RECORD OF TECHNICAL CHANGE

Technical Change No. RM/SM-Phase I Model Approach - 1

Page 1 of 2

Project/Job No. UGTA/IS07-730

Date October 20, 2008

Project/Job Name UGTA/ Modeling Approach/Strategy for Corrective Action Unit 99: Rainier Mesa and Shoshone Mountain, Nevada Test Site, Nye County, Nevada, Revision 1, Report Number S-N/99205-106, dated June 2008

The following technical changes (including justification) are requested by:

Sam J. Marutzky

(Name)

Stoller-Navarro Joint Venture (SNJV) UGTA Project Manager

(Title)

Description of Change:

The Nevada Division of Environmental Protection (NDEP) submitted additional review comments on July 30, 2008, for the Modeling Approach/Strategy for Corrective Action Unit 99: Rainier Mesa and Shoshone Mountain, Nevada Test Site, Nye County, Nevada, Revision 1, report dated June 2008. The Record of Technical Change will address the NDEP comments and SNJV responses to those comments. Specific changes are provided in the attachment.

Justification:

It was agreed upon by the NNSA/NSO UGTA Federal Sub-Project Director and the NDEP representative that the recommend changes be incorporated into the Final Revision 1 document.

The project time will be unchanged.

Applicable Project-Specific Document(s):

Modeling Approach/Strategy for Corrective Action Unit 99: Rainier Mesa and Shoshone Mountain, Nevada Test Site, Nye County, Nevada, Revision 1, Report Number S-N/99205-106, dated June 2008

Approved By:

NNSA/NSO UGTA Federal Sub-Project Director

Date

10/21/2008

NNSA/NSO Federal Project Director

Date

10/21/08

NDEP

Date

10/21/2008

**Attachment
Request for Technical Change
Modeling Approach/Strategy for Corrective Action Unit 99:
Rainier Mesa and Shoshone Mountain,
Nevada Test Site, Nye County, Nevada, Revision 1
Report Number S-N/99205-106, dated June 2008**

Technical Change (list specific page/section/paragraph as appropriate):

1. **Page ES-3, second paragraph, seventh sentence which includes "... and any evaluated uncertainties ..."** Change from: "and any evaluated uncertainties" to "and all evaluated uncertainties. . ."

Comment: The intent is that all the uncertainties from the vadose zone modeling that can be captured by the saturated-zone CAU model would be used as input to the CAU-scale modeling. It is planned that the UZ model uncertainties will be propagated into fluid and radionuclide flows to the SZ model, but the details are not yet clear.

2. **Page 3-11, Section 3.5, fourth paragraph.** Add the following sentence at the end of the fourth paragraph: "The results from this modeling will be used to evaluate the potential for contaminants to have reached the regional water table from the remaining RM tunnel complexes and vertical shaft tufts."

Comment: Although the sentence was not included in the final document, the DOE intends to use the results of the sub-CAU modeling to evaluate the remaining RM tunnel complexes and vertical shaft tufts as shown in Figure 1-3 on page 1-10 in the subject document.

3. **Figure 1-3, page 1-10 and Figure 1-4, page 1-11.** Remove triangle symbol which states "Do contaminants reach regional water table in < 1,000 years?" from Figure 1-3 and Figure 1-4 flow diagrams.
4. **Pages 3-12, Section 3.6, first sentence.** Remove sentence reading: "Should the vadose zone flow and transport modeling indicate that contaminants from any of the test sites have reached the regional water table in less than 1,000 years, a saturated zone flow and transport model will be developed."
5. **Page 3-18, third paragraph, fifth sentence.** Remove sentence reading: "If this is correct then saturated zone CAU-scale models will not be necessary."

S-N/99205--106

Modeling Approach/Strategy for Corrective Action Unit 99: Rainier Mesa and Shoshone Mountain, Nevada Test Site, Nye County, Nevada

Revision No.: 1

June 2008

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MODELING APPROACH/STRATEGY FOR CORRECTIVE ACTION UNIT 99: RAINIER MESA AND SHOSHONE MOUNTAIN, NEVADA TEST SITE, NYE COUNTY, NEVADA

Revision No.: 1

June 2008

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Reviewed and determined to be UNCLASSIFIED.
This review does not constitute clearance for public release.

Derivative Classifier: Joseph Johnston, DC

(Name, personal identifier and position title)

Signature: /s/ Joseph Johnston

Date: 06/04/2008

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**MODELING APPROACH/STRATEGY FOR CORRECTIVE ACTION UNIT 99:
RAINIER MESA AND SHOSHONE MOUNTAIN, NEVADA TEST SITE,
NYE COUNTY, NEVADA**

Approved by: /s/ Sam Marutzky

Date: 06/04/2008

Sam Marutzky, UGTA Project Manager
Stoller-Navarro Joint Venture

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LIST OF ACRONYMS AND ABBREVIATIONS, AND STRATIGRAPHIC UNIT ABBREVIATIONS

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
AA	Alluvial Aquifer
amsl	Above mean sea level
ATCU	Argillic Tuff Confining Unit
BFCU	Bullfrog Confining Unit
BRA	Belted Range Aquifer
BRT	Belted Range Thrust
BRCU	Belted Range Confining Unit
C	Carbon
CA	Carbonate aquifer
CADD	Corrective Action Decision Document
CAI	Corrective Action Investigation
CAIP	Corrective Action Investigation Plan
CAP	Corrective Action Plan
CAU	Corrective Action Unit
CCU	Clastic confining unit
CHVTA	Calico Hills Vitric-Tuff Aquifer
Cl	Chlorine
CP	Control Point
CPT	Control Point Thrust
CR	Closure Report
DOE	U.S. Department of Energy
DRI	Desert Research Institute
DVRFS	Death Valley Regional Flow System
ER	Environmental Restoration
EV [®]	EarthVision [®]

LIST OF ACRONYMS AND ABBREVIATIONS, AND STRATIGRAPHIC UNIT ABBREVIATIONS (CONTINUED)

FCCM	Fortymile Canyon Composite Unit
FEHM	Finite Element Heat and Mass Transfer code
FF	Frenchman Flat
FFACO	<i>Federal Facility Agreement and Consent Order</i>
ft	Foot
H	Hydrogen
HFM	Hydrostratigraphic framework model
HGU	Hydrogeologic unit
HST	Hydrologic source term
HSU	Hydrostratigraphic unit
KA	Kersarge Aquifer
k_d	Chemical distribution coefficient
km	Kilometer
LaGrit	Los Alamos Grid Toolbox
LANL	Los Alamos National Laboratory
LCA	Lower carbonate aquifer
LCA3	Lower carbonate aquifer-thrust plate
LCCU	Lower Clastic Confining Unit
LCCU1	Lower Clastic Confining Unit-Thrust Plate
Lpm	Liters per minute
LTCU	Lower Tuff Confining Unit
m	Meter
m^3/yr	Cubic meters per year
MGCU	Mesozoic Granite Confining Unit
MINC	Multiple INTERacting Continuum
NAD	North American Datum
NDEP	Nevada Division of Environmental Protection
NNSA/NSO	U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office

LIST OF ACRONYMS AND ABBREVIATIONS, AND STRATIGRAPHIC UNIT ABBREVIATIONS (CONTINUED)

NTS	Nevada Test Site
O	Oxygen
OSBCU	Oak Spring Butte Confining Unit
PEST	Parameter estimation software
PLVTA	Paintbrush Lower Vitric-Tuff Aquifer
PM	Pahute Mesa
PMOV	Pahute Mesa/Oasis Valley
PVTA	Paintbrush Vitric-Tuff Aquifer
RM	Rainier Mesa
RMSM	Rainier Mesa/Shoshone Mountain
RVA	Redrock Valley Aquifer
RVBCU	Redrock Valley Breccia Confining Unit
RVC	Redrock Valley caldera
RVICU	Redrock Valley Intrusive Confining Unit
SCVCU	Silent Canyon Volcanic Confining Unit
SDWA	<i>Safe Drinking Water Act</i>
SM	Shoshone Mountain
SNJV	Stoller-Navarro Joint Venture
Sr	Strontium
T2R3D	TOUGH2 (with hydrodynamic dispersion for transport in 3-D)
TCA	Tiva Canyon Aquifer
TPA	Twin Peaks Aquifer
TCU	Tertiary confining unit
TMCM	Timber Mountain Composite Unit
TMLVTA	Timber Mountain Lower Vitric-Tuff Aquifer
TMUVTA	Timber Mountain Upper Vitric-Tuff Aquifer
TMWTA	Timber Mountain Welded Tuff Aquifer
TOUGH2	Transport of Unsaturated Groundwater Heat
TPA	Twin Peaks Aquifer

***LIST OF ACRONYMS AND ABBREVIATIONS, AND STRATIGRAPHIC
UNIT ABBREVIATIONS (CONTINUED)***

TSA	Topopah Spring Aquifer
TSM	Total system model
TUBA	Tub Spring Aquifer
UCA	Upper carbonate aquifer
UCCU	Upper clastic confining unit
UGTA	Underground Test Area
USGS	U.S. Geological Survey
UTCU	Upper Tuff Confining Unit
UTM	Universal Transverse Mercator
UZ	Unsaturated zone
VTA	Vitric confining unit
WW	Water well
YF	Yucca Flat
YFCM	Yucca Flat/Climax Mine
YMCHLFA	Yucca Mountain Calico Hills Lava Flow Aquifer
δ	Delta value

EXECUTIVE SUMMARY

This document describes an approach for preliminary (Phase I) flow and transport modeling for the Rainier Mesa/Shoshone Mountain (RMSM) Corrective Action Unit (CAU). This modeling will take place before the planned Phase II round of data collection to better identify the remaining data gaps before the fieldwork begins. Because of the geologic complexity, limited number of borings, and large vertical gradients, there is considerable uncertainty in the conceptual model for flow; thus different conceptual models will be evaluated, in addition to different framework and recharge models. The transport simulations will not be used to formally calculate the Contaminant Boundary at this time. The modeling (Phase II) will occur only after the available data are considered sufficient in scope and quality.

The U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Site Office initiated the Underground Test Area (UGTA) Project to assess and evaluate the effects of underground nuclear weapons tests on groundwater at the Nevada Test Site (NTS) and vicinity through the *Federal Facility Agreement and Consent Order* (FFACO), 1996 (as amended February 2008). The processes for completion of UGTA corrective actions are described in the Corrective Action Strategy in the FFACO. The UGTA corrective action strategy objectives are to predict the location of the contaminant boundaries, develop and implement a corrective action(s), and close each CAU. The process to achieve this strategy includes modeling to define the maximum extent of contaminant transport within a 1,000-year time frame.

Modeling is a method used to forecast hydrogeologic system behavior, including the underground test cavities, with the goal of assessing the migration of radionuclides away from the cavities and chimneys. The DOE and Nevada Division of Environmental Protection have agreed to modify the strategy for RMSM, choosing to focus on a shortened initial (Phase I) modeling analysis, to improve system understanding and evaluate quantitatively what additional information should be collected during the next round of field activities, and to reduce uncertainty in the contaminant boundary predictions. This shortened analysis (Phase I) is focused on model prediction,

sensitivity, and uncertainty results as tools to identify priority data requirements without the burden of full calculation of the contaminant boundary. Simplified representations of flow, transport processes, and radionuclide inventory will be used for Phase I modeling. The full contaminant boundary calculation will be done in a more detailed round of analysis (Phase II in terms of scheduling) after additional field activities (nominally Phase II).

The hydrostratigraphic and hydrogeologic conceptualization for the RMSM investigation forms the framework that define the modeling needs and implementation. The hydrostratigraphic framework model (HFM) provides the three-dimensional framework for the flow and transport models and consists of five HFMs (one base and four alternatives). These alternative models are structural interpretations of the hydrostratigraphy present in the base model. Rainier Mesa (RM), located adjacent to the northeast part of the Timber Mountain caldera complex in the northern part of the NTS, is capped by a densely welded tuff, which is relatively resistant to erosion. Beneath the welded tuff cap, is a thick nonwelded section of tuff that has a vitric section at the top, and an altered and zeolitized section below, containing water considered perched above the regional water table. These volcanic rocks were deposited on a substrate of complexly folded and faulted Paleozoic sedimentary rocks, Precambrian sedimentary and metamorphic rocks, and locally Mesozoic intrusive rocks. Directly beneath the volcanics at RM is a carbonate unit, the Lower Carbonate Aquifer (LCA) Thrust Plate Hydrostratigraphic Unit (HSU). This unit is thought to have been placed on top of a thick siliciclastic confining unit, the Upper Clastic Confining Unit HSU, by the Belted Range Thrust fault, which is from the west. The LCA is saturated and water levels in the unit are considered to be representative of the regional water table. Shoshone Mountain (SM) is comprised of several ridges and peaks, which consist of interbedded welded and nonwelded tuffs and lava flows. Shoshone Mountain is adjacent to the southeastern part of the Timber Mountain caldera complex in the central part of the NTS. The older, nonwelded and bedded tuffs tend to be altered to zeolites and lesser clays. Unlike RM, no perched water has been found in these units. Like RM, these volcanic rocks were deposited on a substrate of complexly folded and faulted Paleozoic sedimentary rocks, and Precambrian sedimentary and metamorphic rocks. Directly beneath the SM volcanics is a section of argillite which is part of the Upper Clastic Confining Unit HSU. The first water encountered is in carbonate rocks that appear to be part of the regional carbonate aquifer (LCA HSU).

The RMSM CAU is different from the other CAUs because all contaminant sources are hundreds of meters above the regional water table. These sources are a result of tests in tunnel complexes and vertical shafts. Although well above the regional water table, some of the tunnel complexes (notably N, T, and E) appear to be in perched water zones.

It is proposed to model the RM and SM areas separately. The RM area will be modeled in a multistep approach. First, a Hydrologic Source Term (HST) model will be developed. The releases from the HST model will then provide input to sub-CAU scale models of the RM N- and T-Tunnel complexes. Second, the T- and N-Tunnel areas in the perched and unsaturated zone down to, but not including, the regional water table will be modeled. Work on the RM saturated-zone model will begin with model mesh construction, sensitivity analysis and calibration, then particle tracking will be used as a simplified representation of flow directions and transport. When the sub-CAU results are ready, the radionuclide and water fluxes at the water table, and any evaluated uncertainties from the vadose zone modeling, would be used as input to the CAU-scale saturated-zone model as the final stage of analysis, after issues have been evaluated with more simple, efficient approaches. The SM area will be modeled with a similar approach.

