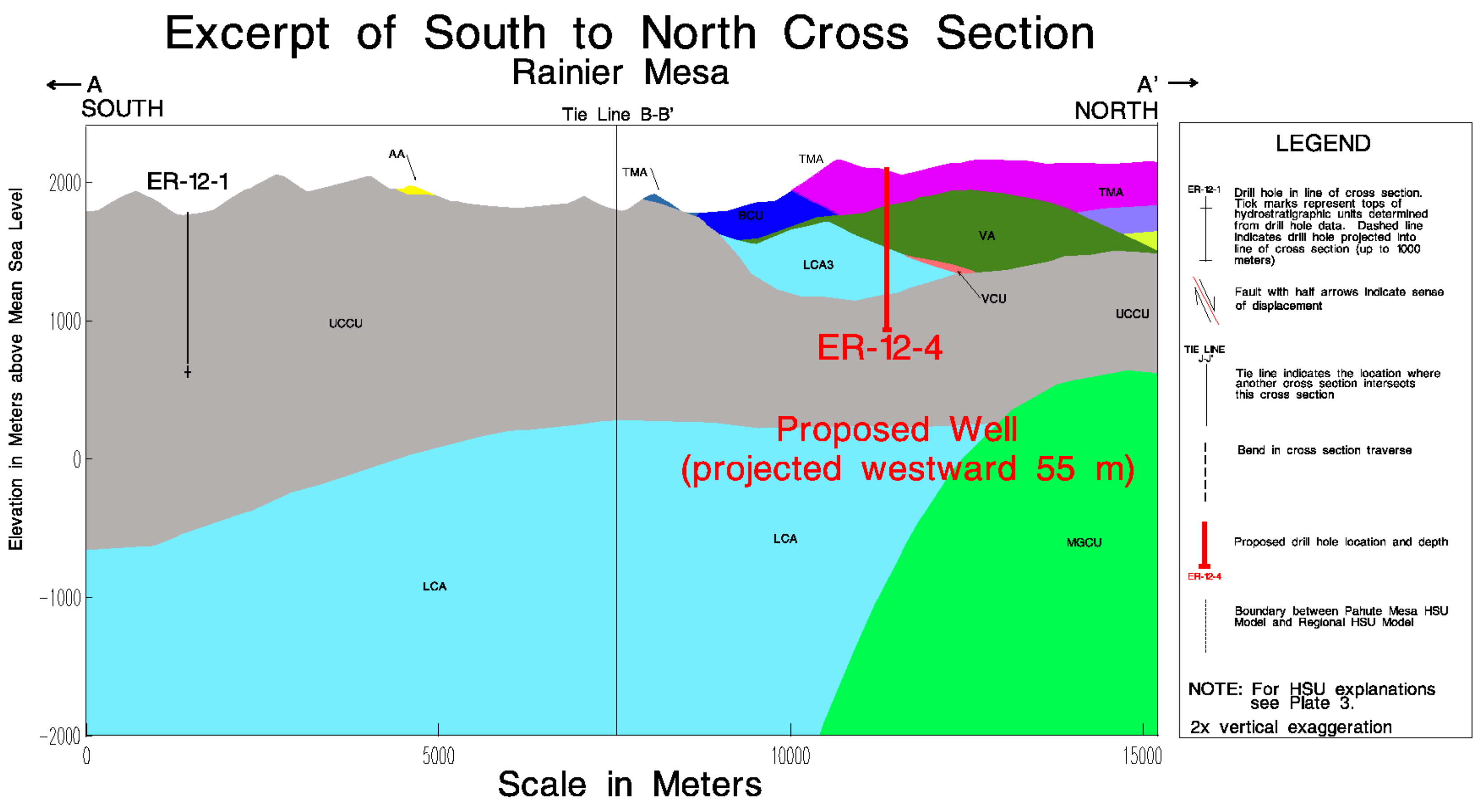


Figure 6-4
Cross Section Showing the Proposed Location of Well ER-12-4

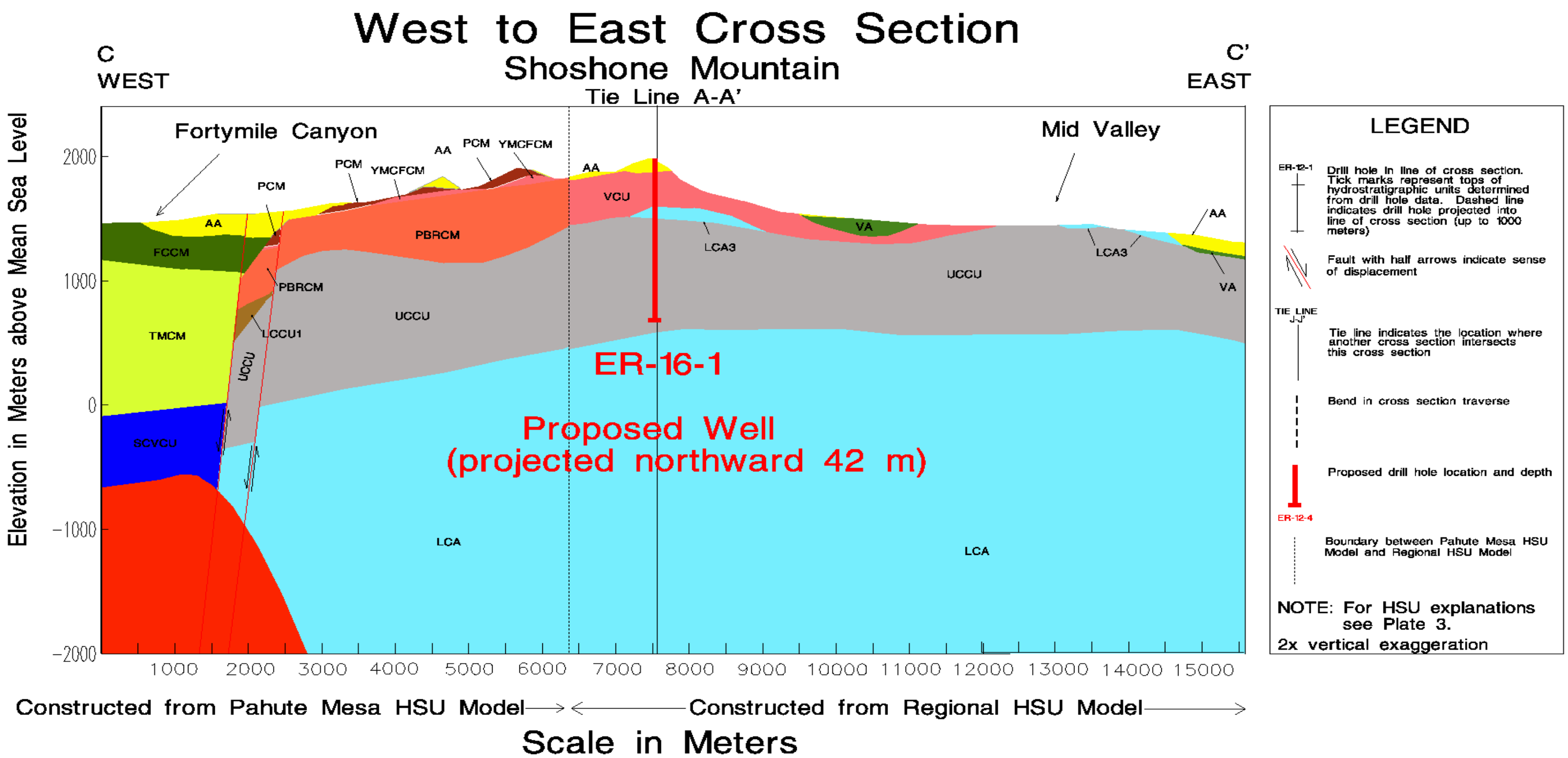


Figure 6-5
Cross Section Showing the Proposed Location of Well ER-16-1

Pre-Tertiary Rocks

The planned wells will provide new data, supplement existing information, and improve understanding of the nature of the pre-Tertiary geologic units under Rainier Mesa and Shoshone Mountain, facilitating the interpretation of the hydrogeologic settings near the contaminant sources within areas of Rainier Mesa and Shoshone Mountain. Data from these wells will address:

- HSUs that directly underlie the working points of tests conducted on Rainier Mesa and Shoshone Mountain
- Influence of the Gold Meadows Stock on the distribution of pre-Tertiary sedimentary and metamorphic rocks beneath the CAU that may be incorporated into the geologic framework model
- Potential presence of the Belted Range thrust
- Identification of a significant structure in the pre-Tertiary rocks (i.e., a paleo-valley and/or a fault) by the depositional synform observed in the tuff section
- Structural factors that control the region between Aqueduct and Rainier Mesa
- The nature of fracturing in the TCU (BCU), LCCU1, and LCA3

Regional Water Table

These new wells will provide information on the elevation of the regional water table at Rainier Mesa and Shoshone Mountain, and improve understanding of regional groundwater gradients. Data from these wells are presented to address the following subjects:

- Influx of groundwater from the north
- The significance of the influence of the Gold Meadows Stock on a groundwater influx
- Significant vertical groundwater gradients
- The hydraulic character of the LCA3 and other HSUs under the areas of investigation
- The effect of the synform on the migration of perched groundwater

Perched Water

No existing boreholes or wells located in the areas of Rainier Mesa or Shoshone Mountain have provided any hydraulic information on the perched water system. The nature of perched water in the CAU was only studied for part of T-Tunnel (not including water chemistry). Data from the new wells will be assessed with respect to the following:

- Multiple perched groundwater systems
- The hydraulic character of the various confining units (Tertiary and pre-Tertiary) below the working points
- Contaminants present in the perched groundwater systems

6.1.1.1 Well ER-12-3

Well ER-12-3 is sited in north central Rainier Mesa, about 1,450 ft northeast of Hagestad #1, and west of the B-Tunnel complex (Figure 6-1). It may be accessed by existing dirt roads that provide access to older drill holes on top of Rainier Mesa.

Figure 6-3 and cross section B-B' from Plate 3 show the interpretive subsurface geology of Well ER-12-3. The surface geology is Rainier Mesa ash-flow tuff. Pre-Tertiary quartzite rocks are expected to be encountered at a depth of approximately 2,250 ft bgs.

The hole will be drilled to 4,500 to 5,000 ft bgs, with the goal of penetrating the thrust sheet and drilling into the UCCU. The proposed well will be completed with a single open interval within the pre-Tertiary, and piezometers may be installed if perched water is identified at shallower depths.

The scientific objectives for Well ER-12-3 are the following:

- Identification of perched water zones
- Determine synformal structural geometry, especially at depth
- Determine the depth to the pre-Tertiary units
- Determine pre-Tertiary stratigraphy/lithology/HSU and the presence of the LCA3 or LCCU1
- Identify pre-Tertiary structures
- Identify the regional static water level
- Define the vertical hydraulic gradient
- Better define the spatial extent of the Belted Range Thrust fault
- Determine the hydraulic characteristics of permeable zones
- Geochemical characterization of water in permeable zones
- Find potential test-related radionuclides in groundwater

6.1.1.2 Well ER-12-4

Well ER-12-4 is sited at the west end of T-Tunnel near UE-12t #4. The proposed location may be accessed by existing dirt roads that provide access to older drill holes on top of Rainier Mesa. The proposed access road to Well ER-12-4 will go around the east side of the MIGHTY OAK (U-12t.08) surface ground zero.

Figure 6-4 and cross section A-A' from Plate 3 show the interpretive subsurface geology of Well ER-12-4. The surface geology is Rainier Mesa ash-flow tuff. Pre-Tertiary limestone is expected to be encountered at a depth of approximately 2,400 ft bgs.

The hole will be drilled to approximately 3,500 ft bgs, with a goal of penetrating the pre-Tertiary units. The proposed well will be completed with a single open interval within the pre-Tertiary, and piezometers may be installed if perched water is encountered and identified.

The scientific objectives for Well ER-12-4 are the following:

- Identification of perched water zones
- Determine synformal structural geometry, especially at depth
- Determine the depth to the pre-Tertiary units
- Investigate older Tertiary and pre-Tertiary stratigraphy/lithology/HSU
- Identify pre-Tertiary structures
- Determine regional static water level
- Determine hydraulic gradient
- Identify potential test-related radionuclides
- Determine hydraulic characteristics of permeable zones
- Geochemical characterization of water in permeable zones

6.1.1.3 Well ER-16-1

This well is sited on top of Shoshone Mountain, near Tippipah Point on the UE-16a#1 drill pad (Figure 6-2). It may be accessed along the existing road from the west and south from Mid Valley.

Figure 6-5 and cross section C-C' from Plate 3 illustrate the current understanding of the geology in the Shoshone Mountain area. The surface geology is Tiva Canyon ash-flow tuff. Pre-Tertiary rocks are expected to be encountered at approximately 1,900 ft bgs.

The hole will be drilled to a depth of approximately 4,000 ft bgs, with the goal of drilling through the UCA and terminating drilling within the UCCU. The well will be completed with a single open interval within the pre-Tertiary. Piezometers may be installed if perched water is encountered and identified in the Tertiary and/or UCA. Alternatively, the main completion will require an open interval within the UCA with piezometers in the overlying volcanic section and the underlying UCCU.

The scientific objectives for ER-16-1 are the following:

- Investigate perched water (it would be below the tunnel level)
- Define geology below the tunnel level
- Determine the depth to the pre-Tertiary
- Determine tertiary and pre-Tertiary stratigraphy/lithology/HSU
- Determine regional static water level
- Determine hydraulic characteristics of permeable zones
- Characterization of groundwater in permeable zones
- Define relationship of the UCA/UCCU/LCA

Current models suggest very thick UCCU as the upper pre-Tertiary unit. Another possibility is a thin UCA of Syncline Ridge over thick UCCU.

6.1.2 Sample New and Existing Locations

The sampling and analysis of new and existing data at Rainier Mesa/Shoshone Mountain include groundwater characterization samples for geochemical analysis, long-term water-level monitoring, and surface-water investigations. The following sections address these issues.

6.1.2.1 Geochemical/Isotopic Analysis of Groundwater

Geochemical analysis activities include the compilation and review of Rainier Mesa/Shoshone Mountain geochemistry data and their interpretation. A component of the data interpretation may include geochemical modeling. These activities will further define and explain the geochemical evolution of groundwater within the Rainier Mesa and Shoshone Mountain groundwater flow systems.