The experience gained through the development of the Frenchman Flat and Pahute Mesa CAU transport models has yielded refinement of multiple modeling concepts and findings that will be implemented in the RMSM CAU modeling strategy. These modeling concepts include:

- Source-term release, which is the driving factor on the volume of groundwater impacted, and the degree to which it is contaminated.
- The conservative radionuclide species such as hydrogen-3, carbon-14, and chlorine-36 (found predominantly in the cavity rubble) dominate the predictions of the extent of the contaminant boundary.
- Both flow model parameter and HFM uncertainty will be evaluated.

The overall approach for the RMSM CAU modeling strategy is to integrate the conceptual model components (e.g., unsaturated and saturated flow and transport) at an early stage of the modeling process, along with the results of the sub-CAU and CAU models. The process of the Phase I CAU modeling described in this document will identify parameter sensitivities and uncertainties, and

use such insight to prioritize data gathering for parameters judged to be important for reducing contaminant migration uncertainty and the resulting uncertainty in contaminant boundary predictions. Data gathering will be optimized for the Phase II data collection activities and the Phase II modeling studies will use additional information to develop model predictions of the contaminant boundaries.

The major change in approach for the Phase I saturated zone modeling is a decreased emphasis on formal contaminant boundary predictions for all sets of calibrated models and alternative HFMs. Simplified representations of flow and transport will be used in the Phase I modeling to develop improved understanding of model responses and the effects of parameter sensitivities and conceptual uncertainties on model predictions. The emphasis for both approaches is to better understand data sensitivities and how these identified data sensitivities can be used to more efficiently gather data during the Phase II characterization activities. Model predictions for multiple sets of alternative contaminant boundaries will be developed during the Phase II modeling activities.

1.0 GENERAL DESCRIPTION OF THE CORRECTIVE ACTION UNIT MODEL PROCESS

The objectives of the Underground Test Area (UGTA) Project are to: (1) evaluate the extent of contamination in groundwater as a result of underground nuclear testing on the Nevada Test Site (NTS), (2) develop and implement a corrective action for each Corrective Action Unit (CAU), (3) close each CAU, and (4) achieve regulatory agreement on appropriate measures to manage the groundwater resource. A key element of the strategy to meet the UGTA objectives is the development of groundwater flow and radionuclide transport models to predict the migration of contaminants away from the underground test locations.

This document describes a modeling approach for the Phase I CAU Flow and Transport modeling. The U.S. Department of Energy (DOE) and Nevada Division of Environmental Protection have agreed to modify the strategy for Rainier Mesa/Shoshone Mountain (RMSM) by choosing to focus on a shortened initial modeling analysis herein referred to as the Phase I CAU Flow and Transport Modeling. The analysis is intended to improve understanding of modeling system response and the effects of parametric and conceptual uncertainty on transport predictions. This understanding will be used to evaluate quantitatively what additional information should be collected during the next round of field activities to reduce uncertainty in the Phase II CAU Flow and Transport Model contaminant boundary predictions. This shortened analysis focuses on flow and transport model sensitivity and prediction uncertainty results. It is to be used as a tool to identify priority data requirements without the burden of a full calculation of the contaminant boundary. The full contaminant boundary calculation will be estimated in a more detailed round of analysis (Phase II in terms of scheduling), after additional field activities and data collection, following Phase I modeling.

This section provides an overview of the generic aspects of the UGTA CAU modeling approach, and a brief review of differing features and processes between CAUs. The overview will address the role of modeling in:

- The *Federal Facility Agreement and Consent Order* (FFACO), 1996 (as amended February 2008).
- Understanding system behavior.

1.1 Role of Modeling in the FFACO Corrective Action Strategy

The DOE, U.S. Department of Defense, and State of Nevada have negotiated the FFACO to address environmental restoration activities at DOE National Nuclear Security Administration Nevada Site Office (NNSA/NSO) facilities and sites. The Office of Legacy Management is also a signatory of the FFACO; however, it has no current role in the UGTA Project. The FFACO is the primary regulatory driver for DOE environmental restoration activities in Nevada. The FFACO sets the framework and contains the requirements to prioritize and enforce the Environmental Restoration (ER) activities for contaminated NNSA/NSO facilities and sites. Technical strategies for these activities are provided in the FFACO. The DOE, through the UGTA Project, is responsible for the completion of corrective actions for five CAUs associated with historical underground nuclear testing on the NTS. The UGTA Project CAUs (i.e., Frenchman Flat [FF], Central and Western Pahute Mesa [PM], Yucca Flat/Climax Mine [YFCM], and RMSM) are shown in [Figure 1-1](#). The hydrostratigraphic framework models (HFMs) have been developed for each of these CAUs.

Specific requirements established by the FFACO are to:

- 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.”

The UGTA corrective action strategy is described in Section 3.0 of Appendix VI, Revision No. 2 of the FFACO, 1996 (as amended February 2008). The UGTA strategy was modified following completion of the DOE review of the FF CAU model. In this document, subsequent references to the

Figure 1-1
UGTA CAUs and CASs and the RMSM HFM Area

FFACO or its appendices are made to the FFAO as a whole. The objective of the Corrective Action Investigation (CAI) process is specified in the FFAO as:

- “The objective of the CAI process is to define the boundaries around each UGTA CAU to establish areas that contain water that may be unsafe for domestic and municipal use.”

The referred to boundaries are those to which contaminants are predicted to have migrated within 1,000 years. The FFAO also outlines the objective of the UGTA Corrective Action Strategy as:

- “The objective of the strategy is to analyze and evaluate each UGTA CAU through a combination of data and information collection and evaluation, and modeling groundwater flow and contaminant transport. This analysis will estimate the vertical and horizontal extent of contaminant migration for each CAU in order to predict contaminant boundaries.”

The FFAO provides a definition of the contaminant boundary:

- “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 (HSU) boundary.”

The requirements for presentation of the modeling results are included in the FFAO as:

- “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.”

The contaminant boundary is the starting point from which a compliance boundary is negotiated between the Nevada Division of Environmental Protection (NDEP) and DOE defined in the FFAO as:

- “The compliance boundary will define the area within which the radiological contaminants above the SDWA standards relative to background are to remain. The DOE will be responsible for ensuring compliance with this boundary. The compliance boundary may or may not coincide with the contaminant boundary. If the predicted location of the contaminant boundary cannot be accepted as the compliance boundary, an alternative compliance boundary will be negotiated by both parties.”

The use of flow models to achieve the objectives of the corrective action strategy as described in the FFACO:

- “For saturated conditions, a flow model of each CAU will be constructed to provide local three-dimensional flow, to evaluate the range of flow conditions in the CAU that may be important in determining maximum extent of transport, and to provide boundary conditions for modeling transport. Saturated conditions are planned to be modeled for FF, YFCM, Western PM, and Central PM CAUs.”

Note that the modeling of saturated conditions may not be required for the RMSM as discussed subsequently. The use of contaminant transport models to achieve the objectives of the corrective action strategy as described in the FFACO:

- “CAU models utilizing tritium as the source term will be used to establish the contaminant boundary for each CAU. The boundary will be composed of a perimeter boundary and a lower HSU 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 HSU boundary will define the lowest aquifer unit affected by the contamination. Long-lived radionuclides, except tritium, 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.”

It is proposed to model the migration of hydrogen-3 (^3H), carbon-14 (^{14}C), and chlorine-36 (^{36}Cl) through the vadose zone at both Rainier Mesa (RM) and Shoshone Mountain (SM). To predict the locations of the contaminant boundary within 1,000 years, the modeling requires integration of multiple individual models, each with a specific purpose. These individual models simulate flow at various scales (regional, CAU, sub-CAU, and hydrologic source term [HST]), as well as transport. The HST model defines the radionuclide fluxes from the radionuclide source locations. The modeling will begin with source term development and simplification followed by fate and transport simulations of the vadose zone (everything above the regional water table). It is recognized that perched water zones are present in the RM area.

The entire process flow leading to the closure of CAUs, as specified by the FFACO, is shown in [Figure 1-2](#).

Figure 1-2
Process Flow Diagram for the UGTA CAUs

The upper portion of the figure shows processes designed for the Corrective Action Investigation Plan (CAIP) and CAI phases. The FFACO requires that several plans and reports be prepared to document the corrective action process. The first step in the Corrective Action Strategy for a CAU is preparation of the CAIP as shown in [Figure 1-2](#). The CAIP provides or references all specific information for planning and investigation activities associated with a CAU or sites. The use of groundwater models to address the FFACO requirements is detailed in the CAIPs for FF (DOE/NV, 1999a), PM (DOE/NV, 1999b), YFCM (DOE/NV, 2000), and RMSM (NNSA/NSO, 2004).

The first steps of the CAI include the evaluation of existing data and the collection and evaluation of new data. In this context, data evaluation may include development of three-dimensional (3-D), CAU-scale flow and transport models. Through agreement between NDEP and DOE, the RMSM strategy has been revised to construct and use sub-CAU and CAU models as tools to direct future data collection activities when the currently available data is judged inadequate for CAU boundary estimation. The models will address parameter sensitivity, uncertainty, and predictive uncertainty to show optimally where and what additional data is necessary to proceed. This step, Develop Phase I CAU Flow & Transport Model, is highlighted in yellow [Figure 1-2](#).

1.2 Role of Modeling in Understanding System Behavior

Given the complexity of the subsurface system, sources, and processes controlling transport, computer models will be used as a tool to meet the revised FFACO strategy objectives. The role of modeling in the FFACO Corrective Action Strategy is discussed in [Section 1.1](#). Simulation objectives are defined in the FFACO. The objective is to develop modeling approaches to assess processes that control contaminant migration through the hydrogeologic units (HGUs) of RMSM, and downgradient locations, and assess the effect of parameter and alternative uncertainties on contaminant transport. Phase I CAU modeling will identify data gaps and guide additional data collection activities important for reducing transport uncertainty.

The objectives of the FFACO will be met via a multistep modeling process. This process includes analysis of hydrologic, geologic, hydrogeologic, and geochemical data, definition of base and

alternative hydrostratigraphic models, specialized analyses related to faults and radionuclide source terms, definition of model boundaries, and development and implementation of flow and transport numerical models. The flow model is calibrated to observed data that may include water levels, groundwater fluxes, and geochemistry constraints. The transport models use information related to calibrated flow models, radionuclide sources, and transport parameters. Finally, the transport simulations evaluate system behavior and associated uncertainty, both of which contribute to predictive uncertainty.

Integrated Model Development

The integrated flow and transport model is generally viewed as the model that will provide final decision support for the FFACO Correction Action Strategy. For the purposes of this document, the integrated flow and transport model will be referred to herein as the CAU model. At this time, the model is preliminary (Phase I) and will be used to direct further data collection activities. Once the available data are deemed adequate, as shown in the CAI phase on [Figure 1-2](#), the CAU model will proceed to Phase II to estimate the CAU boundaries for negotiation with the regulatory agencies.

Building the CAU model begins with compiling all site characterization data and relevant information to provide a technical basis for the model. Based on this information, conceptual models are developed to describe the general geologic and hydrogeologic characteristics of the system and the various flow and transport system processes of interest. Information flows from the data and information compilation level through conceptual model development and process model development to the level of the CAU numerical models.

The RMSM CAU is different from the other CAUs because all contaminant sources are hundreds of meters above the regional water table. These sources are a result of tests in tunnel complexes and in vertical shafts. Although well above the regional water table, some of the tunnel complexes (notably N, T, and E) appear to be in perched water zones. As a result of the unsaturated and/or perched conditions in which the tests were conducted, the modeling process will be implemented in a multistep approach. The first step will consist of HST development and simplification. The second step will be flow and transport modeling of the vadose zone. Results from the vadose zone modeling will then be used as input to the saturated zone modeling below the regional water table.

Figure 1-3 shows the process as proposed for RM. The simplified source terms for the N- and T-Tunnel systems will be used as input for numerical models simulating flow and transport through the vadose zone to the regional water table. The N-Tunnel complex simulations will use the Finite Element Heat and Mass Transfer code (FEHM). The T-Tunnel complex simulations will use the MINC (Multiple INteracting Continuum) code and T2R3D (TOUGH2 with hydrodynamic dispersion for transport in 3-D) program. These simulation results will be used to estimate the probability of contaminant migration to the water table from the other tunnel complex and vertical shaft tests at RM. A flow and transport model of the saturated zone will be developed using FEHM. The migration of contaminants will then be simulated through the end of the compliance period. Although the Phase I CAU modeling results may not indicate the need for full development of saturated-zone flow and transport modeling, that does not imply that such modeling would not be part of Phase II CAU modeling. The Phase II vadose zone modeling will incorporate the data collected after Phase I modeling. Incorporating the additional new data may change the results and indicate migration of radionuclides to the regional water table requiring simulation of contaminant fate and transport in the saturated zone.

Figure 1-4 shows the modeling process as proposed for SM. The general SM modeling approach is the same as RM. One difference is that there is only one tunnel complex (U16a) that is a potential source. The vadose zone modeling will be accomplished with either one-dimensional (1-D) or two-dimensional (2-D) FEHM simulations.

There are two requirements for this integrated model development process to be effective (DOE, 1998). First, information passed from one step to the next must be consistent. Second, essential aspects of the processes described by the detailed process models must be represented accurately in the CAU model. This representation must include the uncertainty associated with the process or parameters.

Figure 1-3
Proposed Flow Diagram for the RM Phase I CAU Modeling

Figure 1-4
Proposed Flow Diagram for the SM Phase I CAU Modeling

1.3 Document Organization

The remaining sections of this document describe the conceptual framework and modeling approach/implementation for RM and SM. [Section 2.0](#) is an overview of the current interpretations of the RMSM CAU base and alternative hydrostratigraphic framework conceptualizations, contaminant sources, site characterization data, and discussions of the hydrogeologic conceptual models for both RM and SM. [Section 3.0](#) provides a summary of the components of the modeling implementation approach for RM and SM including methods and approach for treatment of parameter and conceptual model uncertainty.

2.0 CONCEPTUAL FRAMEWORK FOR THE RAINIER MESA/SHOSHONE MOUNTAIN CORRECTIVE ACTION UNIT HYDROGEOLOGIC SYSTEM

The RMSM 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 RM proper and the contiguous Aqueduct Mesa. [Figure 2-1](#) shows the locations of the tests conducted at RMSM. Shoshone Mountain is located approximately 20 kilometers (km) south of RM, but is included within the same CAU because of geologic setting similarities and the nature and types of nuclear tests conducted. The RMSM CAU falls within the larger RMSM HFM Area, which also includes the northwest section of the Yucca Flat (YF) CAU as shown in [Figure 1-1](#).

[Figure 2-2](#) is a generalized geologic map of the RMSM HFM Area. The RM and SM are adjacent to the Timber Mountain and Silent Canyon Caldera complexes. The uppermost units in the stratigraphic section are composed of volcanic rocks that erupted from these calderas, 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 calderas 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, normal, and strike-slip faults. In both RM and SM, underground nuclear tests were conducted in tunnel complexes excavated above the regional groundwater table. Several tunnel complexes (notably N, T, and E) in RM contain local perched groundwater near the elevation of the tests, which leads to water accumulating in the drifts. There is no perched water evident in the vicinity of the SM complex and the SM tunnel complex is dry.

Figure 2-1
RMSM HFM Area, CAUs, and CASSs
Source: Modified from SNJV, 2008a

2.1 RMSM Hydrostratigraphic Framework Model

A 3-D HFM and alternatives for the RMSM CAU were constructed in 2007 and are documented in NSTec (2007). This section is an overview of the HFM and alternatives. Detailed information about the HFM is in the original report.

The HFM provides the 3-D framework for flow and transport models, and consists of five HFMs: a base and four alternatives. These alternative models are alternative structural interpretations of the hydrostratigraphy present in the base model.

Figure 2-1 is a map of the RMSM area showing the underground nuclear test locations and the HFM boundary. Rocks are classified hydrologically in the HFM using a two-level classification scheme (i.e., HGUs and HSUs). Descriptions of the HGUs and HSUs are in Tables 4-3 and 4-4 of the HFM report (NSTec, 2007).

2.1.1 HFM Base Case

The geology of the RMSM HFM is complex, similar to most of the Basin-and-Range province. However, there are a few generalities that can be applied to the model. One, is that the lower carbonate aquifer (LCA) is the principal aquifer in the model and is modeled at a thickness of up to 4,000 meters (m). The LCA is present throughout the model area with the exception of areas containing intrusive HSUs. Figure 2-3 shows the HSUs present at the water table in the HFM.

Figure 2-4 is a north-south cross section bisecting the HFM that shows the extent and thickness of the LCA and its general dominance as an HSU. The line of section is shown in Figure 2-3.

The LCA is covered by the upper clastic confining unit (UCCU) in all but the southeast corner of the model area. This HSU is shown in Figures 2-3 and 2-4. The thickness of the UCCU, a unit of relatively low permeability, varies but is generally 500 to 1,000 m in the model area. The lower carbonate aquifer-thrust plate (LCA3) is a thrust sheet of LCA stratigraphic unit that is on top of the UCCU in the north-central and eastern parts of the model.

Figures 2-5 and 2-6 are east-west cross sections through the HFM. The locations of both lines of section are shown in Figure 2-3. Figure 2-5 (line of section C-C') cuts across the northern part of the

HFM. The figure illustrates the function of intrusive igneous rocks as shown by the disruption of the LCA by the relatively low permeability Mesozoic Granite Confining Unit (MGCU). As a low permeability unit in the permeable LCA, it diverts flow and adds complexity to the modeling process. In addition, the UCCU is shown to overlie the LCA, which provides a low permeability layer above this aquifer, through which contaminants caused by testing at RM would have to pass before reaching the LCA.

Figure 2-6 (line of section F-F') cuts across the southern part of the HFM at Well ER-16-1 in the general vicinity of the SM tests in the U16a-Tunnel complex. This line of section shows the Tertiary volcanics bounding the HFM to the west. Although many of the volcanic rocks have low permeability, some HSUs (e.g., Timber Mountain Composite Unit and Fortymile Canyon Composite Unit) have high permeability and could allow increased groundwater flow through the western boundary of the HFM. Figure 2-6 shows that the UCCU overlies the LCA. Contaminants caused by testing conducted in the U16a-Tunnel complex would have to pass through this low permeability unit before reaching the LCA.

Detailed descriptions and block diagrams that illustrate the location, extent, and relationships of the HSUs in the model are available in the RMSM HFM report (NSTec, 2007). Several large cross sections are included in Appendix C of the HFM report.

2.1.2 RMSM Alternate Framework Models

Alternative geologic conceptual models of the RMSM HFM area have been developed. Specifically, the four alternative models considered are as follows:

1. No Redrock Valley Caldera (RVC): For this scenario, the RVC is removed from the model. One major difference in this alternative is the replacement of the Redrock Valley Intrusive Confining Unit with an extension of the LCA as shown in Figure 2-7.

Figure 2-5
West-East Model Profile (C-C') through Aqueduct Mesa at Well ER-12-4
Source: Modified from NSTec, 2007

Figure 2-6
West-East Model Profile (F-F') through the Northern End of SM at Well ER-16-1
Source: Modified from NSTec, 2007

Figure 2-7
West-East Profiles through the Base HFM and the No RVC Alternative HFM
 Source: Modified from NSTec, 2007

2. More Extensive LCA3: The LCA3 imbricate thrust sheet is not terminated by the RVC and TM caldera southwest of RM but rather extends further southwest. This scenario is shown in [Figure 2-8](#).
3. Shoshone Mountain Thrust: The carbonate rocks exposed along the west side of Mid Valley are not LCA but rather a thrust sheet of the LCA3 that overlies UCCU. The scenario is shown in [Figures 2-9](#) and [2-10](#).
4. Lower carbonate aquifer-thrust plate at the bottom of Well ER-12-1: The base model designates the carbonate rocks at the bottom of Well ER-12-1 as LCA. This alternative scenario models the carbonate rocks as part of another imbricate thrust slice, and designates them as LCA3-1 to distinguish it from the structurally higher main LCA3 ([Figure 2-11](#)).

These alternatives are considered because of the possible configurations that the current data do not rule out. And because of the potential for developing flow fields that are different from those resulting from the base conceptual model. These models are documented in NSTec (2007).

2.1.3 Uncertainty

Uncertainty in the interpretation of site characterization data allows for multiple permissive alternative HFMs. This uncertainty, a form of structural uncertainty, is evaluated through the development of equally likely discrete framework models.

Initially, alternative models are developed that represent geographically extensive variations of the hydrostratigraphic frameworks. The significance of the alternative models are evaluated through a combination of calibration using uncertain boundary conditions and parameterizations, subjective assessments of the degree of changes in groundwater flow, and evaluation of agreement or disagreement with observed major features of the flow system. Calibration information is enhanced through use of parameter estimation software (PEST) to optimize objective functions and explore parameter sensitivity for the calibrations (Doherty, 2007).

The more extensive LCA3 HFM, in which the LCA3 beneath the RM area has been extended to the south, may have a direct influence on the direction and distance radionuclides will travel by creating a long-distance higher permeability (relative to the base model) pathway to the south. Another alternative (the no RVC HFM), shown in [Figure 2-7](#), removes a major structural feature (RVC) of which the existence is uncertain. Initially, alternatives will focus on conceptual models representing

Figure 2-8
Comparison of the Base HFM with the More Extensive LCA3 Alternative HFM

(Perspective views alluvium, volcanic rocks, and LCCU removed.)

Source: Modified from NSTec, 2007

Figure 2-9
Comparison of the Base HFM with the SM Thrust Sheet Alternative HFM
 (Perspective views of the southern portion of the model area with alluvium and volcanic rocks removed.)
 Source: Modified from NSTec, 2007

Figure 2-10
West-East Profiles through the Base HFM and the SM Thrust Sheet Alternative HFM
 Source: Modified from NSTec, 2007

Figure 2-11
West-East Profiles through the Base HFM and the LCA3
at Bottom of ER-12-1 Alternative HFM

Source: Modified from NSTec, 2007

geographically extensive variations of the hydrostratigraphic framework. Values of boundary conditions, fault permeabilities, and other parameters will be investigated via sensitivity and uncertainty analysis to test the durability of the various HFM hypotheses in representing, via calibration, the observed data and to determine whether they are truly different. The use of the null space Monte Carlo method will be key in this analysis.

2.2 Contaminant Sources

Nuclear testing in the RMSM CAU was primarily in mined tunnels. Information on the tunnels, particularly regarding the hydrogeologic character of the formations in which the tunnels are located and the relationship of the tunnels with groundwater, is discussed as background for evaluating the contaminant mobility from the tests.

2.2.1 Overview of Testing in the RMSM CAU

Within the RMSM CAU, 62 underground nuclear detonations were conducted at RM between 1957 and 1992. Another 6 were conducted at SM between 1962 and 1971 (DOE/NV, 2000). Of the 68 detonations in the RMSM CAU, 66 occurred in mined tunnels. Two detonations at RM, CLEARWATER (U-12q) and WINESKIN (U-12r), were conducted in vertical shafts. The locations are shown on [Figure 2-1](#) (DOE/NV, 1997 and 2000; Grasso, 2003; NNSA/NSO, 2004). [Table 2-1](#) summarizes the number of detonations per testing location, elevations of the working points of the tests at that location, and approximate heights of the working points above the regional water table. The regional water table is estimated to be at an elevation of 1,300 m above mean sea level (amsl) for the RM tests and 762 m amsl for the SM tests.

Townsend et al. (2007) summarized post-test data gathered from the 40 detonations conducted by the Defense Nuclear Agency (now the Defense Threat Reduction Agency) and Sandia National Laboratories at RM. Re-entry (mine-back and/or drill-back) data were analyzed with respect to cavity/chimney dimensions, cavity/chimney physical characteristics, micro-failure (microscopic-scale damage caused to the tuff by the passage of the shock wave), macro-failure (discrete, measurable motion along a planar surface caused by the energy of the explosion), radiation, and water-related observations. Detailed information from this source for the most studied

Table 2-1
Summary of Nuclear Detonation Locations at RMSM
Relative to the Regional Water Table

Area	Detonation Location	Nuclear Detonations Conducted	Range of Working Point Elevations (m amsl)	HGU in which Detonation(s) Conducted	Approximate Height above the Regional Water Table (m)
Rainier Mesa	U12b	6	2,016	VTA	700
Rainier Mesa	U12c	3	2,047	VTA	700
Rainier Mesa	U12d	1	2,047	VTA	700
Rainier Mesa	U12e	9	1,871 - 1,883	TCU	500
Rainier Mesa	U12f	2	2,048	VTA	700
Rainier Mesa	U12g	5	1,878 - 1,896	TCU	500
Rainier Mesa	U12j	1	1,723	TCU	400
Rainier Mesa	U12k	1	1,722	TCU	400
Rainier Mesa	U12n	22	1,849 - 1,860	TCU	500
Rainier Mesa	U12p	4	1,682 - 1,686	TCU	300
Rainier Mesa	U-12q	1	1,711	TCU	400
Rainier Mesa	U-12r	1	1,771	TCU	400
Rainier Mesa	U12t	6	1,715 - 1,718	TCU	400
Shoshone Mountain	U16a	6	1,654 - 1,657	TCU	800

TCU = Tuff confining unit

VTA = Vitric-tuff aquifer

detonations is summarized by Lawrence Livermore National Laboratory (Hu and Zavarin, 2007).

Descriptions of each tunnel complex and vertical borings including the portal elevations, formations intercepted during construction, dates of construction, and tendencies to produce water are in SNJV (2008b). The working point elevations have been updated recently (Townsend, 2008).

2.2.2 Rainier Mesa Tunnels

Six large and several smaller tunnel complexes were constructed at RM for underground nuclear testing from the 1950s to the early 1990s (Figure 2-1). Of the 68 detonations conducted in RMSM CAU, 62 were conducted at RM. The tunnel complexes used for nuclear testing are designated as: U12b, U12c, U12d, U12e, U12f, U12g, U12j, U12k, U12n, U12p, and U12t. Nuclear detonations were also conducted in vertical drill holes U-12r and U-12q.

Figure 2-12 is roughly a southwest-northeast cross section through Well ER-12-3 showing projections of tunnel complexes U12b, U12c, U12d, U12e, U12f, and U12n on the stratigraphic section. The elevations where the tunnel complexes are shown represent the elevations of the working points for the detonations conducted in the respective tunnels. Although the projections are approximate, they serve to place the detonation horizons in the stratigraphic section and in relation to the regional water table. The detonations conducted in U-12r and U-12q were not projected onto the section because of lateral distance from the line of section. The U12g-Tunnel complex is located sufficiently south of the section depicted; therefore, it could not be included. The detonations were conducted in either the VTA or TCU, at heights no less than 400 m above the regional water table, based on the assumption that the regional water table is found at an elevation of 1,300 m amsl.

Figure 2-13 is roughly a southwest-northeast cross section through Well ER-12-4 showing the projection of the U12t-Tunnel complex. Again, the elevation at which the tunnel complex is shown is representative of the working point elevations for the detonations conducted in the tunnel. Tunnel complexes U12j, U12k, and U12p are located north of the line of section and could not be included. However, as with the detonations conducted in the U12t-Tunnel complex, these detonations were conducted in the TCU. Assuming the regional water table is at an elevation of approximately 1,300 m amsl, the detonations were conducted no less than 380 m above it.

There are three tunnel complexes in RM that have had significant groundwater discharge: U12t, U12n, and U12e. Discharge from these complexes has been variable. Tunnel discharge is greatest immediately after mining and with time tapers off to a base discharge rate that varies with seasonal precipitation. Over time, the tunnels were expanded with new drifts in each of the tunnel complexes. The initial discharge of these tunnels was as high as 1,900 liters per minute (Lpm) (about 1 million cubic meters per year [m^3/yr]), but the discharge quickly tapered off. The largest sustained historic discharge for a single tunnel (U12t) is about 350 Lpm ($180,000 \text{ m}^3/\text{yr}$). The discharged water is redirected to unlined ponds where some portion evaporates and the rest re-infiltrates. The U12t-Tunnel complex was sealed in 1993, and the U12n-Tunnel complex was sealed in 1994. These tunnels no longer discharge to the surface. An attempt to seal the U12e-Tunnel complex in 1994 was unsuccessful, and the tunnel currently discharges water at 28 to 35 Lpm (about 14,000 to $18,000 \text{ m}^3/\text{yr}$). Significant long-term discharge has not been observed at other tunnels in RM. A few

Source: Modified from NNSA/NSO, 2006a

Sources: Modified from NNSA/NSO, 2006a; USGS, 2008

Figure 2-12
Southwest-Northeast Hydrogeologic Cross Section A-A' through Well ER-12-3 showing Approximate Test Horizons and Line of Section

small seeps were encountered during the mining of U12a, U12b, and U12g, but there is no evidence of sustained discharge in these tunnels.