6.1.2.1.1 Compilation and Review of Rainier Mesa/Shoshone Mountain Geochemistry Data

This activity provides the first step in the process of conducting a geochemistry-based evaluation to support the definition of flow paths, travel times, and groundwater budgets for the Rainier Mesa/Shoshone Mountain CAU-scale model. This activity will determine if the existing geochemistry data are of sufficient quality and quantity to support geochemical studies of the Rainier Mesa/Shoshone Mountain flow system. In addition, this activity will support geochemical modeling of the CAU-specific flow system.

Groundwater geochemical data will be extracted from the latest edition of the GEOCHEM database. The data sets will include geochemistry data from well and spring locations within the Rainier Mesa/Shoshone Mountain CAU and surrounding area. The data will be evaluated to determine if there are missing historical data, and if there are data gaps within GEOCHEM04 that can be filled.

New geochemical data include groundwater characterization samples from Wells ER-12-3 (Section 6.1.1.1), ER-12-4 (Section 6.1.1.2), ER-16-1 (Section 6.1.1.3), and Well ER-12-1, and from N- and T-Tunnels. Groundwater characterization samples will be collected from existing sampling points located at the gas-sealed doors and gas-sealed grouted plugs at the N- and T-Tunnel complexes to characterize groundwater that has accumulated within the tunnel complexes. At each of these sites, a variety of field parameters will be measured including water temperature, pH, specific conductance, dissolved oxygen, turbidity, and alkalinity. The groundwater samples will be analyzed for the following constituents:

- Major anions and cations
- Trace elements
- $\delta^{13}C$ for inorganic carbon and ^{14}C activity for organic and inorganic carbon
- Radioisotopes, including ^{36}Cl and tritium
- Strontium and uranium isotopic ratios
- Dissolved noble gases, including helium-3 (^{3}He)
- Stable isotopes of hydrogen and oxygen

Groundwater samples will also be collected from Well ER-12-1 using a dedicated electric submersible pump. Groundwater temperature, conductivity, and pH will be monitored during pumping. Stabilization of these parameters will indicate that purging is complete. These data will also be incorporated into future updates of the GEOCHEM database.

6.1.2.1.2 Data Interpretation

Data obtained from the field, laboratory, and compilation activities will be used to identify and verify groundwater flow paths, estimate groundwater ages, and evaluate groundwater flow velocities. Results from the groundwater sampling programs, combined with existing geochemical data from the latest edition of the GEOCHEM database, will be interpreted to provide geochemical constraints on flow paths determined by hydrogeologic modeling. Data that will be used during this activity will include major-ion chemistry, stable isotope results, and selected radioisotope data that correspond to the estimated Rainier Mesa/Shoshone Mountain source inventory.

Data permitting, calculated groundwater flow velocities based on geochemical tracers will be compared to velocities calculated from hydraulic measurements and from groundwater flow modeling. Based on results, consistent interpretations of hydrogeological and hydrogeochemical data will be made. Dissolved isotopic species such as ^{3}He, CFC, and dissolved inorganic and organic ^{14}C may be used to estimate groundwater ages and flow velocities. The ^{3}He and CFC data can be used to estimate travel times for situations where groundwater is older. Dating groundwater with ^{14}C requires knowledge of groundwater flow paths and geochemical reactions along the flow path because dissolved carbon is typically involved in reactions in the groundwater environment. Important chemical reactions that could affect ^{14}C transport are dissolution and precipitation of carbonate minerals along fracture surfaces and isotopic exchange with carbonates or soil gas reservoirs. Groundwater ^{14}C ages will be corrected to account for these reactions using data obtained during this investigation (e.g., $\delta^{13}C$ data from groundwater and calcite and ^{14}C data for calcite).

6.1.2.2 Water-level Monitoring

Long-term water-level monitoring will be conducted in the Rainier Mesa/Shoshone Mountain CAU. Well locations will be selected for their expected ability to provide pertinent information for the hydrologic modeling that will be done for the CAU. Surface and subsurface instrumentation will be installed to evaluate longer-term hydraulic response including elements of well recovery from episodes of pumping, barometric responses, and groundwater chemistry.

6.1.3 Collect and Evaluate Geophysical Data

An understanding of the subsurface hydrogeology is necessary to accurately construct a representative hydrostratigraphic model and simulate groundwater flow and contaminant transport beneath the areas of Rainier Mesa/Shoshone Mountain. Because of implications to the regional groundwater flow system, it is important to define the geologic structure and distribution of the Paleozoic rocks beneath Rainier Mesa/Shoshone Mountain. Distinct sedimentary units of the Paleozoic section form the major regional aquifer and aquitards (Winograd and Thordarson, 1975; Laczniak et al., 1996) and the lower boundary of the regional groundwater flow system

(DOE/NV, 1997a). Because there are no surficial exposures of Paleozoic rocks in Rainier Mesa/Shoshone Mountain, their distribution must be determined from borehole lithologic logs, geophysical logs, or less direct surface-based geophysical methods. Geophysical information will be evaluated for Rainier Mesa and Shoshone Mountain areas to improve the understanding of the geology and hydrostratigraphy beneath and between boreholes in the CAU.

Collection and Analysis of Magnetotelluric Data

Using available and newly collected geophysical data, hydrostratigraphic, structural information, and petrophysical information regarding the character of the pre-Tertiary section may be assessed. One method that will be used is audio magnetotellurics (AMT), which is an electromagnetic sounding technique that measures naturally occurring electric and magnetic fields in the earth's crust. These measurements will be compiled and processed to infer resistivity of the rocks in the subsurface to several kilometers depth.

The AMT 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, AMT data can be used to map lithologic units, if sufficiently thick, such as carbonate and shale that have significant resistivity contrasts. Within the Rainier Mesa/Shoshone Mountain CAU, AMT has the potential to provide hydrostratigraphic and structural information on the pre-Tertiary section, particularly the extent and thickness of the UCCU. Other geophysical methods such as gravity, magnetics, and seismic were unable to provide definitive information within the pre-Tertiary section at the NTS. Preliminary results from an AMT survey currently in progress in the Yucca Flat CAU are promising with regards to determining the extent and thickness of the UCCU beneath Yucca Flat. The Rainier Mesa/Shoshone Mountain AMT survey will include the installation of 25 AMT survey stations in the Rainier Mesa/Shoshone Mountain CAU westward of the existing Yucca Flat lines. Figure 6-6 shows the locations of the Yucca Flat AMT survey stations as well as the locations of the Rainier Mesa/Shoshone Mountain survey stations and the proposed boreholes. The stations will be at about 2 km spacing along five generally east-west transects through the Rainier Mesa/Shoshone Mountain CAU. This will allow consistency with the stratigraphic framework model that was developed for the area to the east of the Rainier Mesa/Shoshone Mountain CAU. Specific objectives for the AMT survey are the following:

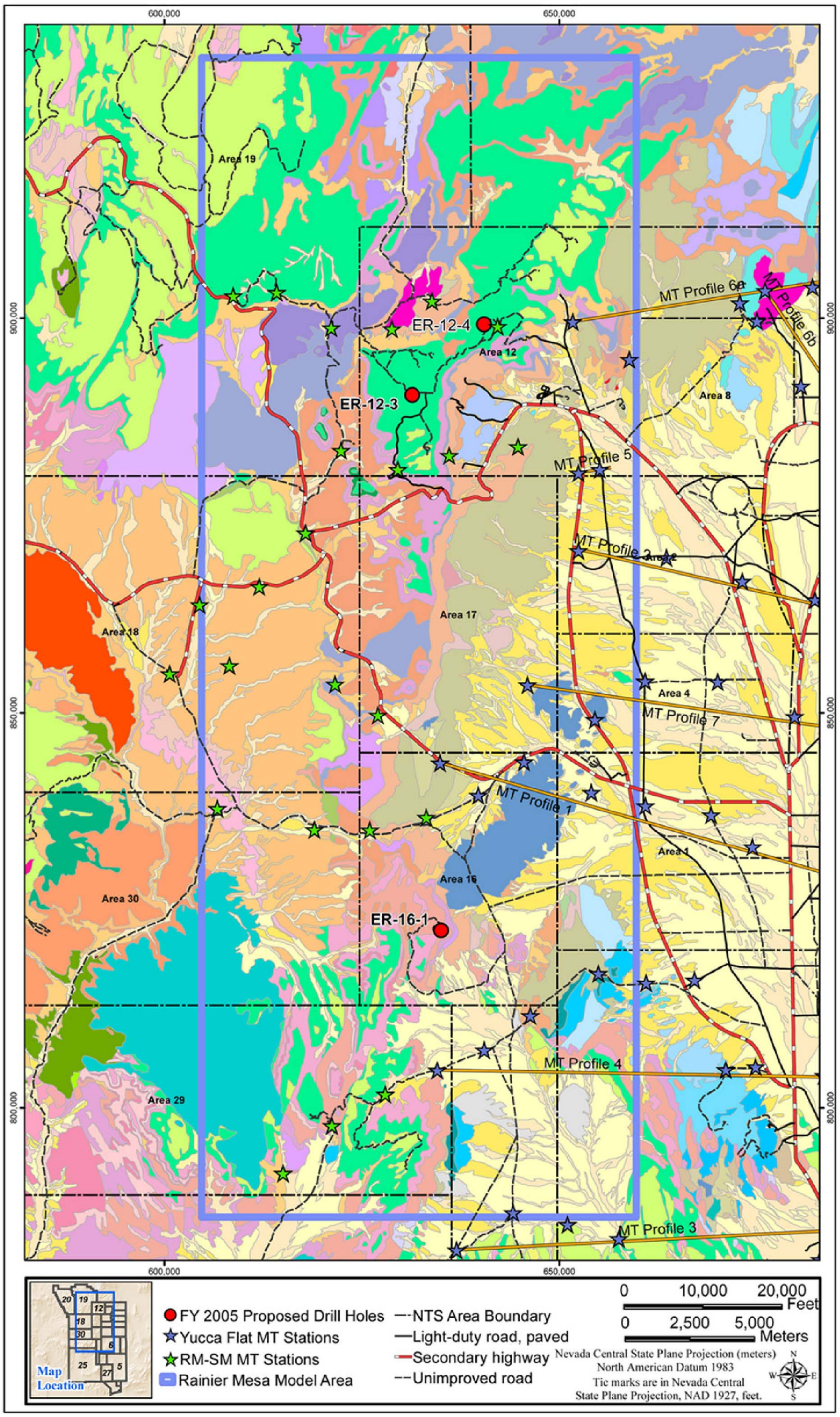


Figure 6-6
AMT Survey Transect Locations

- Determine the western extent of the UCCU
- Better constrain the extent and thickness of the LCCU
- Better constrain the location of the Belted Range thrust fault
- Better constrain the Mesozoic granite confining unit (i.e., Gold Meadows Stock)

Borehole Geophysics

Geophysical data obtained directly from boreholes via wireline geophysical techniques will also be used to help identify specific hydrostratigraphic, hydrogeologic, and structural information within a borehole or well. In addition, various geophysical techniques will be able to provide petrophysical data that will be able to provide direct measurements such as porosity that will be helpful in identifying ranges of hydraulic properties. Hydrophysical logging techniques within the saturated portions of boreholes or wells may also be employed under ambient and stressed conditions to aid in identification transmissive zones of groundwater flow within the borehole.

Although this data may have direct application to the borehole in which it was acquired, the analysis of the data and comparisons to similar data collected in other boreholes or wells may allow for the interpretation of hydrogeologic conditions over the greater area of Rainier Mesa /Shoshone Mountain CAU.

6.2 Additional Characterization Activities

The potential for additional characterization activities is an integral part of the UGTA strategy as discussed in Section 2.0 of this document.

If after completion of the CAU-scale model, NNSA/NSO and NDEP cannot agree upon the model or the contaminant boundary, NNSA/NSO and NDEP will determine if the strategy (as defined in Appendix VI, Revision No. 1 [December 7, 2000] of the FFACO [1996]) can still be achieved through the collection of additional data. If both parties agree that the strategy can still be achieved, NNSA/NSO will collect additional data.

The types and/or locations of the acquisition of new data would be determined using the results of the CAU-scale model, particularly those of the sensitivity analysis and the peer review. Following collection and analysis of the new data, the CAU-scale model would be recalibrated, if necessary, and used to simulate the location of the contaminant boundary. Plans for the new data collection and analysis activities and model update would be documented in an addendum to the CAIP.

6.3 Field Support Activities

Field support includes those activities associated with the acquisition of scientific data and information; including waste management, health and safety, and sampling and analysis. These support activities, along with the current versions of the documents that set forth the corresponding policies and practices to be followed, are discussed in the following subsections. The CAI activities will be conducted under the policies and practices that are in effect at that time. General descriptions of field support activities are provided to cover the CAI work that is previously described Section 6.0 and potential future CAI work.

6.3.1 Waste Management

Waste management is one element of a comprehensive on-site environmental compliance program to be implemented at Rainier Mesa/Shoshone Mountain investigation sites. The development of this program is tailored to anticipated site conditions; however, it includes contingencies in the event field operating conditions change. Periodic field evaluations are conducted to ensure proper implementation of this program and on-site compliance. The program also includes waste minimization (Section 6.3.1.2) and fluid management (Section 6.3.3.2). The details of the comprehensive compliance program may be found in the *Underground Test Area Project Waste Management Plan* (WMP) (NNSA/NV, 2002b) and site-specific planning and field documents. The UGTA Fluid Management Plan (FMP) is included as an appendix to the WMP (NNSA/NV, 2002a).

Waste management covers the segregation, tracking, characterization, and disposal of wastes generated during field activities. Rainier Mesa/Shoshone Mountain CAI activities that are expected to generate waste may include drill site construction, well drilling, well completion, well development, testing, and sampling operations (herein termed well installation activities). Other investigation activities may also include periodic groundwater sampling of newly installed wells and existing wells. Also, waste in the form of personal protective equipment (PPE), sampling equipment, and drilling materials is generated as a result of this investigation.

The largest volume of waste generated during drilling and sampling activities is effluent (fluids) and groundwater. The management of fluids and groundwater produced at the Rainier Mesa/Shoshone Mountain wells is addressed in the UGTA FMP (NNSA/NV, 2002a), discussed later in this section. Other wastes, such as sanitary, hydrocarbon and hazardous waste, are generated as a result of the operation and maintenance of heavy equipment, as well as other support functions as part of the specific type of activity.