2.2.3 Shoshone Mountain Tunnel

The U16a-Tunnel complex was the only tunnel complex constructed at SM. It was constructed between 1961 and 1971 by the U.S. Department of Defense with additional exploratory work continuing through 1973. Six low-yield (less than 20 kilotons) nuclear tests were conducted in the complex. The underground portions of the testing area have been inactive since 1973.

Figure 2-14 is roughly a west-east cross section through Well ER-16-1 showing the projection of the U16a-Tunnel complex on the stratigraphic section. The elevation where the tunnel complex is shown represents the approximate elevation of the test working points for the tests conducted. The CA depicted in the cross section is the regional LCA. The regional water table (762 m amsl) is shown on the figure. This figure shows that the detonations were conducted in the TCU at a height of no less than 800 m above the regional water table. Available mining records suggest that no significant quantities of water were encountered during mining or exploratory drilling. Water that does infiltrate through the test areas must drain through hundreds of meters of low permeability material (i.e., TCU and UCCU) before reaching the CA.

2.2.4 Groundwater at Rainier Mesa

The working points for the tests at RM were conducted within rocks classified as VTA and TCU HGUs. The VTA is composed of bedded ash-fall and reworked nonwelded vitric tuffs. These tuffs display significant interstitial porosity and generally insignificant fracture permeability. However, this unit does not extend far below the water table because saturated conditions tend to alter the tuffs to zeolitic mineral assemblages. The TCU is a zeolitized bedded tuff composed principally of rhyolitic air-fall tuff and nonwelded ash-flow tuff. In the absence of faulting, the permeability of this unit is extremely low. There was no observed water seepage into the tunnels from the interstitial porosity, only from the faults and fractures.

The cross sections discussed above show that contaminants must move through the TCU to reach the LCA3 and regional water table. Groundwater occurs in the TCU within isolated fractures and faults

Figure 2-14
West-East Hydrogeologic Cross Section A-A' through Well ER-16-1 showing Approximate Test Horizons and Line of Section

in some of the RM tunnel complexes and is perched in places above the regional groundwater system. Infiltration occurs across the high elevation plateau of RM, percolating downward through fractures, and forming perched groundwater zones. The construction of underground nuclear tests and associated tunnels significantly disturbed the natural hydrologic system. Previously isolated fracture zones (Figure 2-13) are now connected by the tunnel workings, and connectivity of the perched zones is increased beyond the tunnels due to test-induced fracturing. This creates the potential for significant lateral movement of groundwater from one high conductivity vertical conduit to another. In addition, the presence of blast-induced chimneys (vertical extensions of the blast cavity) may hydraulically connect the test horizons with permeable units stratigraphically above allowing groundwater to drain into the tunnel complexes. This is most applicable to tests in the TCU near the base of the VTA. The result is the potential for significant lateral movement of groundwater from one high conductivity vertical conduit to another, therefore, challenging the concept of strict vertical infiltration beneath the test cavities. The assumption of projecting a nuclear source term directly below a cavity could be a significant error if, in fact, that source is mixed into a saturated tunnel that drains thousands of meters away.

Figures 2-13 and 2-14 both show faults passing through or in the vicinity of test horizons. One goal of modeling will be to test the possible influence of these features on contaminant migration. If the faults are open pathways, contaminants may move by relatively fast fracture flow rather than relatively slow matrix flow.

Beneath the TCU, thrust blocks of LCA (designated LCA3) comprise an aquifer system that may receive recharge from the overlying volcanic tuffs. The thrust blocks of LCA are shown as the CA in Figures 2-12 and 2-13.

2.3 Site Characterization Data

The NTS and surrounding areas have been the subject of intensive scientific study by a constellation of projects, programs, and organizations for more than 50 years. A large body of literature and data support a variety of activities at the NTS, much of which is useful to illuminate conditions and processes that affect radionuclide transport at the site. The sources of these data and ranges of values are discussed in the forthcoming Hydrologic Data and Contaminant Transport Parameter documents

(SNJV, 2008a and b), produced in support of RMSM CAU-scale modeling. This section discusses data specific to the RMSM model area and implications for CAU-scale modeling.

2.3.1 Hydraulic Heads and the Saturated State of the Flow System

In the immediate vicinity of RM, steep hydraulic gradients result from the relatively large amount of areal recharge that occurs on the mesa and the complex geometry of aquifer and confining unit HSUs. Steep vertical hydraulic gradients exist across confining units between permeable aquifer units. Wells discussed in this section are shown in [Figure 2-1](#).

In RM, water levels in the ER-12-4 and ER-12-3 piezometers, and several other nearby wells in the low permeability zeolitized and argillic tuff confining units where nuclear testing was conducted, are approximately 1,800 to 1,875 m amsl. Water levels directly beneath RM in LCA3 in ER-12-3 and ER-12-4 are at about 1,305 and 1,315 m amsl, respectively. These data suggest that the vertical gradient within the confining tuffs down to the LCA3 is slightly less than 1.0. The high hydraulic head in the tuffs is most likely caused by the vertical flux of surface recharge through this low conductivity unit down to the LCA3, although higher conductivity features (e.g., fractures and small welded tuff beds) have some potential to complicate this (NNSA/NSO, 2006 a and b).

The LCA3 is the first unit considered to be part of the regional flow system under RM. The unit is an overthrust of the LCA that sits on top of the UCCU. Although the name is the same, the RM LCA3 was created by the west vergent Belted Range Thrust, which is a different set of tectonic events from the CP Thrust responsible for the LCA3 in western YF.

About 3 km southwest of ER-12-3, just off the edge of RM, ER-19-1 contains three separate completions that illustrate the variability of hydraulic head between aquifers separated by confining units. Water levels in the upper and middle completions are 1,565 and 1,523 m amsl, respectively. The upper completion is in the Oak Spring Butte Confining Unit, the middle completion is in the Redrock Valley Aquifer (RVA), and the hydraulic gradient between the two completions is about 0.11. The lower completion is in the lower carbonate confining unit-thrust plate, a clastic confining unit and thrust assumed to be on top of the LCA3, and the water level in the completion is about 1,330 m amsl, which is comparable to LCA3 water levels in ER-12-3 and ER-12-4. The gradient

between the middle and lower completions is approximately 0.86, which indicates that the head level in the LCA3 is much lower than in the RVA. A detailed discussion of water levels, water level measurements, and data on the hydrostratigraphy, and open intervals at the wells is in SNJV (2008a).

Water levels beneath U16a are considerably lower than the elevation of the tunnel. The water level in the LCA in ER-16-1 is about 762 m amsl and no perched water was found during drilling. There are much higher water levels to the northeast, but these appear to be perched water levels related to the flux of areal recharge at the upper carbonate aquifer (UCA) of Syncline Ridge through the low permeability UCCU. The U16a-Tunnel mining operations did not encounter groundwater, even in drilling operations conducted for the express purpose of exploring for perched water (Davies, 1962).

There are few water level measurements in the western portion of the model area; however, there is some evidence that the upper volcanic HSUs in the western portion of the model area form a continuous aquifer. Water levels in wells ER-19-1-2 and TW-1 in the volcanics are at 1,523 and 1,563 to 1,437 m amsl, respectively. The water level in volcanics in WW-8 on the western edge of the HFM is about 1,410 m amsl. This is still well above the water levels measured in the LCA3 at RM, but lower than levels in the volcanics surrounding the mesa indicating a gradient in the volcanics toward the southwest.

There is minimal control on water levels in the LCA within the RMSM HFM area. As shown in [Figure 2-1](#), ER-16-1 is located at the testing area at SM. The well is completed in the LCA and the water level in the well is about 762 m amsl. ER-12-1 is located just to the east of RM and the lithologic log records several separate intervals of carbonate rock, some of which are not included in the HFM because they appear isolated. There is a single water level in the lowest section of carbonate taken with a pressure transducer during a packer test. The water level is 931 m amsl, but there is at least 7 m of uncertainty in the measurement. This section of carbonate is modeled as LCA in the base HFM, but is included as another isolated carbonate unit (LCA3-1) in an alternative HFM. These two control points leave significant uncertainty in the state of hydraulic head in the LCA in the RMSM HFM area. Water levels in the LCA in YF to the east of the RMSM HFM vary from about 746 to 727 m amsl. The similarity of these water levels to those measured in ER-16-1 suggests little horizontal gradient in the LCA in the area, and water levels in the LCA beneath RM should be much

closer to the levels in YF than in the LCA3 higher in the section. The water levels in the YF LCA should be the lower bound of the levels in the RMSM LCA.

2.3.2 Saturated Media Hydraulic Properties

Saturated media hydraulic properties are evaluated within the context of HGUs in the HFM. The most important hydraulic property for CAU-scale modeling is hydraulic conductivity. Secondary conductivity from faults and fractures is also important in some HGUs. The majority of the hydraulic conductivity data for the volcanic units are transferred from other locations on the NTS. However, there are some data specific to RM for the LCA3.

The geologic events that overthrust the RM LCA3 from the west are not the same as those that created the overthrust LCA3 (thrust from the east) in western YF – only the terminology is similar. The Belted Range thrust placed the LCA3 on top of RM in the middle Mesozoic era, roughly 100 to 200 million years ago (Cole, 1997). One conceptual model of LCA3 permeability is that it was shattered by the tectonic forces of the thrust; however, single-well tests (admittedly limited) of the LCA3 at RM, show low permeability radial flow. This may be an overly simplistic conceptual model.

Faulting is thought to be important for flow modeling. Caine et al. (1996) studied a slip fault exposure in Paleozoic clastic rocks and found that where the rock was predominantly shale, the fault core lithology was dominated by clay-rich gouge with a localized damage zone that acted as both barrier and conduit features. The total fault zone width was only a few meters. Seaton and Burbey (2005) investigated a thrust fault and found that the fault plane itself had low permeability, and the highly fractured zone (up to 10 m thick) was localized above the fault plane.

The LCA in the RMSM HFM is generally deeper than in YF, but the data is minimal from the RMSM HFM area. The initial completion of ER-16-1 was in extremely low permeability rocks. It took several months to determine that fluid in the well was left over from drilling and that the formation was unsaturated at the completion elevation. In contrast, the LCA proper in YF (extended by Basin-and-Range faulting) shows high permeability and linear-type flow geometries from the effects of the normal faults. Basin-and-Range extension is more pronounced in the southern part of the framework model area, but no hydraulic test data exists to gauge the effects of faulting changes the

flow properties of the rocks in that area. Faults and fractures also tend to strike north-south (NSTec, 2007; SNJV, 2006c), and it is possible that these features have created an anisotropic, equivalent porous media permeability field. However, the single-well tests conducted at ER-12-3 and ER-12-4 cannot reveal if this is true.

2.3.3 Geochemical Data

Groundwater geochemical and isotopic data are used to identify the areas of origin of groundwater, delineate groundwater flow paths, and calculate groundwater travel times. Results from geochemical and isotopic analysis can be compared to other hydrologic analyses to clarify the conceptual model of the groundwater flow system for the RMSM CAU.

Hershey et al. (2007) created models of flow from the RM tunnels downward to two boreholes in the LCA3, ER-12-3 and ER-12-4. Although the flow could be modeled with hydrogen ($\delta^2\text{H}$), oxygen ($\delta^{18}\text{O}$), dissolved Cl, and strontium (Sr) data, NETPATH and PHREEQC water-rock reaction models of ER-12-4 were unsuccessful because of the isotopically heavy $\delta^{13}\text{C}$ value of ER-12-4. Various models of ER-12-3 were successfully constructed, but the results were highly variable between the different geochemical techniques. Conservative tracer (hydrogen [$\delta^2\text{H}$], oxygen [$\delta^{18}\text{O}$], and dissolved Cl) and Sr models supported downward flow from the RM tunnels to the LCA3. However, because of a heavy $\delta^{13}\text{C}$ value at ER-12-3, successful NETPATH and PHREEQC models required a proportion of isotopically heavy carbon groundwater, which could be either a surrogate upgradient LCA3 water or ER-12-4 water. The percentage of tunnel water making up the chemical composition of ER-12-3 ranged from zero to 34. Calculated dissolved inorganic ^{14}C groundwater travel times for downward flow from the RM tunnels to the LCA3 ranged from 14,800 to 18,500 years. These calculations assume a ^{14}C activity of 85 percent modern carbon expected for waters with late Pleistocene origin because sampled ^{14}C activities have been impacted by nuclear testing and other tunnel activities. Older tunnel waters would create shorter travel times. Absolute groundwater ages for ER-12-3 and ER-12-4 are approximately 5,100 to 12,000 years, when calculated using organic ^{14}C ratios, and approximately 18,500 to 23,200 years when calculated using inorganic ^{14}C ratios.

2.4 Hydrogeologic Conceptual Model

The RMSM model area is geologically complex with thrust and faulted layers of various lithologies and hydrologic properties. It is important to develop conceptual models that incorporate data not input directly into the flow and transport models so that results from the models can be verified. This section discusses small-scale groundwater flow and radionuclide transport at each of the two testing areas in the RMSM CAU, and the conceptualization of flow at the scale of the HFM as a whole. [Figure 2-15](#) shows recharge areas, caldera boundaries, and thrust fault locations.

2.4.1 Rainier Mesa Conceptual Flow Model

As discussed earlier in [Section 2.0](#), the contaminant sources at RM are located in volcanic tuffs above the regional water table. Contaminant sources in four of the tunnels (U12b, U12c, U12d, and U12f) are located in the VTA. These tunnels are located above the saturation zone, but in an area with relatively high recharge. Some potential exists for fracturing caused by the detonations to preferentially channel recharge through contaminant sources. Below the section of VTA, is a section of TCU rocks with much lower permeabilities. The HFM has a discrete contact between the VTA and the TCU. The difference between the two units is caused by post-deposition alteration and may be somewhat gradual. The contact between the two units dips to the west due to a synformal structure in the mesa. The dip could cause perched water to flow down dip along the top contact of the confining unit; however, a gradational contact would lessen this effect. Once in the TCU dominated HSUs, contaminants face the same fate as those from the remainder of the RM detonations.

The remainder of the RM detonations occurred in the TCU HGU. The majority of these detonations occurred in tunnel networks on the east side of the mesa, but there are two detonation locations in vertical shafts of the west side of the mesa. Water levels from 1,800 to 1,875 m amsl have been measured in several wells completed in the TCU. The tunnel networks and fracturing from nuclear testing are likely to channel flow through some of the contaminant sources. The tunnel networks also have the effect of dispersing the contamination source.

The nature of the flow system in the TCU is somewhat atypical and characterized as semiperched because it may be separated from the LCA3 system in some areas. Fractures are also present in the

Figure 2-15
Boreholes with Measured Water Levels Used to Develop
Water-Level Contours at RM and SM Areas
 Source: Modified from Fenelon et al., 2008

TCU and were found to be sources of water in the tunnels during drilling; however, the rapid decrease in the rate of discharge from individual fractures is generally considered as evidence that most of these fractures are only locally hydraulically connected. It is possible that the tunnels intersect a few larger scale fractures that could serve as preferential pathways.

There are several wells to the west and south of RM completed in the Belted Range Aquifer and RVA volcanic aquifer units with water levels at 1,400 to 1,600 m amsl. These are technically downgradient from the tunnel contaminant sources, but are not present in the mesa, and not likely to be paths for contamination in the immediate vicinity of RM, because of their distance from the tunnels. These wells could play an important part in transport from the two detonations conducted in U-12r and U-12q on the western edge of RM.

The LCA3 is the first aquifer present directly beneath the RM tunnel tests. Water levels measured in ER-12-4 and ER-12-3 in the LCA3 are approximately 1,315 and 1,304 m amsl, respectively. Water levels in TW-1 (also called USGS HTH #1) in the LCA3 just to the south of RM are about 1,277 m amsl, indicating a gradient in the unit to southwest. There are no wells to constrain conditions in the LCA3 north of RM. Isotopic geochemical modeling using $\delta^{13}\text{C}$ values suggest that water in the mesa contains a significant portion of upgradient carbonate water, the only plausible source of which is LCA3 north of RM; however, these data are somewhat conjectural. Because there are no data to the north to eliminate the possibility, an alternative conceptual model has been proposed in which recharge at RM into the LCA3 drives flow to the north and to the southwest (Fenelon et al., 2008). It is also possible that a small portion of water flows from the LCA3, under RM, through the UCCU, toward the LCA3 in western YF.

2.4.2 Shoshone Mountain Conceptual Flow Model

The SM conceptual model is simpler than RM because the unsaturated zone does not contain perched zones. The first water encountered during the drilling of ER-16-1 was in the LCA at 762 m amsl. Similar to most of RM, detonations in SM occurred in TCU dominated rocks. Contaminants must be transported 800 to 900 m vertically through unsaturated volcanic and CCUs to the LCA to reach a

saturated flow system. If radionuclides make it through the unsaturated zone, saturated zone flow is thought to be to the south or south-southeast in the LCA.

2.4.3 HFM Scale Conceptual Model

At the HFM scale, the model area is divided into four separate aquifers outlined in Fenelon et al. (2008). The gradients within each of the aquifers are uniform, but there are limited connections between the aquifers and steep gradients across the confining units that separate them. [Figure 2-15](#) shows the recharge areas of the model and the lines of section for cross sections A-A' ([Figure 2-16](#)) and B-B' ([Figure 2-17](#)).

Hydraulically connected volcanic rocks form a continuous volcanic aquifer that spans the western half of the RMSM HFM as shown in [Figure 2-18](#) (Fenelon et al., 2008). The HFM is composed of several alternating lava flow and welded tuff aquifers and zeolitized and argillized nonwelded tuff confining units that do not show clear hydraulic connection; however, the units are faulted and local variations in the units are present. The few data points available show a consistent gradient, and are clearly disconnected from water levels in LCA3 wells in the vicinity of RM. This aquifer is referred to as the Pahute Mesa-Timber Mountain volcanic aquifer by Fenelon et al. (2008). The aquifer is present approximately 1 to 2 km west of RM, and there may be some limited hydraulic connection to the LCA3. Much of the groundwater that flows through this aquifer originates as recharge in the local highlands of RM and PM and flows toward the west and south. In the eastern half of the RMSM HFM area, saturated volcanic rocks are less continuous and less connected hydraulically. These disconnected volcanic rocks form a few scattered volcanic aquifers that typically occur beneath the larger topographic valleys.

There are two separate carbonate aquifers (CAs) present in the HFM formed by different tectonic events, both are classified as the LCA3 HSU. The LCA3 at RM is a sliver that runs from the northern edge of the HFM, south under RM, and southwest. The LCA3 in western YF is separated from the regional LCA at the northern extent by the UCCU, which thins to the south where the LCA3 and LCA are in direct contact. The two LCA3 aquifers are separated by outcropping of the UCCU that forms the Eleana Range to the east and southeast of RM. The only modeled aquifer HSU that connects the

Figure 2-16
North-South Sections through the RM and SM Areas showing Distribution of Hydrologic Units (Upper Sections) and Designations for Major Aquifers and Confining Units (Lower Sections)
Source: Fenelon et al., 2008

Figure 2-17

West-East Sections through the RM and SM Areas showing Distribution of Hydrologic Units (Upper Sections) and Designations for Major Aquifers and Confining Units (Lower Sections)

Source: Fenelon et al., 2008

Figure 2-18
Water-Level Altitudes in Preferred Case Contours for the Volcanic Aquifers in the RM and SM Areas

Source: Modified from Fenelon et al., 2008

two LCA3 aquifers is the alluvial aquifer, which is generally above the water levels of the LCA3. However, there are small isolated, carbonate blocks present at ER-12-1, and it is possible that there is some limited connection between the two units. The extent and groundwater elevation contours of the two LCA3 aquifers is shown in [Figure 2-19](#). The UCA and thrust LCA (LCA3) are combined and referred to as the UCA in Fenelon et al. (2008).

The southern extent of the RM LCA3 is unconstrained by drillholes south of TW-1. The base HFM extends the RM LCA3 only a short distance past TW-1, but the more extensive LCA3 alternative HFM extends the LCA3 significantly to the south, as shown in [Figure 2-8](#), and was the preferred interpretation in the Fenelon et al. (2008) conceptualization shown in [Figure 2-19](#). The connection of the LCA3 to other aquifer units south of TW-1 is also uncertain. Although separated from the upper volcanic aquifer by several volcanic confining units in the HFM, the geology is uncertain and connections could exist through faults. Although the LCA3 is downgradient from the upper volcanic aquifer in the RM area, this relationship could be reversed at the southern extent of the LCA3 where the upper volcanic aquifer is more continuous. The RVA, part of the upper volcanic aquifer and shown in green in [Figure 2-20](#), is continuous to the southeast edge of the Timber Mountain caldera. There is a potential flow path from the southern end of the LCA3 into the RVA in the base HFM.

The LCA persists throughout most of the study area, except beneath major caldera complexes in the west central portion of the HFM, and the low permeability granitic stock to the northwest of RM, as shown in [Figure 2-21](#). In most places, water levels in overlying aquifers are 400 to 800 m higher than in the LCA. The steep gradient and large difference is maintained by the thick siliciclastic confining unit (i.e., UCCU), that separates the LCA from the LCA3 and other units in all but the southeast corner of the HFM area at Mid Valley.

Figure 2-19
Water-Level Altitudes and Preferred-Case Contours for the Upper Carbonate Aquifers in the RM and SM Areas

Source: Modified from Fenelon et al., 2008

Figure 2-20
Redrock Valley Aquifer Extent in the Base HFM

Figure 2-21
Water-Level Altitudes and Contours for the
Lower Carbonate Aquifers in the RM and SM Areas
 Source: Modified from Fenelon et al., 2008

3.0 MODELING APPROACH

This section provides a description of the modeling implementation approach components for RM and SM including the methods and approach to the treatment of uncertainty of parameters and conceptual models.

3.1 Objectives

The role of modeling in the FFACO Corrective Action Strategy is discussed in [Section 1.0](#). Simulation objectives are defined in the FFACO. However, as discussed in [Section 1.0](#), a 95 percent confidence level in the prediction of contaminant extent at 1,000 years is no longer the objective for the Phase I CAU modeling. To reiterate, the revised main objective of the modeling described is to develop modeling approaches for predicting contaminant migration from source locations through the HSUs of RMSM and to determine the uncertainty of the parameters and alternatives with a view toward identifying data collection required to reduce contaminant boundary uncertainty. This will facilitate the direction for additional data collection activities. Many uncertainties will exist because there is little data with which to calibrate a saturated zone model. Some of these uncertainties can be anticipated and will be discussed in the following sections with respect to the conceptual models. Others cannot be anticipated; therefore, the modeling process will be used as a discovery tool to test the probability of unanticipated model results. While this Phase I modeling effort will provide some insight to the RM flow system, it will also provide a platform upon which Phase II modeling efforts can build.

The objectives of the FFACO will be met via a multistep modeling process. This process includes defining model boundaries; analysis of geologic, hydrologic, and geochemical data; defining alternative models; specialized analyses related to faults and geochemical data; and generating the flow model mesh. The flow model is calibrated to observed data that may include water levels, groundwater fluxes, and geochemistry constraints. Sub-CAU models will also be developed to

support the creation of transport models. The transport models use information related to contaminant sources, transport parameters, and heterogeneity.

3.2 Conceptual Model Implementation

The complexity and hydrogeologic differences of the RMSM CAU HFM Area ([Figure 2-2](#)), as compared to other CAUs at NTS, require proactive deviation from previous implementations of the FFACO and the Phase I CAI approach. The CAU and CAU-modeling domain encompass a transitional area between the volcanic highlands of the Timber Mountain caldera complex to the west, and the extended landscape of the YF basin to the east. Additionally, the axis of the CAU (north-south) parallels the strike of two major thrusts systems that juxtapose contrasting lithologies in the Paleozoic stratigraphic section. The hydrologic system of the CAU marks the approximate boundary between two hydrologic sub-basins – upper Forty Mile and YF sub-basins – with relatively steep gradients to the west, south, and east. The goal of the modeling is to identify where to collect additional data to reduce parameter and conceptual uncertainty. Two different modeling approaches are deemed appropriate for the RM and SM CAUs due to hydrogeologic contrasts and physical separation.

Because of the differences in the RM and SM areas (e.g., the hydrogeologic contrasts), and limited data, proposed modeling strategy for the RM area is a multistep approach. First, an HST model will be developed; releases from the HST model will then provide input (the simplified source term) to two sub-CAU scale models of the RM N- and T-Tunnels. Next, vadose zone flow and transport modeling of the perched and unsaturated zone at the N- and T-Tunnel complexes will be conducted. The resultant radionuclide and water fluxes at the water table and associated uncertainties will be used as input to the CAU scale saturated zone model. The saturated zone integrated flow and transport will be modeled with FEHM (Zyvoloski et al., 1997a). The CAU-scale model is anticipated to cover a smaller undetermined footprint in the northern half of the HFM area rather than the full HFM area. The actual footprint of the northern model will be based on a combination of assessments as well as balancing this information with computational efficiencies controlled by model grid density and complexity of the HFM ([Section 3.3](#)).

The SM area will be modeled with a multistep approach but in a more simplified manner. Once the source term has been developed, unsaturated transport of this radiological source term will be evaluated in either 1- or 2-D space using FEHM down to the water table. A saturated zone transport model constructed with GoldSim (Golder, 2000) is proposed at SM because of the simplicity of the saturated-zone hydrostratigraphy; only the LCA is saturated under SM. Computational efficiency is greatly increased without loss of detail with this approach. The groundwater flow model input necessary for GoldSim (Golder, 2000) will come from the regional groundwater flow model with detailed HSUs inserted for all four CAU base HFMs, as discussed in [Section 3.3](#).

3.3 CAU Model Boundaries and Boundary Conditions

The next stage of the process is identification of the CAU model boundaries and boundary conditions. When selecting boundaries for a flow and transport model, natural hydrogeologic boundaries of the aquifer system such as recharge and discharge zones, low permeability rock, or aquifer connections with surface water bodies are preferred because they provide easily described hydrogeologic boundary information. The characteristics of the RMSM CAU are such that hydrogeologic physical boundaries on all but the east side and bottom of the model are too distant to be used for lateral and vertical boundaries of the flow model. The CAU boundaries have been selected to incorporate all relevant radionuclide sources, important hydrogeologic features, and wells providing hydrologic and geologic information. Potential CAU model boundaries encompassing the RMSM CAU as described in the *Corrective Action Investigation Plan for Corrective Action Unit 99: Rainier Mesa/Shoshone Mountain, Nevada Test Site, Nevada* (NNSA/NSO, 2004) are shown in [Figure 1-1](#). The following model boundaries are shown as potential because they could be as large as the HFM area, or as small as the CAU boundary. Lateral boundary conditions will be obtained from the regional groundwater model with NTS CAU inserts, or possibly the overlapping Pahute Mesa/Oasis Valley (PMOV) and YF CAU models. One of the objectives of the Death Valley Regional Groundwater Flow System (DVRFS) model is to provide boundary conditions to CAU models consistent with regional mass-balance information (Belcher et al., 2004). The regional groundwater model provides the necessary information about hydraulic heads and total fluxes to provide boundary conditions for the CAU flow model calibration. Because of uncertainties in the conceptual models and parameters used for the regional model, uncertainties will occur in the prediction of heads and fluxes.