6.3.1.1 Investigation-Derived Waste Management

Management of investigation-derived waste (IDW) is described in the UGTA WMP (NNSA/NV, 2002b), which provides a general framework for waste management at Rainier Mesa/Shoshone Mountain investigation sites. Details regarding the characterization, storage, treatment, and disposal of wastes generated at Rainier Mesa/Shoshone Mountain investigation sites are to be addressed in site-specific field instructions or similar working-level documents. All wastes generated as a result of the Rainier Mesa/Shoshone Mountain investigation activities are to be managed and disposed of in compliance with applicable federal, state, and local laws and regulations.

Based on an evaluation of available data and technical input from scientists supporting the UGTA program, the wells that are currently proposed for drilling and completion are considered to be far-field wells. This indicates that the potential for generating radioactive waste is remote. As for any other well, in the event that the wells are found to be radionuclide-contaminated, they will be converted to near-field wells. The presence of tritium in excess of the fluid management criteria listed in the UGTA FMP (NNSA/NV, 2002a) will require the well to be reclassified as a near-field well. The designation of near- and far-field is important since the waste management strategies for the near- and far-fields wells differ. Near-field activities require establishment of a controlled area where radioactive contamination would be closely monitored and managed; far-field activities do not.

Process knowledge regarding the presence of hazardous materials or radioactive contaminants as well as data from sampling and analysis, combined with available on-site monitoring results, are used to define the waste management strategy for each well location. The potential for generating hazardous, radioactive, and mixed waste streams are assessed separately for each well location. Prevention of hazardous waste generation is emphasized during the operations conducted under this CAIP. When required, personnel are trained and procedures implemented to address management of radioactive and hazardous waste streams.

Waste characterization is based on the results of process knowledge, fluid management monitoring and sampling, and groundwater characterization sampling. This information is used to assign the appropriate waste type (i.e., sanitary, hydrocarbon, hazardous, radioactive, or mixed) to the IDW. Direct sampling of waste may be necessary if process knowledge is inadequate for characterization.

6.3.1.2 Waste Minimization

The generation of IDW is minimized through the implementation of the comprehensive compliance program. Waste minimization is achieved through the control of hazardous materials, materials substitution, and waste segregation. Hazardous materials are controlled, managed, and tracked in accordance with Occupational Safety and Health Administration (OSHA) requirements and applicable procedures and protocols. Material substitution is implemented wherever possible to prevent or minimize the generation of a hazardous waste. Waste such as effluent and PPE are segregated to the greatest extent possible to minimize the generation of hazardous, radioactive, and/or mixed waste.

6.3.2 Health and Safety

The health and safety of workers and the public as well as protection of the environment will have the highest priority during the Rainier Mesa/Shoshone Mountain CAI, in accordance with the DOE Integrated Safety Management System. Worker protection will be achieved through compliance with DOE Orders, OSHA regulations, the primary Real Estate/Operations Permit (REOP) holder's health and safety plan (HASP), and field activity work packages (FAWPs). Requirements specified in these documents are subject to change, and the work performed for this CAI is to be conducted in accordance with the most current published versions of these documents.

The UGTA HASP (BN, 2001b) is the governing document under which all UGTA environmental restoration operations are conducted. The UGTA HASP prescribes the minimum procedures that will be followed while performing field operations and describes the roles and responsibilities of key project personnel. Its requirements are written to comply with DOE Orders and federal regulations such as 29 CFR 1910 (CFR, 2004b) and 29 CFR 1926 (CFR, 2004c).

Individual subprojects, sites, and/or tasks require the production of a FAWP to identify the nature of anticipated work, particular site features, hazards communication, and protective measures to be employed on that site. Work will be conducted in accordance with the FAWP which will address the anticipated physical, chemical, and radiological hazards associated with the activity. The FAWP will be written to comply with the requirements of the HASP.

The principal hazards associated with activities at drilling sites are those general or physical hazards associated with industrial operations. These activities involve heavy equipment operation, potential for falling objects, and rotating and moving machinery. Environmental conditions such as the weather and terrain may increase the potential for accidents. The remoteness of some of these sites and the terrain may delay the response time for medical and fire services. During the spring, summer, and fall months personnel may encounter snakes, spiders, and scorpions. Some deer mice in Nevada have been found to carry the hantavirus. Although the possibility of encountering deer mice in Rainier Mesa/Shoshone Mountain may be low, the risk still exists and needs to be accounted for during planning or field activities.

Hazardous chemicals, including lead, at levels of occupational health concern are not anticipated in the groundwater. The only anticipated source of chemical hazards to workers is from the materials brought on site. These materials may include fuel for the drill rig and generators; small volumes of nitric, hydrochloric, or sulfuric acid to be used as sample preservatives; and testing standards and reagents used for groundwater analysis. Proper storage and handling of these materials, as outlined in the FAWP, reduce the potential for accidents involving chemical hazards.

When radiological constituents are present in groundwater at levels of occupational health concern or are anticipated due to the proximity of the well to an underground nuclear test, additional documents apply. Work controls are guided by the NTS Radiation Protection Program (RPP) (BN, 1999), NV/YMP Radiological Control (RadCon) Manual (BN, 2000b), and 10 CFR 835, “Occupational Radiation Protection” (CFR, 2004a). The NTS RPP establishes the policy by which radiological doses are maintained within acceptable limits and radiation exposures are maintained as-low-as-reasonably-achievable (ALARA) below these limits. The NV/YMP RadCon Manual represents DOE-accepted guidelines and best practices for implementing NTS and YMP radiation protection programs in accordance with 10 CFR 835 regulations (CFR, 2004a).

Groundwater from the wells installed as part of the Rainier Mesa/Shoshone Mountain CAI is not anticipated to contain radionuclide concentrations above levels considered safe to drink. The only radionuclide that may be encountered at elevated levels is tritium in the form of tritiated groundwater. Due to the distance of the wells currently planned for completion from underground nuclear tests, significant amounts of tritium or mixed fission products are not expected to be encountered. As a precautionary measure, operations are conducted to ensure that personnel exposure to water vapor, splashes of groundwater, and drilling fluids are minimized and that access to the site is restricted to only personnel involved in the field activities.

The tritium concentration in groundwater produced at the surface is monitored hourly. If tritium is detected above the action level set in the HASP/FAWP, operations are conducted in accordance with 29 CFR 1910 (CFR, 2004b) and Radiological Work Permits (RWP). Precautions include wearing water-impervious clothing when handling materials that have contacted the groundwater and the establishment of radiologically controlled areas to prevent the contamination of personnel. Engineering controls such as closed fluid transport systems and sampling enclosures may also be invoked to prevent worker contact with groundwater and keep potential exposure ALARA. Workplace radiological monitoring is specified in the RWP(s) and is used to control potentially contaminated materials and to prevent these materials from leaving the established radiologically controlled area. Such precautions also control potential contamination from other radionuclides.

6.3.3 Sampling and Analysis

Sampling and analysis of solids and fluids will be performed during this investigation. The associated activities include sample collection, on-site field screening for potential contamination, and off-site laboratory analysis. On-site field screening for the leading indicator contaminants is conducted to reduce the risks to the environment and ensure the health and safety of project personnel and the public. Laboratory data are used to ensure compliance with program requirements and for characterization of process materials and the groundwater.

6.3.3.1 Solid Sampling and Analysis

Solid samples of interest include surface and subsurface soils and rock cuttings and cores collected from the boreholes during drilling.

Surface and subsurface soil samples may be collected prior to initiation of construction activities. At drilling pad sites, nonintrusive surface radiological surveys will be conducted with portable survey instruments. Surface and shallow subsurface soil samples will also be collected for field and laboratory chemical and radiochemical analysis.

Rock cutting samples are collected from the drilling fluid discharge line as the borehole is advanced. Core samples are collected using percussion sidewall, rotary sidewall, vertical rotary, or similar techniques. The sampling frequency and intervals for collection of rock cuttings and core samples are performed in accordance with task-specific plans and the appropriate procedures. Field screening for any potential contaminants is conducted at each sample interval. Field analysis of rock cuttings and core samples is performed by on-site geologists to describe and identify the rocks penetrated during drilling operations. Laboratory testing to determine hydrologic, physical, and chemical properties may also be performed on selected cuttings and core samples.

The activities associated with the collection, processing, and description of cuttings and core are performed as directed in task-specific plans and in accordance with approved procedures.

6.3.3.2 Fluid Sampling and Analysis

Fluid samples of interest include process fluids and groundwater. Process fluids are those fluids produced during the drilling, well construction, development, and purging activities that occur prior to the collection of a representative groundwater sample. They include drilling compound formulations, water produced during well completion, well development activities, and water purged prior to sampling. Groundwater is defined as water that is considered representative of the aquifer and is suitable for sampling and aquifer characterization purposes.

Fluids generated during all phases of the operation are managed in accordance with the UGTA FMP (NNSA/NV, 2002a), site-specific plans, and field instructions. Fluids produced during drilling, well completion, and well development and testing are collected for both field and laboratory analysis. Fluids that do not meet the fluid management criteria for release to an unlined infiltration basin are contained in lined sumps.

In addition, fluids produced during well purging or development are monitored for pH, conductivity, and temperature to determine stabilization prior to the collection of groundwater characterization samples. These activities are conducted in accordance with the site-specific plans, field instructions, and the appropriate procedures. Additional parameters may be included as prescribed in the site-specific plans and instructions.

Groundwater samples include characterization samples from newly installed wells and samples from wells used as water-supply wells for drilling and well construction. Groundwater characterization samples are collected from the newly installed wells at the completion of well development and periodically thereafter until the well is taken out of service or until monitoring is no longer required. Water-supply wells are sampled prior to their use. Sampling and analysis of the water-supply wells ensure that the groundwater is free of target constituents. It also establishes background water chemistry and radiochemistry levels for constituents of concern and provides baseline data for wells not previously sampled.

Process fluid and groundwater samples are collected, processed, and transported in accordance with state and federal regulations and applicable standard procedures. If on-site monitoring or other knowledge indicates the potential for environmental samples to meet the definition of hazardous material under U.S. Department of Transportation (DOT) regulations, internal contractor procedures for the transport of hazardous materials shall be followed. These contractor procedures mandate compliance with applicable DOT shipping regulations. Specific guidance for this type of sampling is provided in site-specific plans and instructions and in accordance with appropriate procedures. Process fluid samples collected for fluid management purposes are analyzed for selected metals, tritium, gross alpha, and gross beta parameters as specified in the UGTA FMP (NNSA/NV, 2002a). All groundwater samples are then sent to analytical laboratories to be analyzed for the parameters listed in Table 5-1 of the UGTA QAPP (NNSA/NSO, 2003). The analyses listed in this table include metals, major ions, general chemistry, age and migration parameters, radiological indicator parameters, nuclear fuel products, and other radionuclides.

6.3.3.3 Quality Assurance

All sampling and analysis tasks are conducted in accordance with the requirements of the UGTA QAPP (NNSA/NSO, 2003). Section 7.0 of this CAIP provides a summary of the QA program.

6.3.3.4 Field Quality Control

Project participants ensure that field QC samples are collected and submitted to a selected analytical laboratory in a manner consistent with the UGTA QAPP (NNSA/NSO, 2003). The frequency, number, and type of QC samples collected during sampling activities are specified in site-specific plans, project plans, the UGTA QAPP (NNSA/NSO, 2003), and appropriate procedures. The types of QC samples may include field duplicates, equipment rinsate blanks, and, if necessary, rinsate source blanks. Collection and documentation of field QC samples are conducted in accordance with approved plans and procedures that meet the requirements of the UGTA QAPP (NNSA/NSO, 2003).

6.3.3.5 Waste Management

Waste in the form of PPE, sampling equipment, and drilling materials will be generated as a result of this investigation. Specific requirements for characterization sampling of these wastes are contained in Section 6.3.1.1 of this document and in the UGTA WMP (NNSA/NV, 2002b).

7.0 Quality Assurance

A comprehensive QA program was developed for all activities performed under the UGTA Project, including those defined in this CAIP. That program is documented in the UGTA QAPP, Revision 4 (NNSA/NSO, 2003). This CAI requires all three different types of activities addressed in the QAPP: assessment of existing data, modeling, and collection of new data.

7.1 Assessment of Existing Data

Section 5.1 of the UGTA QAPP addresses evaluation of data, including existing data. During the data documentation evaluation for this CAI, the level of knowledge about the data collection process and data traceability will be flagged. The five levels of Data Documentation Evaluation Flags are as follows:

Level 1: Data are collected in accordance with NNSA/NSO 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 is 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., ASTM, EPA methods, USGS procedures) and being 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 and prudency of data use or compliance with referenced 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 and listed in Part II of the Data Information Form.

Based on the traceability of the data, individual records will be further evaluated for suitability of use for the purposes of this CAI.

7.2 Modeling

The QA requirements for modeling are specific in Section 5.2 of the UGTA QAPP (NNSA/NSO, 2003) and generally consist of software/hardware configuration control, technical evaluation of new codes, code verification and validation activities, and software documentation. Output from modeling runs will be well documented and traceable to the code from which it was generated. Participating organizations' procedures will provide for the specific methods used for performing these activities.

7.3 Collection of New Data

Extensive requirements for the collection of samples to obtain new data are provided in Section 5.3 of the UGTA QAPP (NNSA/NSO, 2003). Participating organizations' standard procedures must meet the requirements of the QAPP and will be used to perform sample collection, handling, documentation, and analysis. Data from newly acquired samples will be evaluated against the criteria established in the UGTA QAPP (NNSA/NSO, 2003) and this CAIP prior to use.

8.0 Duration and Records/Data Availability

The duration of the CAI and availability of associated data and records are provided in this section.

8.1 Duration/Data Availability

The duration of the work as described in this plan, up to and including the preparation of the CADD, is projected to be approximately 5,811 days (i.e., 16 years) following the initiation of the CAI. Quality-assured results of sampling will initially be available within 90 calendar days of the date on which they are collected for the purposes of this investigation.

8.2 Document/Records Availability

This CAIP and all unclassified primary supporting documents/documentation are available to the extent allowed by law (and as addressed in paragraph XIII.3 of the FFACO [1996]), in the DOE Public Reading Rooms located in Las Vegas and Carson City, Nevada, and from the NNSA/NSO UGTA Project Manager. The NDEP maintains the official administrative record for all activities conducted under the auspices of the FFACO (1996). For further information about where to obtain documents and other data relevant to this plan contact Mr. Robert Bangerter, Project Manager, NNSA/NSO UGTA Project, at (702) 295-7340.