The DVRFS model for the Yucca Mountain Project and NTS has been developed (Belcher et al., 2004) and provides a basis to evaluate the groundwater flow system on a regional scale as well as the boundary conditions for CAU models consistent with the regional groundwater budget. The DVRFS model (Belcher et al., 2004) has been updated with detailed NTS CAU HSU delineations and geometries for each of the four CAU models, to more closely model groundwater flow at the NTS (designated as DVRFS model/NTS). Because the DVRFS model, using NTS geology, will be used to provide estimates of boundary conditions for the CAU model, a means for determining the impact of uncertainty in the results on the CAU model is required. Two major sources of uncertainty in the DVRFS model/NTS are the fluxes of groundwater calculated to pass through the sides of the model area chosen, and the amount of areal recharge applied. Modeling performed for a series of scenarios for the RMSM Phase I Hydrologic Data document produced significant variations in results for both (SNJV, 2008a). The scenarios involved using the DVRFS model as developed by the U.S. Geological Survey (USGS) and the DVRFS model/NTS. The models were run under three different recharge scenarios – the USGS distributed parameter watershed model, revised UGTA, and Desert Research Institute (DRI) chloride mass balance – and are discussed in detail in SNJV (2008a).

The different recharge scenarios lead to significant variations in the total volume of groundwater flow through the model. The regional recharge scenario is based on the USGS distributed parameter watershed model (Hevesi et al., 2003) with the recharge regridded at the DVRFS model grid spacing of 1.5 km. There is also some adjustment in zones to better match input recharge with the output discharge modeled in the DVRFS model. The revised UGTA recharge scenario uses a modification of the Maxey-Eakin method, which reallocates recharge into canyons and washes (SNJV, 2004). The DRI chloride mass balance recharge scenario uses the flux of chloride through the hydrologic system to determine basin inputs and outputs. A more detailed discussion of these recharge scenarios is in the RMSM Phase I Hydrologic Data document (SNJV, 2008a). The influence of the various recharge models will be determined with respect to the uncertainty introduced to the flow model results. Analysis will then be necessary to evaluate the differences in transport introduced through the different volumes of water moving through the hydrologic system in both the variations in the direction of groundwater flow introduced and the potential represented to transport greater or lesser quantities of contaminant.

3.3.1 Rainier Mesa

The proposed flow regime and boundary conditions for RM are as follows:

- The western boundary consistent with the HFM boundary. This will ensure inclusion of the full RVC and its alternative, and the LCA3 Extension Alternative. There is well data at the northern and southern ends to tie into. The PM model has a 1,000 m spacing of its FEHM mesh that can be utilized to aid with flux analysis between CAU models.
- The northern boundary will be located 3.7 km south of the HFM boundary. This will allow inclusion of well data on the west side. The location also ties into the 1,000 m spacing at the PM FEHM mesh over the western third of the model. The model is primarily extrapolated in this area and is just a continuation of existing units northward. The boundary is still believed to be distant enough to not greatly affect RM area modeled flows.
- The southern boundary will be located near the southern boundary of Area 18, 5 km north of SM. This will allow modeling of the RVC alternative and the LCA3 Extension alternative. There is also a well near the western corner to correlate with.
- The eastern boundary is formed by the regional water table intersecting the top of the UCCU as shown in [Figure 3-1](#). This contact extends from the northeast corner of the model southwest to the eastern edge of Area 18.
- The top of the model will be defined as the regional water table per Fenelon et al. (2008), combining the western volcanic region with the LCA3 area regional water table.
- The bottom of the model will be the top of the UCCU, all caldera intrusive confining units and the tops of the MGCU and subcaldera volcanic confining unit. This boundary is based on the assumption that the UCCU and other confining units act as groundwater barriers of low permeability that are relatively unfaulted. The faults that are observed are oriented generally north-south, and thus do not provide preferential pathways from the RM to the east in YF. The large extent and thickness of the confining unit should not allow much flow through it. These observations are consistent with modeling results from other CAUs and the geochemical age dating results from water beneath the unit that are in excess of 10,000 years (Hershey et al., 2007). The ER-12-1 LCA3 Alternative will be evaluated using changed parameterizations and/or geometries of the UCCU and LCA3.

Figure 3-1
Rainier Mesa Proposed Model Boundaries and Boundary Conditions

The proposed inputs, subject to revision to test alternative conceptual models, for the RM boundaries are as follows:

- Western boundary - Constant head boundaries for the volcanics would be set for the northern two-thirds of the boundary with no flow for the remainder. These boundary conditions are derived from the regional water table contours depicting flow, as described in Fenelon et al. (2008). Head elevations can be supplied by either the USGS DVRFS model with CAU inserts or the PM CAU model.
- Northern boundary - No-flow boundaries for the western half of the model and constant heads applied to, or as a flux calibration target for the remainder. There is no data near the eastern half of model boundary, and this boundary may be inflow or outflow depending on the conceptual flow model proposed by Fenelon et al. (2008).
- Southern boundary - Constant head to be treated the same way as those at the northern boundary.
- Eastern boundary - No flow boundary as the adjacent UCCU is being considered a barrier to flow.
- Top boundary - The location will be the finalized combined version of the Pahute Mesa-Timber Mountain volcanic aquifer and RM upper carbonate aquifer (Fenelon et al. [2008]).

The top boundary condition will be set to the following three recharge scenarios used in CAU modeling to date:

- The DRI Chloride Mass Balance Alluvial and Elevation Mask (Russell and Minor, 2002)
- The USGS distributed parameter watershed model Net Infiltration Model with redistribution (Hevesi et al., 2003)
- Revised UGTA Modified Maxey-Eakin (SNJV, 2004)

Results from the sub-CAU modeling may also provide another distribution for recharge to enter the top of the model.

A no-flow boundary condition will be assumed at the bottom of the model.

3.3.2 Shoshone Mountain

The proposed flow regime and boundary conditions for SM are as follows:

- If one-dimensional:
 - Vertical line at the U16a-Tunnel complex from events downward to top of regional water table.
 - Top boundary will be recharge flux.
 - Bottom boundary will be 100 percent saturation at the water table.
- If two-dimensional:
 - Vertical slice East-West through the U16a-Tunnel complex extending approximately 1 km east of U16a and 5 km west (down dip). This should provide sufficient distance to evaluate horizontal movement in the saturated zone.
 - Both models would have no flow boundaries on the vertical sides.

3.4 Input Parameter Distributions and Heterogeneity

The development of input data parameter distributions includes consideration of the number, location, quality, and representativeness of the data. General guidelines for assigning probability distributions suggested by Mishra (2002) will be used. The process of integrating parameter characterization data into probability distributions begins with the compilation and an examination of the data variance. A decision point occurs after the initial examination of the distributions of parameter values. If there is sufficient data, the probability distributions can be assigned through distribution fitting. If the number of data is small, then subjective judgment is used based on the limits of plausible values using physical/chemical laws and the distribution of limited measurement values. Examples of parameter limits for most aquifer parameters must be non-negative and upper limits can be constrained by the range of the highest measurements. In some cases, the best approach is to assign lower and upper bounds to the data (uniform distributions). In many cases, it is useful to examine data from locations outside the study area. As information becomes available, more constraints on the shape of the distribution between bounds can be assigned by experienced hydrogeologic modelers.

Additionally, an important issue is the scale of the measurement and whether that scale is appropriate to the scale of the model. Two questions to be considered are: (1) Can the physical-chemical processes of the measurement be represented by similar physical-chemical processes at the model scale, and (2) Can statistical approaches be used to transform measurement data to the appropriate model scale?

Some measurements do not represent the same physical-chemical processes as at the model scale. For example, consider laboratory measurements of the hydraulic conductivity of core samples. In porous media, core data could be used if a large number of samples were available to allow calculation of the mean and variance. In fractured media, the best core recovery is obtained for the least fractured portions of the units. Flow is primarily through the fracture network; therefore, the small-scale cores do not sample the appropriate portions of the unit. In this case, the core-scale data are not applicable to the CAU-scale modeling because the physical process of flow through fractures is not represented by the measurements.

Another example of a different physical-chemical process is the adsorption of radionuclides onto rock material. At the small scale of laboratory measurements, adsorption is recognized as interactions governed by thermodynamic processes between specific radionuclides and specific reactive minerals. The CAU-model scale is too coarse to simulate these detailed physical-chemical processes. Rather, the CAU model utilizes bulk representations of sorption processes in the form of K_d (distribution coefficient) or retardation factors. In this case, it appears possible to scale the laboratory measurements up to the CAU-model scale and define approximate bulk parameters applicable to the physical-chemical processes at the model scale (Zavarin et al., 2002).

Scale of measurement is also a consideration with respect to data statistics. Even if the physical-chemical processes of the measurement and CAU model are the same, issues of scale arise. Vanmarke (1983) presents examples of spatially variable data characterized by covariance functions in which the data are averaged inside regions of various sizes. As the size of the averaging volume increases, the variance decreases, and the mean value of the block trends toward the geometric mean for parameters characterized by a lognormal distribution and exponential covariance. This suggests that the variability in the average value of a parameter, applied to an entire HSU, would be much

smaller than the variability of the data itself. This general concept, analogous to the central limit theorem, would apply to datasets where the number of measurements is large (i.e., generally greater than 25), and the data adequately represent the entire HSU. If the number of measurements is small, or spatially unrepresentative, it will be difficult to quantitatively reduce the uncertainty of the mean value.

Parameters that will be needed for the RMSM CAU saturated-zone flow and transport model are summarized in the Hydrologic Data and Contaminant Transport Parameter documents (SNJV, 2008a and b) developed in support of RMSM CAU-scale modeling. The specific task objectives for hydrologic and transport parameter data documentation are as follows:

- Identify and compile available hydrologic and transport parameter data and supporting information required to develop the groundwater flow models for the RMSM CAU.
- Assess the quality of the data and associated documentation and assign qualifiers to denote levels of quality.
- Analyze the data to derive expected values or spatial distributions and estimates of the associated uncertainty and variability.

The physical and chemical properties of the geologic materials that affect groundwater flow and solute transport are spatially variable or heterogeneous. An attempt will be made to ensure the heterogeneity of parameters in the various component models of the CAU model will be represented adequately in the groundwater flow, and radionuclide transport models, to effectively serve the process of defining uncertainty, variability, and predictive uncertainty.

How heterogeneity is represented in the models depends on the parameter in question and scales of the variability and model. For example, some forms of heterogeneity may be represented adequately by the average value defined over an HSU, some may be represented adequately at the nominal grid scale used in the simulations, and others may require additional sub-grid scale considerations. Other considerations include assumptions that constrain heterogeneity later in the modeling process. For example, the assignment of stratigraphic units to HSUs (a necessary step in modeling) places constraints on heterogeneity that may cross HSU boundaries.

Heterogeneity is also important in the scaling of data from the measurement scale to the model scale. In some cases (e.g., the effective porosity of porous units), the scaling process generally retains the mean value but reduces the variability. Other parameters, such as lognormal-distributed hydraulic conductivity, may be modified both in mean and variability by the scaling process. Thus, heterogeneity must be considered carefully during the data analysis and modeling phases.

3.5 Sub-CAU Scale Flow and Transport Models

Sub-CAU scale models are being developed to address specific issues that must be resolved at an intermediate scale. The sub-CAU models may be 3-D, of limited extent, and would feature finer resolution than can be achieved with a model at the CAU scale. The sub-CAU models will be calibrated to local heads.

The purposes of the sub-CAU models are to assess conceptual models and processes of flow and transport in the unsaturated zone at a more detailed scale than is possible with the CAU model. For example, the sub-CAU models will be used to assess the role of faults on groundwater flow in perched groundwater systems, uncertainty due to spatial variability, the impact of alternative hydrostratigraphic framework interpretations, and alternative hydrologic conceptual models (primarily the direction of flow).

The sub-CAU models will assess numerous sources of uncertainty such as uncertainty in local parameter values, uncertainty in ponds as a source, boundary flux uncertainty, source uncertainty, and conceptual model uncertainty. The sub-CAU models will provide input to the CAU model.

Two sub-CAU scale models are being constructed for RM, one for T-Tunnel and one for N-Tunnel. The sub-CAU models will require radionuclide source terms. Upon completion of the sub-CAU transport modeling; the radionuclide flux, groundwater flux, and associated uncertainties at the bottom of the models will be used as input to the saturated flow and transport model.

3.6 Integrated 3-D CAU Groundwater Flow Model Saturated-Zone Flow Model FEHM

Should the vadose zone flow and transport modeling indicate that contaminants from any of the test sites have reached the regional water table in less than 1,000 years, a saturated zone flow and transport model will be developed. The FEHM code (Zyvoloski et al., 1997a), developed by Los Alamos National Laboratory (LANL), was chosen for implementation of the RMSM CAU flow models at RM and for unsaturated flow at SM. The FEHM code simulates 3-D, time-dependent, multiphase, nonisothermal flow and multicomponent, reactive groundwater transport through porous and fractured media. The FEHM code 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:

- 1-, 2-, and 3-D simulations
- Flow of air, water, and heat
- Multiple chemically reactive and sorbing tracers
- Colloid transport
- 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
- Two different reactive, dual-porosity, particle-tracking modules
- Coupled to PEST (Doherty, 2007)
- Linked with Los Alamos Grid Toolbox [LaGriT] (George, 1997) grid generation software
- Supported on SUN, SGI, ALPHA, and Intel (Windows)

Documentation includes a description of the mathematical models and numerical methods used by FEHM (Zyvoloski et al., 1997a), the user's manual (Zyvoloski et al., 1997b), documentation of the functional and performance requirements for FEHM, description of the FEHM software, and verification and validation reports (Dash et al., 1997; Dash, 2000 and 2001). In addition, the software is maintained in configuration management at LANL. With each new release, the software is subjected to rigorous verification testing to ensure the accuracy and functionality of its capabilities.

Assumptions for the flow and energy transport models in FEHM include fluid flow governed by Darcy's law, thermal equilibrium between fluid and rock, an immovable rock phase, and negligible

viscous heating. Specific assumptions are discussed further by Zyvoloski et al. (1997a). Inputs to the flow model include a finite-element mesh, initial conditions, lateral boundary conditions, recharge, and the material properties for the HSUs and faults. For application to isothermal groundwater flow, the calibrated FEHM model produces values of hydraulic head or pressure for each node in the mesh. The strategy is to consider only steady-state groundwater flow for the RM integrated 3-D groundwater flow model. A steady state unsaturated flow and transport model will be built for the SM area using FEHM.