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Appendix A

Data Quality Objectives

A.1.0 Data Quality Objectives for Rainier Mesa/Shoshone Mountain: CAU 99

The Data Quality Objectives (DQO) process is a systematic project planning tool developed by the EPA to help collect environmental data for decision making. The EPA has published DQO guidance for implementing the process for various EPA programs (e.g., EPA, 1993 and 2000). Section 1.5, "Implementing Corrective Action Investigations and Corrective Actions," of the Corrective Action Strategy (Appendix VI of the FFACO [1996], Revision No. 1 [December 7, 2000]) states that DQOs will be conducted. The DOE and NDEP have agreed to hold kickoff meetings at the start of the DQO process for each CAU (DOE/NV, 1996b).

In accordance with this agreement, a kickoff meeting for the Rainier Mesa/Shoshone Mountain DQO process was held on May 6, 2004. Participants included the NNSA/NSO Project Manager, NDEP, and NNSA/NSO contractor personnel. An attendance list for the meeting is provided in Table A.1-1.

Table A.1-1
DQO Kickoff Meeting Attendance List

Name	Organization
Bob Bangerter	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office
Bill Wilborn	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office
Clem Goewert	Nevada Division of Environmental Protection
Michelle Stamates	Nevada Division of Environmental Protection
Barb Deshler	Stoller-Navarro Joint Venture
John Pickens	Stoller-Navarro Joint Venture
Tim Rose	Lawrence Livermore National Laboratory
Chuck Russell	Desert Research Institute
Maggie Townsend	Bechtel Nevada

A.1.1 Data Quality Objectives Approach

The FFACO (1996) requires that the DQO process be used to plan the corrective actions, but does not specify the format that guides the process or reports the results. The EPA has published various methods for implementing a systematic DQO planning approach. Among these methods is a three-step method (EPA, 1987), which was later expanded to a seven-step method (EPA, 1993 and 2000).

Figure A.1-1 presents the DQO approach used for the Rainier Mesa/Shoshone Mountain CAU and its relationship to the two EPA methods (EPA 1987, 1993, and 2000). The approach used for the Rainier Mesa/Shoshone Mountain CAU (center column of Figure A.1-1) is a logical, orderly progression that results in a clear statement of the data needed for the CAI. The approach consists of three major steps consistent with the three-step method (EPA, 1987). Although the approach does not match the seven-step method (EPA, 1993 and 2000), it offers similarities.

The first step is the *formulation of a statement of the decision to be made,* which includes the potential contaminants, the current conceptual model of the problem area, areas of uncertainty, and a statement of the decision at hand. This step corresponds to the first, second, and fourth steps of the seven-step process (i.e., to state the problem, identify the decision, and define the boundaries of the study).

The second step is to define the information needed for the decision, and includes identifying the sensitive groundwater flow and transport parameters and other the necessary data, and identifying the appropriate characterization activities. This step corresponds to the third, fifth, and sixth steps of the seven-step process (i.e., to identify the inputs to the decision, develop a decision rule, and specify acceptable limits on decision errors).

The third and last step is the *design* of *a program that addresses information needs*. This step corresponds to the seventh step of the seven-step process, which is to optimize the design by conducting a decision analysis and select candidate characterization activities for the acquisition of the missing information.

The DQO process feeds on several elements of the UGTA project, namely the FFACO (1996), the regional model of groundwater flow and contaminant transport (DOE/NV, 1997), the VOIA (SNJV, 2004), and other factors unaccounted for in the VOIA. These relationships are illustrated in Figure A.1-2. The statement of the decision, which corresponds to Step I of the DQO process, is derived from information obtained from the regional model, the FFACO, and the VOIA. Identifying the inputs to the decision, which corresponds to Step II of the DQO process, is entirely covered under the VOIA. Optimizing the design, which corresponds to Step III of the DQO process, is partly

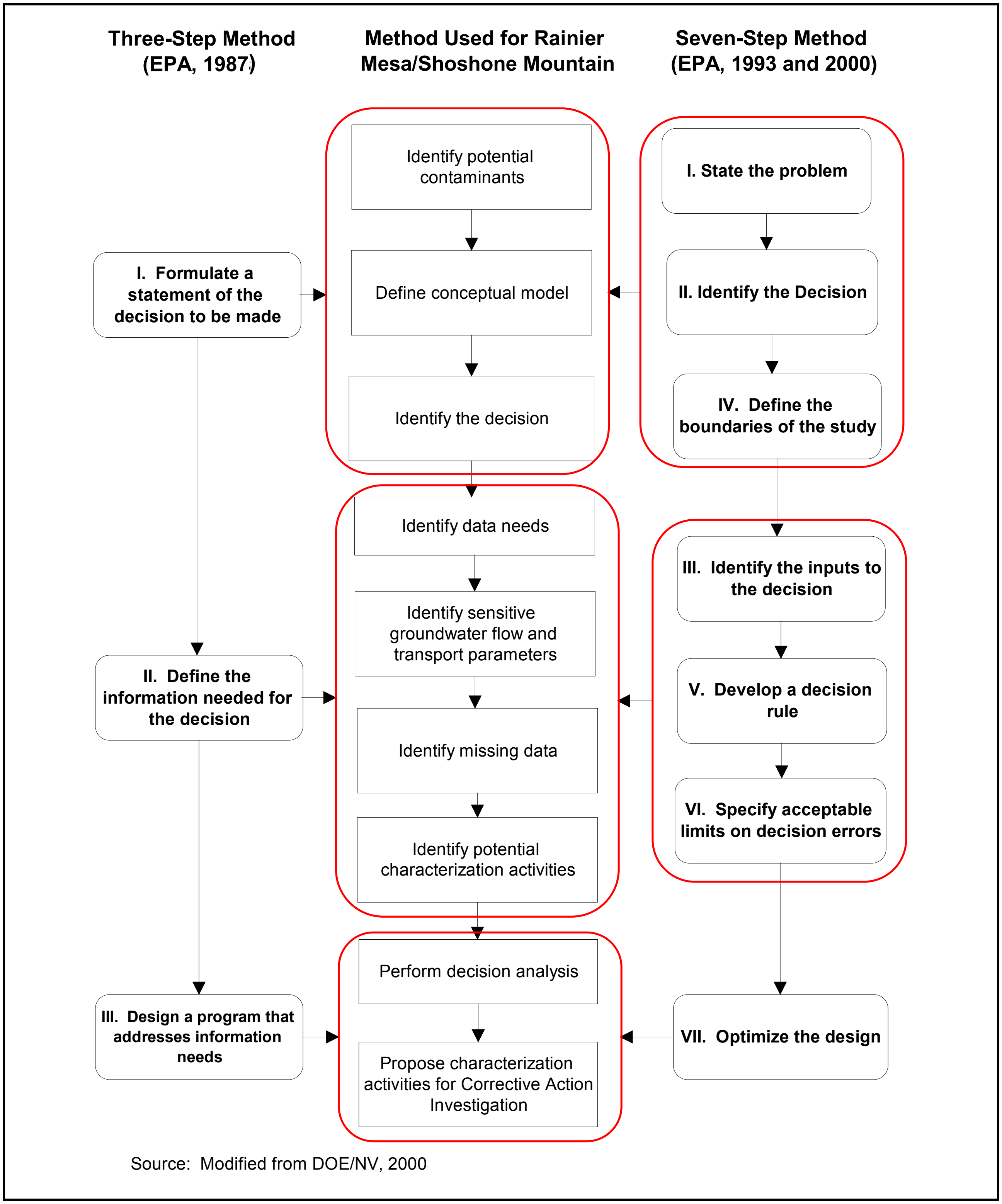


Figure A.1-1
Comparison of Data Quality Objectives Process Used for Rainier Mesa/Shoshone Mountain with EPA Methods

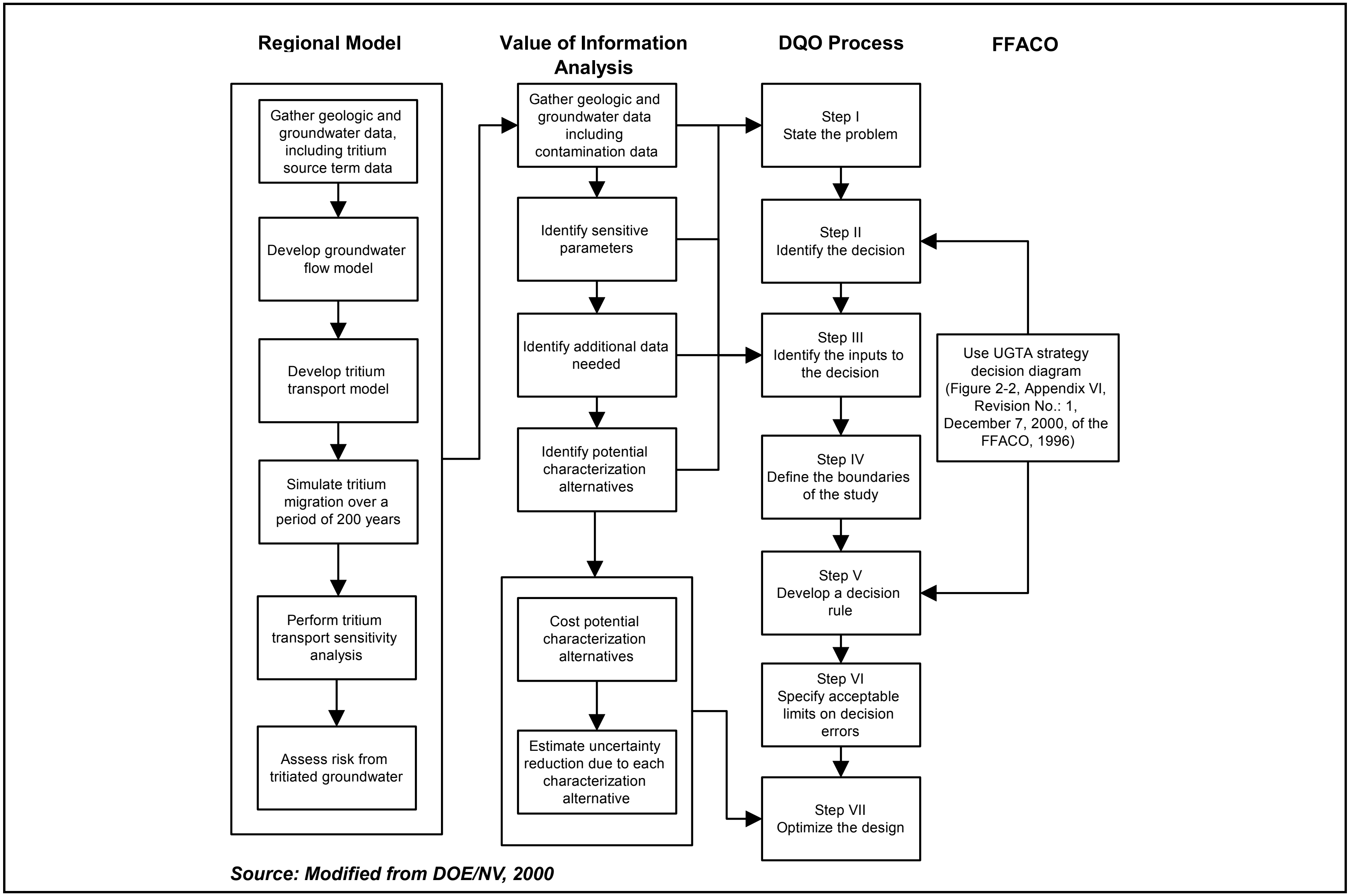


Figure A.1-2
Relationship of the Data Quality Objectives Process to Other UGTA Project Elements

conducted under VOIA. The final step of the DQO process is completed by the NNSA/NSO UGTA Project Manager, who considers factors unaccounted for in the VOIA.

The VOIA (SNJV, 2004) included the following steps:

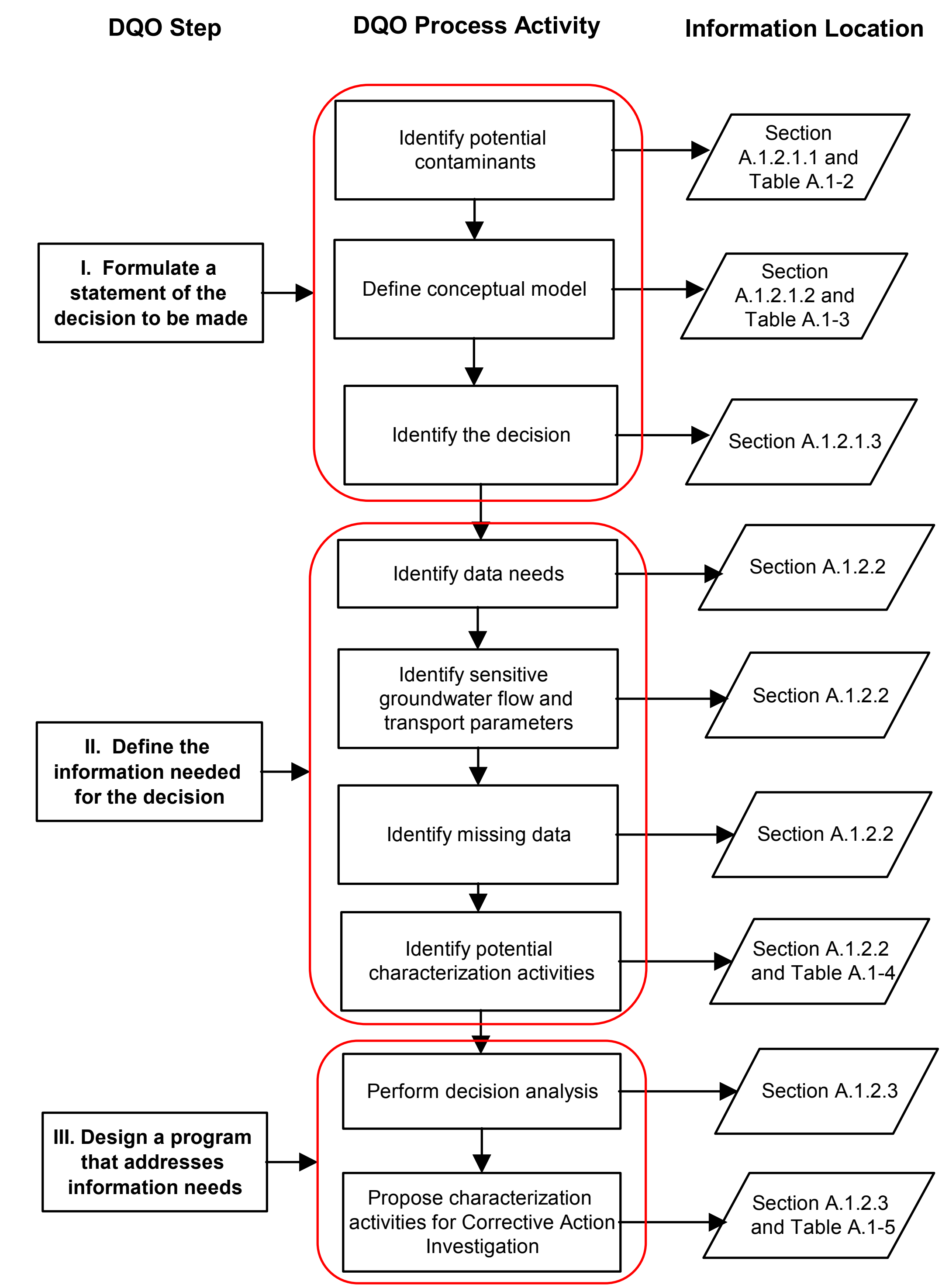
- Compilation of existing data from the regional data documentation packages
- Identification of data needs and data gaps
- Evaluation to determine sensitive parameters
- Identification of quantity and quality of additional data needed and associated characterization options
- Costing of characterization options
- Quantification of effect of data characterization options on uncertainty reduction
- Comparison of characterization options through decision analysis

A nonprobabilistic approach was used to identify the quantity and quality of the additional data needed for the Rainier Mesa/Shoshone Mountain CAI. This is consistent with the EPA approach (EPA, 1987, 1993, and 2000). As stated by EPA (1993), statistical procedures may not be applied to certain environmental problems. “Non-probabilistic or subjective (judgmental) sampling approaches can be useful and appropriate for satisfying certain field investigation objectives” (EPA, 1993). The approach used to design the characterization activities for the Rainier Mesa/Shoshone Mountain CAI was specifically directed at filling the data gaps relevant to contamination migration.

Groundwater flux along a generic path-line was calculated from hydraulic heads (gradient) and hydraulic conductivities derived from the regional groundwater flow model (DOE/NV, 1997). This groundwater flux term was used as an input to the 1-D contaminant transport model to simulate radionuclide transport along the generic path-line.

A.1.2 Data Quality Objectives Results

The DQO process used for the Rainier Mesa/Shoshone Mountain CAU is described in terms of the EPA three-step process (Figure A.1-3).



Source: Modified from DOE/NV, 2000

Figure A.1-3
Data Quality Objectives Process Used for the Rainier Mesa and Shoshone Mountain CAU

A.1.2.1 Formulation of a Statement of the Decision to be Made

The first step is the *formulation of a statement of the decision to be made,* and identifies potential contaminants, describes the current conceptual model and areas of uncertainty, and includes a statement of the decision at hand.

A.1.2.1.1 Potential Contaminants

Table A.1-2 lists the major potential contaminants which were selected based on empirical measurements, knowledge of the sources, and information about the risk posed by radioactive and hazardous contaminants. The table shows the range of values estimated for each isotope included in the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004). Concentration ranges for hazardous constituents were not estimated. The PALs proposed for each potential contaminant were derived in Section 3.7. If these levels are exceeded, they will be used to trigger further action during the CAI, either through measurements or modeling. The PALs are based on the MCLs (40 CFR Part 141, 2004) which are promulgated in regulations authorized by the *Safe Drinking Water Act*; however, the PALs are not intended as compliance levels at this time. The table lists analytical protocols for measuring the potential contaminants and specifies practical quantitation limits for each protocol contaminant. This will enable comparisons to be made among the predicted range of concentration, PAL, and practical quantitation limit for each potential contaminant.

A.1.2.1.2 Conceptual Model

An overview of the current conceptual model of the Rainier Mesa/Shoshone Mountain CAU is presented below.

The area referred to as "Rainier Mesa" includes Rainier Mesa proper and the contiguous Aqueduct Mesa. Rainier Mesa is a mesa capped by erosionally resistant densely welded tuff located adjacent to the northeast part of the Timber Mountain caldera complex in the northern part of the NTS. Shoshone Mountain is located about 20 km south of Rainier Mesa and consists of several ridges and peaks consisting of interbedded welded and nonwelded tuffs and lava flows adjacent to the southeastern part of the Timber Mountain caldera complex, in the central part of the NTS. The older volcanic rocks exhibit increasing degrees of alteration to zeolites and clays with increasing depth. In both locations these volcanic rocks were deposited upon a substrate of complexly folded and faulted

Table A.1-2
Preliminary List of Major Potential Contaminants

Contaminant	Minimum Concentration in Test Cavity[a] (pCi/L)	Maximum Concentration in Test Cavity[a] (pCi/L)	Preliminary Action Level[b]	Minimum Detectable Concentration (MDC)	Analytical Protocol
Americium-241	2,044	3,066	1.5 pCi/L	0.1 pCi/L	HASL 300[c]
Carbon-14	0	1,212.2	200 pCi/L	500 pCi/L	C-01[d]
Cesium-137	26,411	49,049	20 pCi/L	10 pCi/L[e]	EPA-600/4-80-032[f] Method 901.1
Chlorine-36	0	124.3	70 pCi/L	NA	NA
Europium-154	636.3	1,181.7	6 pCi/L	65 pCi/L (Based on ^{137}Cs)	HASL 300
Neptunium-237	1	1,000	1.5 pCi/L	0.2 pCi/L	Lab specific
Plutonium-238	2,127.2	3,190.8	1.5 pCi/L	0.1 pCi/L	ASTM[g]
Technetium-99	5.4719	10.1621	90 pCi/L	10 pCi/L	HASL 300
Tritium	0	3,058,000	20,000 pCi/L	400 pCi/L	EPA-600/4-80-032 Method 906.0
Uranium-235	0.13736	0.20604	30 :Ci/L	0.1 pCi/L	ASTM[h]

Source: Modified from DOE/NV, 2000

[a]Based on uncertainties in Bowen et al., 2001
[b]The regulatory source for all PALs is 40 CFR Part 141 (CFR, 2004)
[c]DOE/NV, 1997
[d]EPA, Eastern Environmental Radiation Facility Procedure Manual
[e]As required of analytical laboratories by NNSA/NSO (2003)
[f]EPA, 1980
[g]Method D3865-02, Standard Test Method for Plutonium in Water
[h]Method D3972-02, Standard Test Method for Isotopic Uranium in Water by Radiochemistry

pCi/L = Picocuries per liter

Paleozoic sedimentary rocks, precambrian sedimentary and metamorphic rocks, and locally (at Rainier Mesa) Mesozoic intrusive rocks. Nuclear tests were conducted at 61 underground locations in Rainier Mesa and 6 locations at Shoshone Mountain. All of these tests were conducted in tunnels with the exception of two tests on Rainier Mesa that were conducted in vertical shafts. The tests were conducted above the regional water table beneath Rainier Mesa or Shoshone Mountain, although localized zones of perched water exists above the regional water table at both locations. Contaminated media produced by these underground nuclear tests consists of subsurface rock and rock rubble above the regional groundwater level. Groundwater transport is the primary means of contaminant migration away from the underground test locations beneath Rainier Mesa and Shoshone Mountain, but contaminants must first traverse the interval of the UZ lying between the test cavity and the regional water table. Altered and zeolitized nonwelded tuff form a confining unit that acts to retard infiltration at the test horizon at Rainier Mesa and Shoshone Mountain, but the distribution of these rocks beneath the test horizon is less well understood. Table A.1-3 presents a summary of the major elements of the conceptual model of the Rainier Mesa/Shoshone Mountain area, and includes the groundwater flow system, contamination sources, UZ delay factor, current extent of contamination, future extent of contamination, current and future land use, potential receptors, and potential exposure routes. In addition, this section also describes groundwater flow and contaminant transport in the Rainier Mesa/Shoshone Mountain conceptual model. The primary sources of information supporting the Rainier Mesa/Shoshone Mountain conceptual model are the regional modeling results (IT, 1996a through g; IT, 1997; DOE/NV, 1997) and the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004).

Groundwater Flow System

The geology and hydrogeology at, and downgradient of, the Rainier Mesa/Shoshone Mountain area are described below.

The surface and subsurface geology of the Rainier Mesa/Shoshone Mountain area contains all rock units found in the region, including the following in chronological order: Precambrian and Paleozoic sedimentary rock units, Mesozoic intrusive rocks, Tertiary volcanic and sedimentary rocks, and Quaternary alluvial fill.

Table A.1-3
Summary Conceptual Model of the Rainier Mesa/Shoshone Mountain CAU

Conceptual Model Element	Description	Source
Groundwater Flow System	The groundwater flow system and down-gradient areas include groundwater below the water table from northern boundary of NTS south to Jackass Flats, and include Rainier Mesa, Shoshone Mountain, western Yucca Flat, and eastern Timber Mountain. Geologic units include bedded tuffs, welded tuffs, lava flows, Paleozoic carbonates, and Paleozoic clastic units. Aquifers include VA, BAQ, LCA, and LCA3, and confining units include TCU and UCCU.	Regional modeling results (DOE/NV, 1997)
Contamination	Source terms from 67 underground nuclear tests constitute the sources of contamination for groundwater at Rainier Mesa and Shoshone Mountain. Potential contaminants include tritium, cesium-137, carbon-14, chlorine-36, technetium-99, europium-154 plutonium-238, uranium-235, americium-241, and neptunium-237.	Value of Information Analysis (SNJV, 2004)
Current Extent of Contamination	The contamination is currently located within the test cavities. Vertical extent of the contamination is not believed to reach the LCA or LCA3.	HRMP reports Regional modeling results (DOE/NV, 1997)
Future Extent of Contamination	The potential contaminants are predicted to dwell within the UZ, then infiltrate into groundwater and migrate south, southwest, and southeast. Lateral migration of contamination is not expected to reach NTS boundary within the 1,000 year time-frame. The direction and rate of contaminant migration will vary due to geologic variability and recharge variability.	Regional modeling results (DOE/NV, 1997) Value of Information Analysis (SNJV, 2004)
Current and Future Land Use	Rainier Mesa and Shoshone Mountain are reserved as nuclear test zones. The area down-gradient includes the southern part of NTS.	Environmental Impact Statement (DOE/NV, 1996a)
Potential Receptors	Off-site and on-site users of groundwater are potential receptors.	Environmental Impact Statement (DOE/NV, 1996a)
Potential Exposure Routes	Exposure routes include ingestion, dermal contact, and irradiation. For purposes of the CAI, the drinking water scenario is used in the definition of the contaminant boundary.	Regional evaluation (DOE/NV, 1997)

Precambrian and Paleozoic rocks are regionally extensive and exist beneath Tertiary volcanic and sedimentary rocks as basement rocks. The uppermost 4,600 m (15,088 ft) Cambrian through Pennsylvanian strata consist of dolomite, limestone, shale, and quartzite. The lowermost 3,000 m of the pre-Tertiary stratigraphic section consists of Late Precambrian to Middle Cambrian quartzite, siltstones, and shale. Paleozoic sedimentary rocks crop out east of Rainier Mesa and Shoshone Mountain, and occur at depth in drill holes at Rainier Mesa.

Mesozoic intrusive rocks of the Climax Stock crop out at the northern edge of Yucca Flat, about 13 km northeast of Rainier Mesa. The Climax stock is a composite intrusion consisting of granite, granodiorite, quartz monzonite, and pegmatite dikes. Mesozoic-age lamprophyre potentially related to the Climax stock has been encountered at depth in drill holes beneath Rainier Mesa.

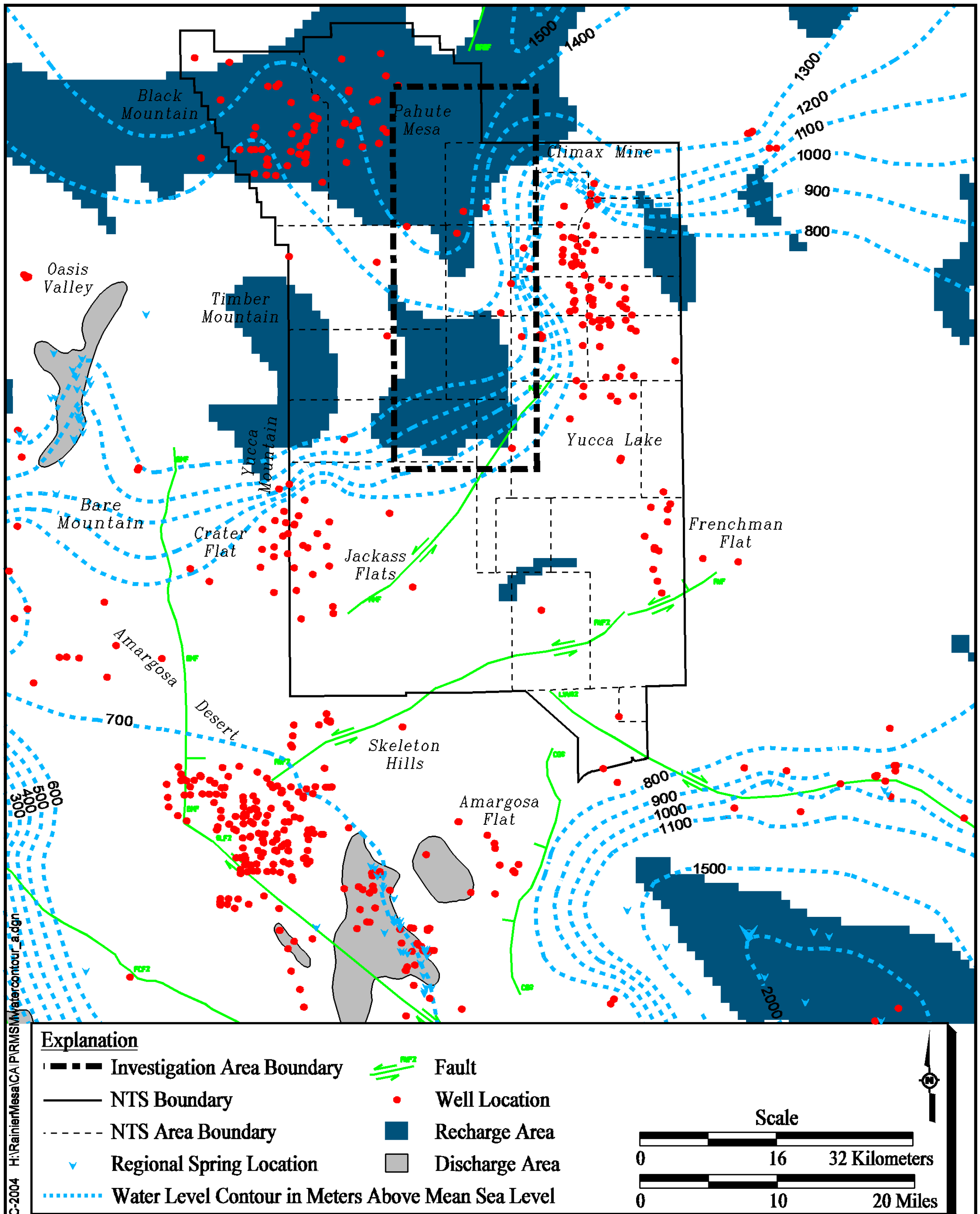
Outflow sheets of tuffs erupted from the caldera complex located west of Rainier Mesa and Shoshone Mountain were deposited on an irregular paleotopographic surface during the Tertiary Period. Post-volcanic erosion incised valleys and canyons into the volcanic strata, and Quaternary age sand and gravel have been deposited in the bottoms of these valleys as well as the basins east and south of Rainier Mesa and Shoshone Mountain.