Mesh Generation

Simulations of flow and transport, including particle tracking, in a 3-D domain representing the complex hydrostratigraphy, described in the hydrogeologic models, will be conducted on a finite-element mesh. The mesh is composed of discrete interconnected tetrahedra that, when connected, capture the structure of the hydrostratigraphy. The flexibility of finite elements allows for the resolution of the grid to vary spatially and capture source areas and complex structures, (e.g., faults) with higher resolution than areas where coarser discretization is sufficient. The mesh model distances can be as long as 1 km or as short as 50 m.

Elevations describing the surface of each HSU and traces of each fault will be extracted from the EarthVision® (EV®) model for a given HFM to become inputs to the mesh generation software (LaGriT [George, 1997]), which is composed of a suite of mesh generation tools. This software provides an integrated system for all grid generation steps. Unique properties can be assigned to each HSU and fault in the grid.

Mesh generation will require decisions on the location of high-resolution areas. Possible candidates for high resolution include fault zones and thin HSUs. Calibration efficiency can be increased by keeping the flow model meshes coarse and then adding higher resolution to source regions and plume pathways for the transport simulations.

Flow Model Calibration

Each alternative hydrogeologic model will require calibration. Calibration consists of determining model parameter values such that simulated heads and fluxes are consistent with observed or target

values. The model parameters for a CAU flow model will include the permeabilities of the HSUs and faults in the model. Specified observations for a CAU model will include hydraulic heads measured in wells within the model domain as found in Table 1 of the Fenelon et al. (2008) report, and fluxes through lateral model boundaries calculated from the regional groundwater flow model. These data provide “targets” for the calibration process. Recharge is defined by a recharge model and may be adjusted during calibration. Data required for calibration includes information from hydrologic data analysis including well locations, locations of open intervals, HSUs represented by open intervals, transient head measurements in wells, and fluxes from the DVRFS model/NTS at the finalized CAU-flow model boundaries. Methods for propagating uncertainty in boundary conditions from the DVRFS model/NTS are discussed in [Section 3.9](#). The RM-specific calibration objectives will differ for each hydrogeologic conceptual model. These objectives focus on producing the conceptual flow field, and simultaneously honor the hydrologic data.

The commercially available PEST software package provides a nonlinear parameter estimation routine that can be used to automatically calibrate a flow model (Doherty, 2007). This software can be used with any existing computer modeling program for model calibration. The FEHM has been modified to efficiently provide necessary data to PEST at each iteration with no additional post-processing. This software runs the model initially and calculates the weighted sum of squared differences between model-generated heads and observed heads and between simulated flux values and regional model fluxes. This sum is referred to as the objective function. The PEST software then repeatedly runs the flow model to guide the adjustment of parameters until the objective function is minimized. In principle, PEST can be set up to adjust permeabilities, until simulated fluxes on the CAU model boundary match those calculated by the regional model, and simulated heads match measured heads within the CAU model domain. Because of random and systematic errors, there is always some discrepancy between modeled and measured values. The PEST routine attempts to minimize this discrepancy and provides estimates of uncertainty in the results. Because the flow model must be run numerous times during calibration, this part of the process requires heavy use of computing resources. A model calibration will be specific to the selected hydrogeologic model, parameter zonation, recharge specified, and the lateral boundary fluxes and hydraulic heads used as calibration targets. Alternative geologic models, alternative recharge models, or changes in

calibration targets, require additional calibrations. The PEST optimization process will produce expected values for parameters, and a measure of sensitivity for HSU and fault hydraulic properties. It is recognized that parameter sensitivity in PEST is from the calibration objective function, not predictive results.

For complex models with sparse data, calibration is generally nonunique. That is, more than one set of parameter values provided to the flow model could result in permissible fits to the observed hydraulic heads and fluxes. Analysis of geochemical data will be integrated into the calibration process to provide independent lines of evidence to support parameters leading to the prediction of groundwater flow paths and travel times. Work for PM by Rose et al. (2002) is an example of the types of flow system constraints. A recent study specific to RMSM is contained in *Geochemical and Isotopic Evaluation of Groundwater Movement at Rainier Mesa and Shoshone Mountain* (Hershey et al., 2007).

3.7 Integrated 3-D CAU Transport Model

The integrated radionuclide migration model, which provides the HST to the SM unsaturated model and RM sub-CAU flow and transport models, is developed from outputs from a glass dissolution model, reactive transport model, and flow simulator. The framework for this approach is documented in Tompson (1999) and Pawloski et al. (2001 and 2002), which provided an HST for the FF CAU model and PM CAU model. The source term (possibly developed for each test), transported through the thick overlying unsaturated zone, will provide time varying input functions to the CAU transport model. The model will then be used to simulate concentrations and mass fluxes in the saturated-zone groundwater system.

Transient transport simulations will be conducted to predict the movement of contaminants in the groundwater and determine the associated uncertainty. The primary tool for process model simulations will be the dual-porosity, streamline, particle-tracking module of FEHM.

A smaller model area and a higher mesh resolution may be required for the transport simulations than for the groundwater flow simulations. Increased resolution may be necessary near sources and in the plume migration domain. Further, portions of the mesh may need to be structured in near source

regions to accommodate geostatistical attribute simulations and dispersed source term integration. The strategy involves a coupled link between the EV® hydrostratigraphic modeling software and the LaGriT grid generation software. The process will allow for appropriate grids to be developed for the specific flow and transport needs of the CAU model.

An understanding of the natural geochemical system may provide constraints on the contaminant transport model for the RMSM CAU. Modeling of geochemical transport in the vicinity of RM and SM (Hershey et al., 2007) demonstrated that interpretation of geochemical data combined with transport modeling can provide a tool for characterization of the groundwater system and information required to understand the movement of radionuclides. The objective of this study was to calculate groundwater flow directions from the RMSM while accounting for the mixing of different groundwater inputs. This geochemical information will aid the model development, construction, and calibration by placing constraints on possible scenarios that the geochemistry evaluation predicts cannot occur.

3.8 Total System Model

In addition to the integrated 3-D CAU and sub-CAU model development, a modeling platform for dynamic, probabilistic simulations will be used to develop simplified abstraction models that will attempt to provide model representations of the system, and capture dominant processes and behaviors and their uncertainty, in 1-D models of transport. This is particularly relevant for use at SM for the saturated zone and possibly the unsaturated zone, an area with limited data and hydrogeologic uncertainty, but simple saturated-zone stratigraphy. Using a probabilistic system approach, uncertainty in processes and parameters can be explicitly represented including the impact of limited characterization data. Probabilistic modeling using a system approach facilitates sensitivity and uncertainty analysis of the important parameters and model components using probabilistic model outputs obtained through Monte Carlo simulation.

The results of the DVRFS model/NTS calibrated groundwater flow model with embedded CAU HSU details will be used as the flow fields for the saturated total system model (TSM) transport. Once constructed, the TSM is flexible and the TSM simulations allow simultaneous assessment of conceptual model uncertainty, source module uncertainty, HSU geometry uncertainty, and flow

parameter and transport parameter uncertainty. For each realization, the concentration of radionuclides is recorded for later analysis. The TSM allows for an easy and quick assessment of the relative importance of various sources of uncertainty on the predicted transport of radionuclides to and through the LCA. As key parameters or processes are identified, they can be targeted for additional analysis, hence, focusing resources on the CAU model where they will be most beneficial. The TSM is a tool to assess the transport of radionuclides through flow and transport systems under uncertainty.

3.9 Uncertainty Analysis Approach

As required in Appendix VI, Revision No. 2 of the FFACO and the RMSM CAIP (NNSA/NSO, 2004) a probabilistic assessment (the 95 percent level of confidence defined in Appendix VI) of the contaminant boundary is required. Thus, some type of uncertainty analysis is required. However, DOE and NDEP have agreed to modify the strategy for RMSM, choosing to focus on a shortened initial (previously known as Phase I) modeling analysis, to improve system understanding and evaluate quantitatively what additional information should be collected during the next round of field activities, to reduce uncertainty in the predictions of the contaminant boundary. This shortened (Phase I) analysis is focused on model prediction sensitivity, and uncertainty results as a tool, to identify priority data requirements without the burden of the full calculation of the contaminant boundary – simplified representations of transport processes and radionuclide inventory will be used. The full contaminant boundary calculation will be performed in a more detailed round (Phase II in terms of scheduling) of analysis after additional (Phase II) field activities.

The *External Peer Review Report on Frenchman Flat Data Analysis and Modeling Task for the Underground Test Area Project* (IT, 1999) listed uncertainties including:

- Hydrostratigraphic framework
- Vertical flow
- Boundary conditions
- Recharge
- Groundwater-level measurements
- Hydraulic properties
- Partitioning of radionuclides between rubble and melt glass
- Reactive surface area of melt glass
- Porosity, retardation coefficients, and dispersivity

The UGTA sub-project recognizes parameter and model uncertainty. Parameter uncertainty is the lack of knowledge about an empirical quantity (e.g., hydraulic properties, porosity) stemming from limitations of measurement, disagreement among measurements, or extrapolation errors. This includes, for instance, the large-scale effective permeability of a given rock, as represented by continuous material zones, and the spatial variability of such a property. Model uncertainty, like parameter uncertainty, is caused by lack of knowledge, and represents uncertainties in model structure. This is partially addressed via different HFM interpretations, each permissive with the data. Models are approximations of real-world systems and have implicit uncertainties because of methodological decisions that must be made about model form with incomplete knowledge.

Uncertainty in parameters is quantified by developing distributions of values (probability distribution functions) for the parameters rather than using a single value for the model. The distribution fully represents the range and the likelihood of occurrence of a particular parameter value. The method used to develop the distribution varies depending on the availability of relevant data (distribution fitting) or subjective process knowledge. The parameter uncertainty is propagated using the Monte Carlo method as proposed in the RMSM CAIP (NNSA/NSO, 2004). This method is ideally suited for analyzing the model effects of parameter uncertainty described in the form of statistical distributions, or elements of a conceptual model that can be represented parametrically (e.g., sorption from none to some higher value), rather than high-level conceptual uncertainty. The data available for RMSM is discussed in [Section 2.3](#).

Traditionally, the focus of uncertainty analysis in groundwater modeling has been on model parameters. However, significant uncertainties can also arise because of uncertainty in the system conceptual model. For instance, geochemical isotopic age dating (Hershey et al., 2007) has initially determined that the LCA3 regional water table age dates are well over the 1,000-year time frame. This indicates long travel times through the vadose zone. If this is correct then saturated zone CAU-scale models will not be necessary. This is one conceptual model of the RMSM hydrologic system. There is a growing acceptance in the hydrological community that the modeling paradigm should be expanded to include more than one plausible conceptual model of the system (e.g., Neuman and Wierenga, 2003). One high-level component of this uncertainty considered by the UGTA

sub-project is multiple permissive alternative models of the subsurface geologic framework discussed in [Section 2.1](#).

The shortened initial phase of modeling analysis, while seeking to avoid the time and computational burden of the full contaminant boundary calculation, still requires uncertainty analysis to better identify and understand key hydrogeologic system components represented by the model that affect contaminant transport predictions. The development of the FF and PM CAU transport models allowed refinement of multiple modeling concepts that will be implemented in the modeling strategy for RMSM. These include:

1. The source-term release was the driving factor in explaining the volume of water contaminated above the SDWA.

The sources from underground nuclear testing on RMSM (see [Section 2.2](#)), primarily are in tunnels located several hundred meters above the water table. The RMSM CAIP states that:

- For the RMSM CAU, where unsaturated groundwater conditions prevail, unsaturated 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 (NNSA/NSO, 2004).

In the initial phase of modeling analysis, the sub-CAU models of unsaturated zone (UZ) flow and transport investigate the UZ conceptual models and processes that control the source term released to the saturated zone. The saturated-zone CAU model will use these results to assess the uncertainties influencing contaminant migration. However, the RM CAU model will also use general flow-system analysis via particle tracking and mass weighted particle tracking to assess groundwater velocity and other useful performance metrics relating to both calibration (which, with the available data, will be to flow only), and transport.

2. Conservative species such as ^3H , ^{14}C , and ^{36}Cl (found predominantly in the cavity rubble) dominate model predictions of the extent of the contaminant boundary, much more so than [most] sorbing species.

Much of the transport model effort in FF was spent calculating the contribution of individual radionuclides to the contaminant boundary. The radionuclide species provided by the sub-CAU models as input to the CAU model will be used for a limited investigation of CAU-scale transport, but efficiency independent CAU model analyses will use a generic conservative species to evaluate

general patterns of flow and transport behavior. The particle tracking feature of FEHM is ideally suited for this purpose, allowing fracture-matrix interactions to be simulated without a continuum transport model. The semianalytic solutions in GoldSim (Golder, 2000) also facilitate this approach.

3. Flow and transport model uncertainties should be considered jointly.

The technique used to assess flow model parameter uncertainty of the FF and PM flow models is the “null space” Monte Carlo method available in PEST version 11.2 (Doherty, 2007). This process produced a set of calibrated flow models with which predictive analysis could be conducted, allowing assessment of the influence of flow model parameter uncertainty on predictions. It is important to identify model parameters that are not informed by the calibration process, but have consequences on the predictions, as well as parameters that generally influence the prediction.

The results of sub-CAU model predictions can be considered with and factored into the flow model uncertainty. This combined uncertainty will be evaluated as part of the CAU modeling strategy. However, at present, it is unknown which component of uncertainty will predominate in flow modeling analysis for the RMSM CAU.

It may be desirable for the CAU modeling strategy to jointly vary transport parameters and flow field uncertainty (e.g., combine parameter uncertainty with null space Monte Carlo analysis). This is possible, but the utility of such an approach has not yet been assessed by the UGTA sub-project.

4. When multiple discrete HFM-derived contaminant boundaries are considered, the uncertainty is larger than the contaminant boundary uncertainty from a given HFM flow model parameter uncertainty.

The concept behind this approach is shown in [Figure 3-2](#) where the predictive uncertainty in each HFM is less than the combined HFM uncertainties. Each HFM is treated as a deterministic (discrete) representation of geologic system uncertainty with equal weighting of each alternative model. The goodness-of-fit of each alternative framework for calibration with reasonable hydraulic properties and boundary conditions could be treated as a metric of the likelihood of each alternative model (e.g., a likelihood function). However, with the sparse data sets available for calibration, all framework models may give acceptable and nondiscriminatory calibrations because of

Figure 3-2
Hypothetical Effects on Uncertainty of Combining
Different Conceptual Model Uncertainties

over-parameterization. In this case, more qualitative predictive measures will be considered for identifying differences between and/or the adequacy of calibration assessments of alternative framework model differences. In these instances, framework models with equally acceptable calibration may be discriminated on the basis of, for example, significantly different transport behavior or the ability to represent major documented features of the flow field or other key conceptual aspects.