Thrust faulting began as early as the Permian and lasted throughout the Mesozoic, resulting in older Paleozoic sedimentary formations being thrust upon younger Paleozoic formations throughout the region of the NTS. Surface mapping and drilling results confirm that thrust faults exist beneath Rainier Mesa, and potentially exist beneath Shoshone Mountain. Basin and Range style normal faulting occurred before, during, and after depositing of the volcanic rocks. Early Tertiary normal faulting resulted in the irregular topography upon which the volcanic rocks were deposited, and syn-volcanic faulting resulted in greater deformation of older volcanic strata than of younger volcanic strata. The youngest faults offset all volcanic strata and even some of the Quaternary-age alluvial deposits. Most of the normal faults in the vicinity of Rainier Mesa and Shoshone Mountain strike north-south.

The hydrostratigraphy of the Rainier Mesa and Shoshone Mountain area consists of several aquifers and confining units. The major aquifers include the VA, BAQ, and the LCA3. The main confining units are the LCCU, UCCU, and the BCU. Based on site-specific data from Well ER-12-1, the hydraulic conductivity of the LCA and/or LCA3 ranges from 0.77 to 0.03 m/d, hydraulic conductivity of the LCA3 + UCCU is about 0.011 m/d, and hydraulic conductivity of the VCU ranges from 0.000122 to 0.000815 m/d. No site-specific hydraulic conductivity data are available for the VA; however, data from the NTS region indicates that hydraulic conductivity ranges from 0.0003 to 12 m/d.

Several wells exist in the Rainier Mesa area, but none exist at Shoshone Mountain. Although only a few wells at Rainier Mesa provide water-level information, wells throughout the NTS indicate that groundwater elevations grossly mimic topography. For example, static groundwater table elevations are highest at Pahute Mesa, Rainier Mesa, and Shoshone Mountain and descend down a steep hydraulic gradient eastward into Yucca Flat and southward into Jackass Flats. Although there are springs fed by local perched groundwater at both Rainier Mesa and Shoshone Mountain, there are no discharges from the regional flow system within either area. According to the NTS regional model (DOE/NV, 1997), regional groundwater flows south and southwest and eventually discharges at Franklin Playa, Ash Meadows, and Death Valley (Figure A.1-4).

Groundwater flow within the Rainier Mesa/Shoshone Mountain area is part of the NTS groundwater flow system, which is part of the Death Valley flow system. The Rainier Mesa/Shoshone Mountain groundwater flow system has no physical lateral hydrologic boundaries. Groundwater exists within the VA, VCU, LCA, and LCCU. Regional groundwater flow beneath the Rainier Mesa/Shoshone Mountain area occurs through fractures and solution cavities of the LCA. The general groundwater flow direction is to the south and southwest towards the Amargosa Desert (Figure A.1-4). The bulk of the groundwater flow from Rainier Mesa/Shoshone Mountain area to the Amargosa Desert occurs through a band of the LCA towards the south and southwest, potentially along buried structures in Jackass Flats, Fortymile Canyon, and Yucca Mountain, and into the Amargosa Valley. This flow path is locally perturbed by thrust faults buried beneath Rainier Mesa and Shoshone Mountain, but the LCA forms a preferential flow path because of its relatively higher transmissivities. The high-transmissivity zone ends in the Amargosa Desert where groundwater velocity decreases and flow paths split into two directions, south toward Ash Meadows and southwest toward Death Valley. Groundwater moving southwest towards the Death Valley discharge area slows down considerably when it moves into the AA of the Amargosa Desert. Groundwater moving south continues in the LCA, locally discharging from surface exposures of the LCA, but more commonly flowing into the



Source: Modified from IT, 1996d

Figure A.1-4
Composite Predevelopment Water Level Contour Map for the Rainier Mesa/Shoshone Mountain Investigation Area

AA and then discharging to the surface in springs and wetlands in Ash Meadows. Observed trends of vertical hydraulic gradients are downward from the Cenozoic units into the Paleozoic carbonate units.

Groundwater recharge occurs by underflow from areas to the north and northwest, and from infiltration of local precipitation. Precipitation in the highland areas of Rainier Mesa and Shoshone Mountain recharges perched aquifers within the volcanic strata. Although the perched volcanic aquifers at Rainier Mesa and Shoshone Mountain discharge to the surface at seeps and springs (Captain Jack Spring, Gold Meadows Spring, Tippipah Spring, and Topopah Spring), most of this shallow groundwater flows down the steep hydraulic gradient toward Yucca Flat, Mid Valley, and Jackass Flats. Thordarson (1965) indicates that perched groundwater also is moving downward into the LCA. No surface discharge from the regional flow system occurs within the Rainier Mesa/Shoshone Mountain area. A portion of the groundwater at Rainier Mesa that flows toward Yucca Flat ultimately discharges at Ash Meadows. Most of the groundwater at Rainier Mesa and Shoshone Mountain flows southward into the Amargosa Desert where it divides to discharge locally at Ash Meadows or flows west to discharge in Death Valley.

Particle tracking simulations were performed during the regional evaluation (DOE/NV, 1997) and during the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004). These simulations were used to identify the pathlines that imaginary particles would follow from specific nuclear test locations through the groundwater flow model. Pathlines help define groundwater flow directions and potential migration pathways. Particle tracking results for CLEARWATER (Figure 7-26 in DOE/NV [1997]) show that a pathline originating at Rainier Mesa follows the general direction of flow south and southwestward to Yucca Mountain, then south into the Amargosa Desert, ultimately flowing southwest and west into the Death Valley discharge area. Multiple particle path simulations were completed for the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004). Whereas most of the flow paths from Rainier Mesa are similar to, and parallel with, the CLEARWATER path, a small portion of the flow paths originate in eastern Rainier Mesa flow eastward into Yucca Flat and join the rest of the Yucca Flat flow paths southward towards Ash Meadows. Flow paths from Shoshone Mountain form a tighter group than those from Rainier Mesa, and experience a short jog to the northeast as a result of encountering the UCCU in the upper plate of a thrust fault beneath the volcanic strata. Eventually these particle tracks flow to the southwest into the Amargosa Desert and discharge at Ash Meadows. The trace of these particle tracking pathlines suggests that structural features such as thrust faults (Belted Range Thrust, CP Thrust, Calico Hills Thrust, Specter Range Thrust), normal faults (Paintbrush Canyon Fault, faults in Fortymile Wash), and strike-slip faults (Rock Valley Fault) exert a degree of local control (Potter et al., 2002; Sweetkind et al., 2001).

Contaminant Transport

This overview of contaminant transport in the Rainier Mesa/Shoshone Mountain area includes summary descriptions of sources of contamination, the release mechanisms to groundwater, migration routes, contaminant transport processes, and simulated extent of contamination.

Each of the underground nuclear tests resulted in a test cavity, rubble chimney, and a disturbed area extending beyond the cavity by approximately two to three cavity radii (Bowen et al., 2001). The saturated portion of a test cavity, rubble chimney, and disturbed area forms the volume of the contamination source created by a given underground test. However, the working point of all the underground nuclear tests at Rainier Mesa and Shoshone Mountain were above the regional water table by at least two test cavity radii. Potential contaminants include tritium, fission products, actinides, and activation products used in the device and created by the test, and other hazardous constituents potentially used in the test (Bowen et al., 2001). As shown on Table A.1-2, major radionuclides include tritium, ^{14}C, ^{36}Cl, ^{99}Tc, ^{137}Cs, ^{154}Eu, ^{238}Pu, ^{241}Am, ^{237}Np, and ^{235}U (SNJV, 2004).

During a nuclear test, thermal energy from the fireball and mechanical energy from the shock wave vaporize a volume of rock and create a cavity in a few tenths of a second. A shock wave from the detonation propagates outward creating a volume of fractured rock about two to three times the radius of the cavity. Contaminants can be promptly injected into the subsurface materials surrounding the device, although it is believed that only a very limited amount of prompt injection occurs. Vaporized material condenses within the cavity and flows down the cavity walls to mix with a melt phase that has pooled in the bottom of the cavity. Once condensable gases have liquefied, cavity pressures drop below lithostratigraphic pressure and the cavity begins to collapse. The collapse front propagates upward until the cavity is filled with rubble, forming a rubble-filled chimney (Bowen et al., 2001). Following nuclear tests below the water table, the test cavity refills with groundwater and contamination is released. To date, no site-specific information on contaminant release processes exists. However, general information indicates that contaminants are released into the groundwater by leaching and ion exchange (Borg et al., 1976). Contaminants may leach from the melt glass, rubble chimneys, or fracture surfaces and pore spaces adjacent to the test cavity. Ion exchange processes may also release contaminants that are bound to minerals of the rubble after groundwater refills the chimney. For tests located above the static water table, such as the tests at Rainier Mesa and Shoshone Mountain, release of contaminants to the groundwater is delayed. For tests located within one or two cavity radii of the static water table, it is possible for prompt injection to introduce some contaminants. Additional contamination must rely on infiltration through the rubble-filled chimney and into the groundwater from surface recharge, or lateral recharge from local perched water. Perched groundwater has completely filled N-tunnel and P-tunnel at Rainier Mesa. The magnitude of the delay for tests conducted in the UZ and the degree of communication between local perched water and regional groundwater are currently unknown.

The major contaminant migration processes of interest for contaminants that exist within the groundwater include advection, dispersion, sorption, matrix diffusion, and radioactive decay. Simulated particle tracking within a calibrated model using head and flux distributions is a good method for evaluating advective transport of contaminants in the groundwater. One underground test, CLEARWATER, was selected for tritium transport simulations from the Rainier Mesa area during the regional evaluation (DOE/NV, 1997). The particle transport pathway results of these simulations for CLEARWATER are presented in Figures 7-25 and 7-26 of the *Regional Groundwater Flow and Tritium Transport Modeling and Risk Assessment* (DOE/NV, 1997). The simulated travel distance for particles originating at the water table at CLEARWATER location on Rainier Mesa is 1.55 km after 100 years. This figure does not include travel time through the UZ from the test cavity to the water table. Sensitivity tests indicated that increasing transmissivity by a factor of two did not change the travel distance by more than 2 percent, or about 31 m.

Generic path lines were used to model transport from sources located on Rainier Mesa in the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004). The particle transport paths originate in the LCCU of the upper plate of a thrust fault, and bifurcate in the vicinity of the Eleana Range, where part of them go eastward into Yucca Flat and the rest go south. The paths that go east into Yucca Flat join Yucca Flat path lines that eventually discharge in the Franklin Playa/Ash Meadows area (DOE/NV, 2000). The paths that travel southward go through non-welded tuffs (VCU) and welded tuffs (WTA) before entering the TMA within the Timber Mountain caldera complex. North of Calico Hills, the particle path goes through the UCCU and into the LCA of the upper plate of the Belted

Range thrust. East of Yucca Mountain the particle path passes through the upper plate of the Belted Range thrust, into and through the UCCU of the lower plate, then into the LCA where the path stays until reaching the Funeral Mountains. In Death Valley, the particle path passes through the LCCU and the TSDV to discharge into the AA (DOE/NV, 1997), terminating near Salt Springs in Death Valley. Generic Path lines from Shoshone Mountain also originate in the UCCU of the upper plate of a thrust fault, following a circuitous path southeast, southwest, southeast, and northeast before entering the LCA and traveling to the southwest. This erratic path was thought to result from numerical instabilities within the model (DOE/NV, 1997), but may also reflect flow paths dominated by structural complexities of the thrust faults and normal faults in the region. South of the Calico Hills, the particle track crosses Jackass Flats variously in the LCA and the UCCU, then into the LCA beneath the Amargosa Desert where it stays until discharging in Death Valley near Salt Springs.

More than 300 different radionuclides are produced during a nuclear test but most have half-lives so short (microseconds to minutes) that they decay to undetectable concentrations within a few hours. Other radionuclides have half-lives so long as to present a persistent presence in the environment for thousands of years. Six radioactive contaminants (^{3}H, ^{14}C, ^{137}Cs, ^{36}Cl, ^{238}Pu, and ^{99}Tc) were determined to be the most important in predicting the 4 millirem per year (mrem/yr) boundary in a 1,000-year timeframe, based on inventory estimates, health effects, and transport simulations (SNJV, 2004). After 1,000 years the distance along generic path lines for Rainier Mesa for the 4-mrem/yr dose at the 95 percentile probability is about 4,200 m (SNJV, 2004). Based on results of these transport simulations, the distance to the 4-mrem/yr dose is not expected to extend out of the central part of the NTS after 1,000 years. The fate and transport of contaminants in perched water at both Rainier Mesa and Shoshone Mountain has not been modeled. Active springs exist at Rainier Mesa and Shoshone Mountain that present discharge sites for some perched water, but it is currently not known how these are related to perched groundwater that has filled the N- and T-Tunnel complexes.

Uncertainties

The current conceptual model of the Rainier Mesa/Shoshone Mountain area has several areas of uncertainty, as follows:

- The large-scale average effective porosity of the fracture system in the LCA3 along the contaminant flow path
- The mean residence time of the contamination in the UZ
- The extent of test-induced, fracture-dominated fast-pathways through confining units
- Initial ^{14}C concentration: the volume over which the ^{14}C source term will be diluted
- Darcy-flux: the large-scale average regional groundwater flux through Rainier Mesa, Shoshone Mountain, and down-gradient regions

A.1.2.1.3 Statement of the Decision

Based on information of the potential contaminants and the current conceptual model described above, a statement of the decision was made as follows: *Can an acceptable groundwater flow and transport model be formulated for the Rainier Mesa/Shoshone Mountain Corrective Action Unit using the existing data?*

A.1.2.2 Definition of the Information Needed for the Decision

The second step in the process is defining the information needed for the decision which includes the identification of the necessary data, sensitive groundwater flow and transport parameters, additional data needed, and associated characterization activities.

The information needed for the decision is necessary to develop a groundwater flow and contaminant transport model that represents reality to an acceptable level of uncertainty. This information consists of geologic data, groundwater data including contamination sources and concentrations in groundwater, and an understanding of the processes that cause contaminants to migrate in groundwater. As stated before, such information was gathered during the regional evaluation (DOE/NV, 1997) and the Rainier Mesa/Shoshone Mountain VOIA (SNJV, 2004), and was used to define the current conceptual model described in the previous step. The areas of uncertainty that exist in this conceptual model correspond to data or information gaps identified during the regional evaluation (DOE/NV, 1997). These include data gaps in uncharacterized portions of the area of interest and an insufficient understanding of the hydrochemical framework, contaminant transport processes at work, and the sources of contamination. Due to the uncertainties, it was determined that an acceptable groundwater flow and transport model could not be formulated for the Rainier Mesa/Shoshone Mountain area using the current conceptual model. Additional data were deemed necessary to address the areas of uncertainty.

The DQO approach used for the Rainier Mesa/Shoshone Mountain CAU to gather the missing information does not include the use of statistical procedures. A non-probabilistic approach was used instead. This is inconsistent with the EPA approach (EPA, 1987, 1993, and 2000). As stated by the EPA (1993), statistical procedures may not be applied to certain environmental problems. "Non-probabilistic or subjective (judgmental) sampling approaches can be useful and appropriate for satisfying certain field investigation objectives" (EPA, 1993). This is the case for the Rainier Mesa/ Shoshone Mountain CAU. The objective of the CAI is to predict the location of the contaminant boundary using a model. The prediction of a credible contaminant boundary must rely on a digital model that is representative of reality, which in turn depends on how the conceptual model of the problem is defined. The current conceptual model is believed to be sufficiently defined except in specific areas where relevant data gaps exist. Thus, the approach used to design the characterization activities was specifically directed at filling these data gaps.

To prioritize the additional data needed, sensitivity analysis were conducted. The sensitivity analyses were performed to determine which groundwater flow and transport parameters have the most effect on the results of flow and transport modeling. In the Rainier Mesa/Shoshone Mountain VOIA, the results indicate that the most sensitive parameters are groundwater flux and hydrologic path length in the first confining unit. In the 1-D transport model, flux is used to represent the results of the groundwater flow model and incorporates groundwater flow variables such as definition of the HSUs (types, thickness, structure, and hydrologic properties) and recharge distribution.

Based on the identified areas of uncertainty and the results of the sensitivity analyses, the following priority information needs were defined:

- Source term concentrations and Darcy flux
- Geologic information including unit extent and structural information including faults, thrusts, and fractures within and beneath Rainier Mesa and Shoshone Mountain

- Hydrogeologic data and groundwater chemistry data for Rainier Mesa and Shoshone Mountain
- Verification of the origin and flow paths of groundwater and estimates of travel times from Rainier Mesa and Shoshone Mountain
- Estimates of transport parameters, including porosity, dispersivity, matrix diffusion, adsorption, and colloidal transport
- Estimation of delay time in the UZ

During the VOIA (SNJV, 2004), a variety of possible data-collection options were identified that could potentially address the data deficiencies. Table A.1-4 lists the individual activities considered, describes each activity, and identifies the specific parameter(s) each activity addresses. Further information on the VOIA process is available in the VOIA report (SNJV, 2004).

All data collected for improving the current conceptual model of Rainier Mesa and Shoshone Mountain must be collected using stringent QA procedures as specified in the QAPP.

A.1.2.3 Design of a Program That Addresses Information Needs

The third and last step in the process is the *design of a program that addresses information needs.* During this step of the DQO process, further analyses conducted during the VOIA (SNJV, 2004) and results from the regional evaluation (DOE/NV, 1997) were used as tools to design a program that addresses the information needs.

During the VOIA (SNJV, 2004), the characterization options identified in the second step of the DQO process were evaluated and compared with respect to their cost and ability to reduce uncertainty in the model input parameters or the location of the contaminant boundary. The analysis compared the cost of executing the characterization options with their usefulness in reducing uncertainty and resulted in rankings of the options. The VOIA resulted in the determination of a short list of activities and groups of activities that are optimal for uncertainty reduction and cost minimization. Characterization activities were then selected for inclusion in the Rainier Mesa/Shoshone Mountain CAI based on the results of the VOIA (SNJV, 2004) and other DOE concerns. All data collected for the purposes of building the CAU model of the Rainier Mesa/Shoshone Mountain area will be in compliance with the QAPP (NNSA/NSO, 2003). The data collected may include “screening data” as

Table A.1-4
Potential Characterization Activities

Activity	Activity Description
1	Drillhole down synform axis into Paleozoics southwest of N-Tunnel
2	Geophysical (surface contour) mapping of HSUs using CSAMT[a] at Rainier Mesa
3	Recharge investigations at Rainier Mesa
4	Vertical drillhole at non-water producing locations west near P-Tunnel and several adjacent holes
5	Drillhole southwest of T-Tunnel with approaches to better quantify transit in the unsaturated zone
6	Characterization of fracture transport properties from multiwell tracer tests (forced gradient; requires 3 additional wells)
7	Characterization of natural groundwater velocity using natural-gradient tracer test (huff-puff plus borehole dilution; utilizes existing well)
8	Characterization of natural groundwater velocity using natural-gradient tracer test (multiwell natural gradient; requires 3 additional wells)
9	Drill and sample cavity hole
10	Data acquisition in support of small-scale hydrologic source term modeling and application to the CAU model
11	^{14}C diffusion parameters, retardation factor
12	Geochemical characterization of groundwater flow paths
13	Additional drillhole location to characterize path lines south of Rainier Mesa
14	Characterization of rock matrix properties affecting matrix diffusion in the fractured rock units
15	Geophysical (surface contour) mapping of HSUs using CSAMT at Shoshone Mountain
16	Drillhole near existing shallow hole at Shoshone Mountain

[a]Controlled source audio-frequency magnetotelluric (CSAMT) surface electromagnetic geophysical technique

defined by EPA (1993) to provide for the timely detection of contamination indicators (tritium for radionuclides and lead for metals), health and safety, and fluid management purposes. The selected characterization activities are listed in Table A.1-5. Summary descriptions of these activities are described in the following paragraphs.

Characterization Activity - Drill and Construct Wells

Two wells are planned for the Rainier Mesa area and one well for the Shoshone Mountain area. One well will be placed in the axis of a synform in the Paleozoic rocks southwest of the N-Tunnel. This structure is probably a syncline, less likely that it is an overturned anticline, although this will be

Table A.1-5
List of Activities Proposed for the Rainier Mesa/Shoshone Mountain CAI

Proposed Activity
Drill 2 wells at Rainier Mesa, 1 well at Shoshone Mountain
Sample new wells and existing locations
Collect and evaluate geophysical information at Rainier Mesa and Shoshone Mountain

determined from the rock samples returned during drilling. A second well will be placed southwest of T-Tunnel. These wells are located down gradient from the potential source of the contamination in N- and T-Tunnels, and will assist in characterizing potential flow paths within the saturated zone of the regional groundwater, as well as characterizing the tuffs between the test horizon within the Tunnel Formation and the Paleozoic rocks. The well at Shoshone Mountain will be located south or southwest of the test tunnels and down gradient from the contamination, and will assist in characterizing potential flow paths in the saturated zone as well as the tuffs in the UZ.

Characterization Activity - Sample New Wells and Existing Locations

Water samples from the new and existing locations will be analyzed for radionuclides in order to characterize actual contaminant migration within the perched water and within the regional groundwater. Major cations and anions will be analyzed to characterize perched water and regional groundwater beneath Rainier Mesa and Shoshone Mountain. The studies will support modeling the small-scale hydrologic source term for the CAU-scale model. Stable isotopes will be analyzed in order to characterize the perched water and potential recharge from Rainier Mesa and Shoshone Mountain. Stable isotopes and major element geochemistry data will assist in characterizing groundwater flow paths for both perched water and regional groundwater. Rock samples collected from the new drill holes will be used to characterize the fracture network and secondary alteration minerals in the tuffs beneath the test horizon and within the Paleozoic rocks beneath the tuffs. Determining fracture density within the siliciclastic rocks in the UCCU bears on how this unit is treated in the CAU-scale model.

Characterization Activity - Evaluate Geophysical Information

This activity includes the analysis of seismic data, gravity data, magnetic data, and down-hole geophysical logs. Analysis of down-hole geophysical logs will assist characterizing tuffs within the

TCU and the VA, and the Paleozoic rocks within the UCCU, the LCA3, and the LCA with regard to porosity, permeability, potential fracture density, and saturation levels above and below zones of perched water. Analysis of existing seismic data will be used to characterize the 3-D extent and distribution of the surfaces formed by contacts between and within the volcanic and Paleozoic rocks. Key features such as faults, formational pinchouts, and juxtapositions will be investigated throughout the Rainier Mesa and Shoshone Mountain area. This activity entails analysis of existing data and acquisition of new data.

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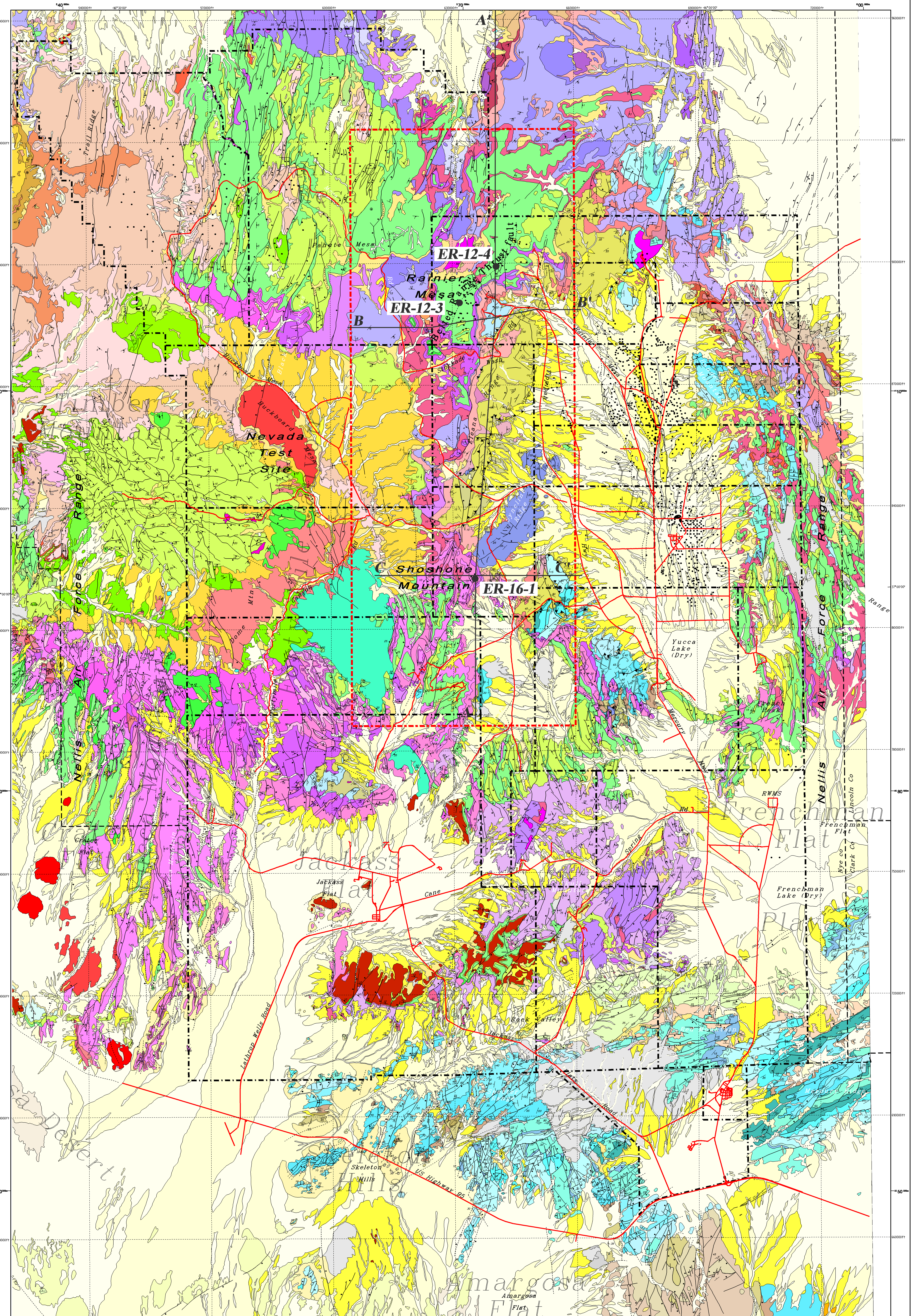
Plates

Plate 1
Location of Corrective Action Sites in the Rainier Mesa/Shoshone Mountain Corrective Action Unit

PLATE 2
GEOLOGIC MAP OF RAINIER MESA, SHOSHONE MOUNTAIN, AND ADJACENT AREAS

GEOLOGY



EXPLANATION

- Nevada Test Site Boundary
- County Boundary
- Improved Road
- Contact
- Fault (Dashed Where Inferred), Ball on Downthrown Side
- Probable Fault
- Less Certain Fault
- Thirsty Canyon Lineament
- Axis of an East-Striking Lineament
- Caldera Margin (Wall)
- Rainier Mesa/Shoshone Mountain Investigation Area
- Rainier Mesa/Shoshone Mountain CAS Location