In conjunction with each HFM, transport parameter distributions will be developed from the data to facilitate Monte Carlo analysis of transport behavior.

5. Consider many elements of conceptual model uncertainty.

For groundwater modeling analysis the conceptual model can be defined as follows (ASTM, 1993):

- *“...an interpretation or working description of the characteristics and dynamics of the physical system. The conceptual model identifies and describes important aspects of the physical hydrogeologic system, including: geologic and hydrologic framework, media type (for example, fractured or porous), physical or chemical processes, hydraulic properties, and sources and sinks (water budget).”*

The UGTA sub-project has considered the high-level uncertainties in the framework model, but has not comprehensively addressed all possible aspects of conceptual model uncertainty.

Conceptual uncertainty, for some elements of the RMSM CAU, is quite large. For instance, as described in [Section 2.4](#), there is a possibility that regional groundwater flow in the LCA3 is north, not south. The degree and direction of flow east into YF and west into Fortymile Canyon is also highly uncertain. Some types of conceptual uncertainty can be represented by other model inputs, such as boundary conditions in the aforementioned case. Some reduction in uncertainty can be accomplished by drilling a well for more information. This modeling effort will provide some guidance to the best locations.

The modeling approach proposed for the RMSM CAU is to evaluate the combined results of the TSM of the SM area and the integrated 3-D CAU-scale model of the RM area in the early stages of the modeling task to help identify the primary geologic and model parameters controlling flow and transport. These results will be evaluated to identify data needed to reduce any significant uncertainty in transport predictions. After additional data collection analysis, a similar set of integrated flow and transport models will be developed (Phase II). These models will incorporate the newly acquired information and make predictions for the contaminant boundary.

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Appendix A

Comments from Nevada Division of Environmental Protection

(5 Pages)

NEVADA ENVIRONMENTAL RESTORATION PROJECT

DOCUMENT REVIEW SHEET

1. Document Title/Number: Modeling Approach/Strategy for Corrective Action Unit 99: Rainier Mesa and Shoshone Mountain, Nevada Test Site, Nye County, Nevada (Final)			2. Document Date: June 2008	
3. Revision Number: Rev. 1			4. Originator/Organization: Tad Beard (702) 295-2349	
5. Responsible DOE NNSA/NSO Subproject Mgr.: Bill Wilborn			6. Date Comments Due: May 9, 2008	
7. Review Criteria: Complete Document				
8. Reviewer/Organization Phone No.: State of Nevada; Mr. John J. Jones (702-486-2850)			9. Reviewer's Signature:	
10. Comment Responses transmitted via email from NDEP to Bill Wilborn on May 5, 2008			11. Comment Response Date: May 22, 2008	
12. Comment Number/Location	13. Type ^a	14. Comment	15. Comment Response	16. Accept/Reject
1) General		<p>The modeling approach strategy for the Rainier Mesa/Shoshone Mountain (RM/SM) Corrective Action Unit (CAU) presented in Figures 1-3 and 1-4 and Section 3.2, page 3-2, second paragraph is not the strategy negotiated between the National Nuclear Security Administration/Nevada Site Office (NNSA/NSO) and the NDEP in accordance with the FFACO, Appendix VI, UGTA strategy in early 2007. From information in the figures and the statements in Section 3.2 of the document, the goal of the vadose zone modeling appears to be to predict the time for contaminants to reach the water table and, based on those results, reach a decision concerning the need to conduct a saturated zone modeling study. Again, this strategy was not agreed to by the NDEP.</p> <p>In meetings between the NNSA/NSO and the NDEP in early 2007, NNSA/NSO proposed a shortened Phase I modeling schedule that would focus on where to best collect data for the Phase II flow and contaminant transport model. The data would be collected in a Phase II data collection activity and the Phase II flow and contaminant transport modeling, focused on a contaminate boundary, would then be initiated using the new "adequate" data. This strategy is actually presented in statements in Section 1.2 (page 1-8, second paragraph), Section 3.1 (page 3-1, first paragraph), and Section 3.9 (page 3-17, first paragraph and page 3-22, last paragraph) of the document. However, the details of the strategy are missing and must be included.</p> <p>In order for this document to follow the negotiated, agreed-upon strategy, the modeling strategy presented in Figures 1-3 and 1-4, related text and Section 3.2 must be removed and the agreed-upon strategy must be fully explained. Otherwise, a new strategy will need to be negotiated between the NNSA/NSO and the NDEP.</p>	Figures 1-3, 1-4 and related text have been revised to indicate saturated zone modeling will be performed and is now consistent with the negotiated strategy.	Accept
2) ES-1		<p>Replace the last full sentence at the bottom of the page with: This shortened (Phase I) analysis is focused on model prediction sensitivity and uncertainty results as a tool to identify priority data requirements without the burden of full calculation of the contaminant boundary - simplified representations of flow, transport processes and radionuclide inventory will be used for the Phase 1 modeling.</p>	The new sentence as suggested in the comment has replaced the last full sentence at the bottom of page ES-1.	Accept

^aComment Types: M = Mandatory, S = Suggested.
RMSM Modeling Approach Strategy, Final Rev. 1

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DOCUMENT REVIEW SHEET

12. Comment Number/Location	13. Type ^a	14. Comment	15. Comment Response	16. Accept/Reject
3) ES-3, first full paragraph		<p>Replace the first full paragraph of the page with the following paragraph:</p> <p style="padding-left: 40px;">It is proposed to model the RM and SM areas separately. The RM area will be modeled in a multi-step approach. First, a Hydrologic Source Term (HST) model will be developed. The releases from the HST model will then provide input to sub-CAU scale models of the RM N- and T-Tunnel complexes. Second, the T- and N-Tunnel areas in the perched and unsaturated zone down to, but not including, the regional water table will be modeled. Work on the RM SZ model will begin, using particle tracking as a simplified representation of flow directions and transport. When the subCAU model results are ready the radionuclide and water fluxes at the water table, and any evaluated uncertainties from the vadose zone modeling, would be used as input to the CAU-scale saturated-zone model as the final stage of analysis, after issues have been evaluated with simpler, efficient approaches. The SM area will be modeled with a similar approach.</p>	The first full paragraph on page ES-3 has been replaced with the suggested paragraph from the comment.	Accept
4) ES-3, last two bullets on the page		<p>Delete the last two bullets of the page and replace with the following single bullet:</p> <ul style="list-style-type: none"> • Both flow model parameter and HFM uncertainty will be evaluated 	The last two bullets of page ES-3 have been replaced with the suggested single bullet in the comment.	Accept
5) ES-3, last sentence		<p>Replace the last sentence of page ES-3 with:</p> <p style="padding-left: 40px;">The process of the Phase I CAU modeling described in this document will be to identify parameter sensitivities and uncertainties and use these insights to prioritize data gathering for parameters judged to be important for reducing contaminant migration uncertainty and the resulting uncertainty in contaminant boundary predictions. Data gathering will be optimized for the Phase II data collection activities and the Phase 2 modeling studies will use the additional information to develop model predictions of the contaminant boundaries.</p>	The last sentence on page ES-3 has been replaced with the suggested sentence in the comment.	Accept

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12. Comment Number/Location	13. Type ^a	14. Comment	15. Comment Response	16. Accept/Reject
6) Page 1-1, second paragraph		<p>Replace the second paragraph with the following:</p> <p>This document describes a modeling approach for the Phase I CAU Flow and Transport modeling. The U.S. Department of Energy (DOE) and Nevada Division of Environmental Protection have recently agreed to modify the strategy for Rainier Mesa/Shoshone Mountain (RMSM), choosing to focus on a shortened initial modeling analysis herein referred to as the Phase I CAU Flow and Transport Modeling. The intent of this analysis is to improve understanding of modeling system response and the effects of parametric and conceptual uncertainty on transport predictions. This understanding will be used to evaluate quantitatively what additional information should be collected during the next round of field activities to reduce uncertainty in contaminant transport predictions, and thus reduce uncertainty in the Phase II CAU Flow and Transport Model predictions of the contaminant boundary. This shortened analysis is focused on flow and transport model sensitivity and prediction uncertainty. It is to be used as a tool to identify priority data requirements without the burden of the full calculation of the contaminant boundary. The full contaminant boundary calculation will be estimated in a more detailed round of analysis (Phase II in terms of scheduling) after the additional field activities and data collection following the Phase I modeling.</p>	The second paragraph on Page 1-1 has been replaced with the suggested paragraph in the comment.	Accept
7) Page 1-6, last two sentences		<p>Replace the last two sentences with:</p> <p>The objective is to develop modeling approaches to assess processes controlling contaminant migration through the hydrogeologic units (HGU) of RMSM and downgradient locations, and assess the effect of parameter and alternative conceptual model uncertainties on contaminant transport. This Phase I CAU modeling will identify data gaps and guide additional data collection activities important for reducing transport uncertainty.</p>	The last two sentences on page 1-6 have been replaced with the suggested paragraph in the comment.	Accept
8) Page 2-16, first sentences		<p>Replace the first sentences in the first paragraph with the following insert: (Note: The last sentence of the paragraph is deleted. This correction makes the modeling strategy more consistent with the results of the Frenchman Flat transport studies and is not specific to the Phase 1 and Phase 2. Models will not be eliminated based on a calibration weighting scheme).</p> <p>Values of boundary conditions, fault permeabilities, and other parameters will be investigated via sensitivity and uncertainty analysis to test the durability of the various HFM hypotheses in representing, via calibration, the observed data, and to determine whether they are truly different. The use of the null space Monte Carlo method will be key in this analysis.</p>	The suggested paragraph in the comment has replaced the first sentences of the first paragraph of Page 2-16.	Accept
9) Page 2-16, section 2.1.3, first paragraph, last sentence		The subjective weighting scheme needs to be defined.	The weighting scheme has been deleted from the text and all alternatives will be evaluated equally.	Accept

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12. Comment Number/Location	13. Type ^a	14. Comment	15. Comment Response	16. Accept/Reject
10) Page 3-1, first paragraph, 4 th sentence		Replace 4 th sentence in the first paragraph under Section 3.1 with: To reiterate, the revised main objective of the modeling described is to develop modeling approaches for predicting contaminant migration from source locations through the HSUs of RMSM and to determine the uncertainty of the parameters and alternatives with a view toward identifying data collection required to reduce contaminant boundary uncertainty.	The 4 th sentence in the first paragraph on page 3-1 has been replaced with the paragraph suggested in the comment.	Accept
11) Page 3-2, first partial paragraph		Delete the last sentence of the first partial paragraph at the top of the page.	This sentence has been deleted per comment.	Accept
12) Page 3-2, last paragraph		Delete the sentence starting: "If the vadose zone modeling . . ." and delete the sentence starting: "This is the third step . . ."	The two sentences stated in the comment have been deleted.	Accept
13) Page 3-5, Section 3.3.1		The discussion of the proposed flow regime and boundary conditions refers to Figure 3-1. A legend should be added to the figure to indicate the difference between the green and white hydraulic head contours.	A legend has been added to Figure 3-1 to indicate the difference between the green and white hydraulic head contours.	Accept
14) Page 3-7, Section 3.3.1		It is stated that "The initial conditions for the RM boundaries are as follows . . ." The use of the term "initial" in modeling generally refers to transient modeling which is not being conducted at NTS. Is the use of "initial" in this document indicating that the boundary conditions will be modified? If so, please elaborate on how this will be performed. Also, additional discussion is needed on how the constant head sections of the boundary were selected. Replace the sentence before the first bullet list with the following: The proposed inputs, subject to revision in order to test alternative conceptual models, for the RM boundaries are as follows.	The word "initial" has been deleted and the text has been revised per the suggested new sentence in the comment. Additional discussion on the selection of boundary constant head sections has been added.	Accept
15) Page 3-7, Section 3.3.1, first paragraph		In discussions between the NNSA/NSO and NDEP, it was determined that there was a lack of data and understanding of the geology in the ER-12-1 area, therefore, an alternate model of the ER-12-1 area was added to the RMSM HFM. Without new data, the understanding of the area does not change and the ER-12-1 LCA3 alternate must still be addressed. Therefore, The ER-12-1 LCA3 alternate should not be eliminated until new data provides contrary information.	The ER-12-1 alternative approach has been revised in the text to be included in the analysis.	Accept
16) Page 3-8, Section 3.3.2		Delete the last sentence of section 3.3.2 Shoshone Mountain.	The last sentence of section 3.3.2 Shoshone Mountain has been deleted.	Accept
17) Page 3-8, Section 3.4, first paragraph, sixth sentence		It is stated, "If the number of data is small, then subjective judgment is used based on the limits of plausible values . . ." With a small number of data, who will be making this subjective judgment?	The text has been revised to indicate that the "experienced hydrogeologist" makes the subjective judgment.	Accept
18) Page 3-11, Section 3.5, second paragraph		The second paragraph gives the purposes of the sub-CAU models. The fourth paragraph in that section, third and fourth sentences, contradict the statement in the second paragraph.	The contradictory statements have been deleted from text.	Accept

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12. Comment Number/Location	13. Type ^a	14. Comment	15. Comment Response	16. Accept/Reject
19) Page 3-13, last paragraph		Delete the first sentence of the next to last paragraph (starts with "With multiple hydrogeologic . . .")	First sentence of the next to last paragraph deleted as suggested in comment.	Accept
20) Page 3-17, next to last sentence, first paragraph, section 39		Replace the next to the last sentence of the first paragraph of Section 3.9 Uncertainty Analysis approach with: This shortened (Phase I) analysis is focused on model prediction sensitivity and uncertainty results as a tool to identify priority data requirements without the burden of full calculation of the contaminant boundary - simplified representations of transport processes and radionuclide inventory will be used.	The next to the last sentence of the first paragraph of Section 3.9, page 3-17, has been replaced as suggested in the comment.	Accept
21) Page 3-19, end of first sentence, second paragraph		Insert at the end of the first sentence of the second paragraph: . . . that affect contaminant transport predictions.	Suggested end to first sentence of the second paragraph has been inserted per comment.	Accept

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