NOTES

Projection and Grid: Nevada Coordinate System, Central Zone, 1927 North American Datum Feet

UTM Zone 11, 1927 North American Datum Meters and Geographic (Longitude, Latitude) is Shown for Reference Only

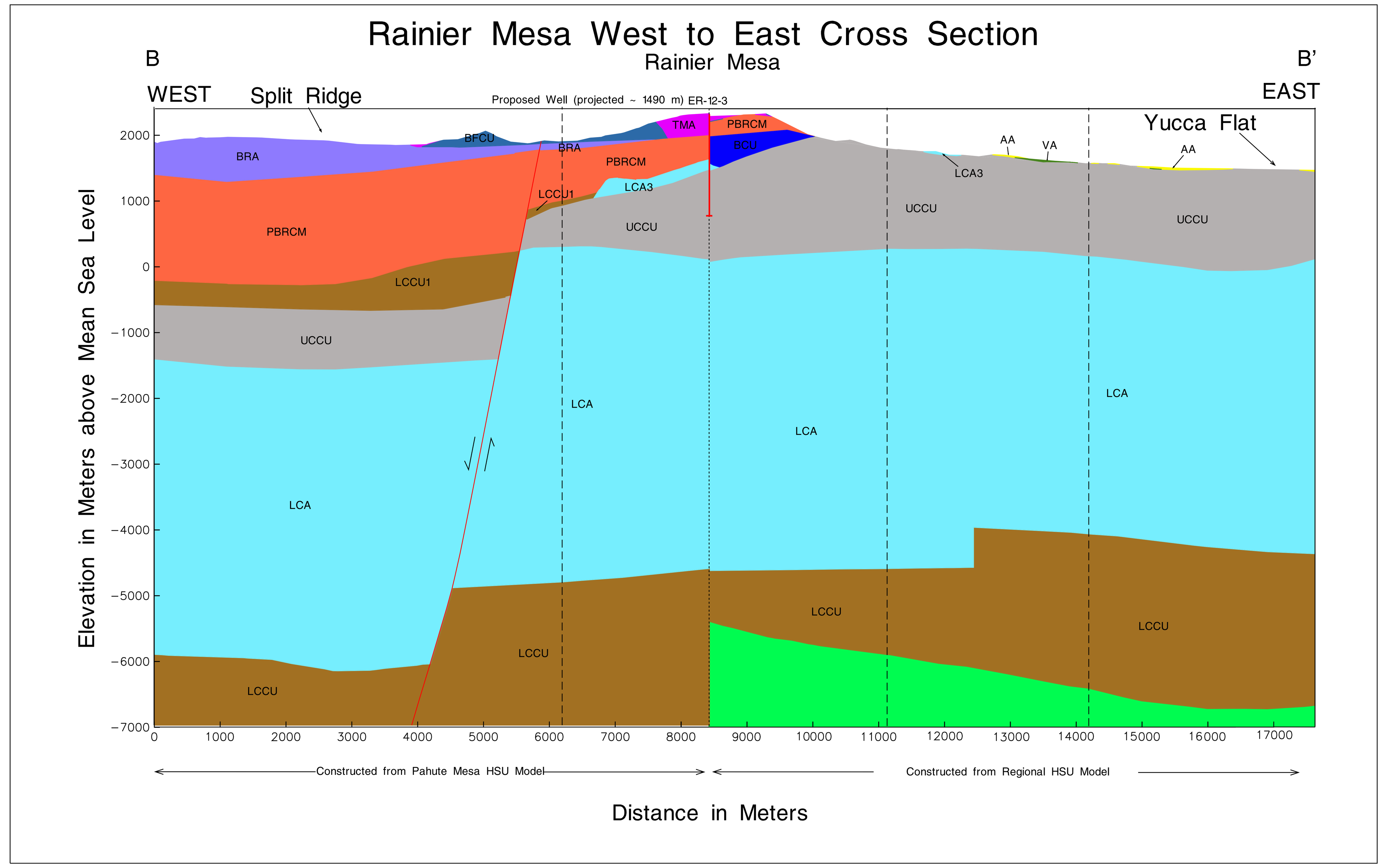
SCALE 1 : 100,000

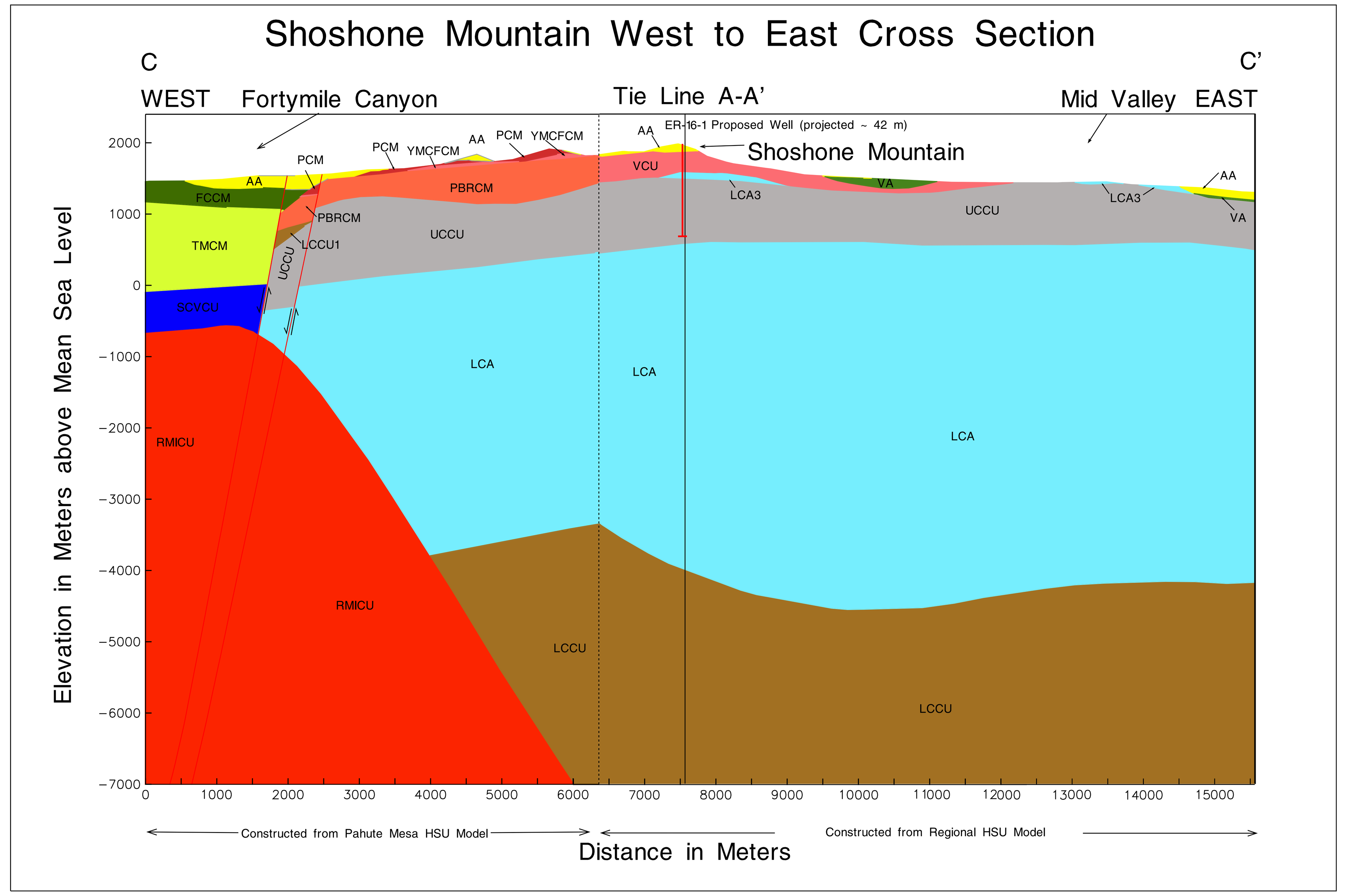
Miles 0 2 4

Kilometers 0 2 4

SOURCES: Slate et al., 1999 (Surface Geology)

Rainier Mesa / Shoshone Mountain South to North Cross Section



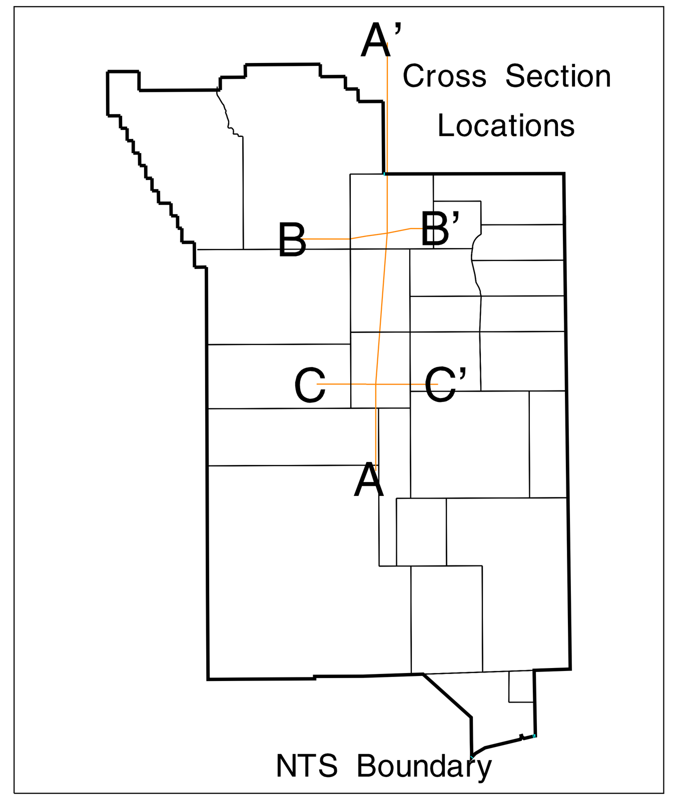


Pahute Mesa Hydrostratigraphic Units

AA	Alluvial Aquifer
DVA	Detached Volcanic Aquifer
DVCM	Detached Volcanic Composite Unit
YVCM	Younger Volcanics Composite Unit
TCVA	Thirsty Canyon Volcanic Aquifer
FCCM	Fortymile Canyon Composite Unit
FCA	Fortymile Canyon Aquifer
THLFA	Tannenbaum Hill Lava–Flow Aquifer
THCM	Tannenbaum Hill Composite Unit
TMA	Timber Mountain Aquifer
WWA	Windy Wash Aquifer
PCM	Paintbrush Composite Unit
PVTA	Paintbrush Vitric Tuff Aquifer
FCCU	Fluorspar Canyon Confining Unit
BA	Benham Aquifer
UPCU	Upper Paintbrush Confining Unit
TCA	Tiva Canyon Aquifer
PLFA	Paintbrush Lava–Flow Aquifer
LPCU	Lower Paintbrush Confining Unit
TSA	Topopah Spring Aquifer
YMCFCM	Yucca Mountain Crater Flat Composite Unit
CHVTA	Calico Hills Vitric–Tuff Aquifer
CHVCM	Calico Hills Vitric Composite Unit
CHZCM	Calico Hills Zeolitized Composite Unit
CHCU	Calico Hills Zeolitized Confining Unit
IA	Inlet Aquifer
CFCM	Crater Flat Composite Unit
CFCU	Crater Flat Confining Unit
KA	Kearsarge Aquifer
BFCU	Bullfrog Confining Unit
BRA	Belted Range Aquifer
PBRCM	Pre–Belted Range Composite Unit
TMCM	Timber Mountain Composite Unit
SCVCU	Subcaldera Volcanic Confining Unit
LCA3	Lower Carbonate Aquifer – Thrust Plate
LCCU1	Lower Clastic Confining Unit – Thrust Plate
UCCU	Upper Clastic Confining Unit
LCA	Lower Carbonate Aquifer
LCCU	Lower Clastic Confining Unit
SCICU	Silent Canyon Intrusive Confining Unit
MGCU	Mesozoic Granite Confining Unit
BMICU	Black Mountain Intrusive Confining Unit
CHICU	Calico Hills Intrusive Confining Unit
CCICU	Claim Canyon Intrusive Confining Unit
RMICU	Rainier Mesa Intrusive Confining Unit
ATICU	Ammonia Tanks Intrusive Confining Unit

Regional Model Hydrostratigraphic Units

AA	Alluvial Aquifer
TMA	Timber Mountain Welded Tuff Aquifer
TC	Consolidated Paintbrush and Calico Hills Tuff Cone
TCB	Bullfrog Confining Unit
TBA	Belted Range Aquifer
BCU	Basal Confining Unit
BAQ	Basal Aquifer
VA	Consolidated Volcanic Aquifer
VCU	Consolidated Volcanic Confining Unit
VU	Volcanics Undifferentiated
TSDVS	Tertiary Sediments Death Valley Section
LCA3	Lower Carbonate Aquifer – Upper Thrust Plate
UCCU	Upper Clastic Confining Unit
LCA	Lower Carbonate Aquifer
LCCU	Lower Clastic Confining Unit
LCA1	Lower Carbonate Aquifer (Upper Plate)
LCCU1	Lower Clastic Confining Unit (Upper Plate)
LCA2	Lower Carbonate Aquifer (Lower Plate)
LCCU2	Lower Clastic Confining Unit (Lower Plate)
MGCU/I	Mesozoic Granite Confining Unit



LEGEND

ER-12-1 — Drill hole in line of cross section. Tick marks represent tops of hydrostratigraphic units determined from drill hole data. Dashed line indicates drill hole projected into line of cross section (up to 1000 meters).

Fault with half arrows indicate sense of displacement.

TIE LINE J-J' — Tie line indicates the location where another cross section intersects this cross section.

Bend in cross section traverse.

ER-12-4 — Proposed drill hole location and depth.

Boundary between Pahute Mesa HSU Model and Regional HSU Model.

Plate 3

HYDROSTRATIGRAPHIC CROSS SECTIONS ACROSS RAINIER MESA/SHOSHONE MOUNTAIN INVESTIGATION AREA

No Vertical Exaggeration

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