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# External Peer Review Team Report for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada National Security Site, Nye County, Nevada

Navarro-Intera

Revision No.: 0

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/s/ Joseph P. Johnston 01/29/2015

Joseph P. Johnston, N-I CO Date

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# EXTERNAL PEER REVIEW TEAM REPORT FOR CORRECTIVE ACTION UNIT 97: YUCCA FLAT/CLIMAX MINE, NEVADA NATIONAL SECURITY SITE, NYE COUNTY, NEVADA

Revision No.: 0
January 2015
Navarro-Intera, LLC
c/o U.S. DOE
P.O. Box 98952
Las Vegas, NV 89193-8952

Prepared for U.S. Department of Energy under Contract No. DE-AC52-09NA28091.

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**EXTERNAL PEER REVIEW TEAM REPORT**
**FOR CORRECTIVE ACTION UNIT 97: YUCCA FLAT/CLIMAX MINE,**
**NEVADA NATIONAL SECURITY SITE, NYE COUNTY, NEVADA**

Approved by: /s/ Sam Marutzky Date: 1-29-15

Sam Marutzky, UGTA Project Manager
Navarro-Intera, LLC

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# LIST OF ACRONYMS AND ABBREVIATIONS

## General Acronyms and Abbreviations

| | |
|---|---|
| 2-D | Two dimensional |
| 3-D | Three dimensional |
| amsl | Above mean sea level |
| BN | Bechtel Nevada |
| BP | Before the present |
| CADD | Corrective action decision document |
| CAI | Corrective action investigation |
| CAIP | Corrective action investigation plan |
| CAP | Corrective action plan |
| CAU | Corrective action unit |
| CDF | Cumulative distribution function |
| CFR | *Code of Federal Regulations* |
| Ci/g | Curies per gram |
| cm/yr | Centimeter per year |
| CR | Closure report |
| DoD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOE/NV | U.S. Department of Energy, Nevada Operations Office |
| DVRFS | Death Valley Regional Flow System |
| ECDF | Empirical cumulative distribution function |
| EPA | U.S. Environmental Protection Agency |
| FF | Frenchman Flat |
| FFACO | *Federal Facility Agreement and Consent Order* |
| FS | Flow system |
| ft | Foot |
| ft/day | Feet per day |
| HFM | Hydrostratigraphic framework model |
| HST | Hydrologic source term |
| HSU | Hydrostratigraphic unit |
| IAEA | International Atomic Energy Agency |
| ka | Thousand years |
| $K_d$ | Distribution coefficient |

## LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

| | |
|---|---|
| kg/s | Kilogram per second |
| km | Kilometer |
| K-S | Kolmogorov-Smirnov |
| kt | Kiloton |
| LANL | Los Alamos National Laboratory |
| LLNL | Lawrence Livermore National Laboratory |
| m | Meter |
| $m^2$ | Square meter |
| m/day | Meters per day |
| MDL | Minimum detection limit |
| MCL | Maximum contaminant level |
| mg/L | Milligrams per liter |
| mi | Mile |
| mL/g | Milliliters per gram |
| mm/yr | Millimeters per year |
| mol/L | Moles per liter |
| mrem/yr | Millirem per year |
| MWAT | Multiple-well aquifer test |
| m/yr | Meters per year |
| NA | Not available |
| N/A | Not applicable |
| NAD | North American Datum |
| NBMG | Nevada Bureau of Mines and Geology |
| NDEP | Nevada Division of Environmental Protection |
| N-I | Navarro-Intera, LLC |
| NNSA/NFO | U.S. Department of Energy, National Nuclear Security Administration Nevada Field Office |
| NNSS | Nevada National Security Site |
| NRC | National Research Council |
| NSMC | Null Space Monte Carlo |
| NSTec | National Security Technologies, LLC |
| NTS | Nevada Test Site |
| pCi/L | Picocuries per liter |
| PM | Pahute Mesa |

## LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

| | |
|---|---|
| ppb/kg | Parts per billion per kilogram |
| RMSM | Rainier Mesa/Shoshone Mountain |
| RN | Radionuclide |
| RREMP | Routine Radiological Environmental Monitoring Program |
| RST | Radiological source term |
| SDWA | *Safe Drinking Water Act* |
| SNJV | Stoller-Navarro Joint Venture |
| TFS | Tributary flow system |
| UGTA | Underground Test Area |
| USGS | U.S. Geological Survey |
| UTM | Universal Transverse Mercator |
| UZ | Unsaturated zone |
| XRD | X-ray diffraction |
| XRF | X-ray fluorescence |
| YF/CM | Yucca Flat/Climax Mine |
| °C | Degrees Celsius |
| $R_c$ | Cavity radius |
| µg | Microgram |
| µg/L | Micrograms per liter |

# LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

## Stratigraphic, Geologic, Hydrostratigraphic, and Hydrogeologic Unit Abbreviations and Symbols

| | |
|---|---|
| AA | Alluvial aquifer |
| AA1 | Alluvial aquifer 1 |
| AA2 | Alluvial aquifer 2 |
| AA3 | Alluvial aquifer 3 |
| ATCU | Argillic tuff confining unit |
| BFLA | Basalt lava flow aquifer |
| BRA | Belted Range aquifer |
| BRCU | Belted Range confining unit |
| LCA | Lower carbonate aquifer |
| LCA3 | Lower carbonate aquifer thrust plate |
| LCCU | Lower clastic confining unit |
| LCCU1 | Lower clastic confining unit thrust plate 1 |
| LCCU2 | Lower clastic confining unit thrust plate 2 |
| LTCU | Lower tuff confining unit |
| LVTA | Lower vitric-tuff aquifer |
| MGCU | Mesozoic granite confining unit |
| OSBCU | Oak Spring Butte confining unit |
| PCUT | Playa confining unit |
| PRETBG | Pre-Grouse Canyon Tuff lava flow aquifer |
| PRETBG1 | Pre-Grouse Canyon Tuff lava flow aquifer 1 |
| TCU | Tuff confining unit |
| TMLVTA | Timber Mountain lower vitric-tuff aquifer |
| TMUVTA | Timber Mountain upper vitric-tuff aquifer |
| TMWTA | Timber Mountain welded-tuff aquifer |
| TSA | Topopah Spring aquifer |
| TUBA | Tub Spring aquifer |
| UCA | Upper carbonate aquifer |
| UCCU | Upper clastic confining unit |
| UTCU | Upper tuff confining unit |
| VA | Volcanic aquifer |
| VCU | Volcaniclastic confining unit |

# LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

## Symbols for Elements and Compounds

| | |
|---|---|
| Al | Aluminum |
| Am | Americium |
| Ar | Argon |
| C | Carbon |
| Ca | Calcium |
| $CaCO_3$ | Calcite |
| CaO | Lime |
| $Ca(OH)_2$ | Calcium hydroxide |
| Cd | Cadmium |
| Cl | Chlorine |
| Cm | Curium |
| Cs | Cesium |
| DIC | Dissolved inorganic carbon |
| DOC | Dissolved organic carbon |
| Eu | Europium |
| H | Hydrogen |
| $^{2}H$ | Deuterium |
| $^{3}H$ | Tritium |
| Ho | Holmium |
| I | Iodine |
| K | Potassium |
| Kr | Krypton |
| Nb | Niobium |
| Ni | Nickel |
| Np | Neptunium |
| O | Oxygen |
| Pd | Palladium |
| Pu | Plutonium |
| Sm | Samarium |
| Sn | Tin |
| Sr | Strontium |
| Tc | Technetium |

## LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

| | |
|---|---|
| Th | Thorium |
| U | Uranium |
| Zr | Zirconium |

# EXECUTIVE SUMMARY

The peer review team commends the Navarro-Intera, LLC (N-I), team for its efforts in using limited data to model the fate of radionuclides in groundwater at Yucca Flat. Recognizing the key uncertainties and related recommendations discussed in Section 6.0 of this report, the peer review team has concluded that U.S. Department of Energy (DOE) is ready for a transition to model evaluation studies in the corrective action decision document (CADD)/corrective action plan (CAP) stage.

The DOE, National Nuclear Security Administration Nevada Field Office (NNSA/NFO) clarified the charge to the peer review team in a letter dated October 9, 2014, from Bill R. Wilborn, NNSA/NFO Underground Test Area (UGTA) Activity Lead, to Sam J. Marutzky, N-I UGTA Project Manager:

> "The model and supporting information should be sufficiently complete that the key uncertainties can be adequately identified such that they can be addressed by appropriate model evaluation studies. The model evaluation studies may include data collection and model refinements conducted during the CADD/CAP stage. One major input to identifying 'key uncertainties' is the detailed peer review provided by independent qualified peers."

The key uncertainties that the peer review team recognized and potential concerns associated with each are outlined in Section 6.0, along with recommendations corresponding to each uncertainty. The uncertainties, concerns, and recommendations are summarized in Table ES-1. The number associated with each concern refers to the section in this report where the concern is discussed in detail.

The first question and the related four sub-questions addressed by the peer review team are as follows:

1. Are the approaches, assumptions, and results consistent with the use of the models as decision tools for meeting *Federal Facility Agreement and Consent Order* regulatory requirements?

    a. Are the models of sufficient scale/resolution to adequately forecast contaminant transport in the Yucca Flat/Climax Mine (YF/CM) setting?

    b. Have the key processes been included in the models?

c. Are the flow and transport modeling results and uncertainties technically sound and defensible?

d. Are the conceptual models used in the different flow and transport models sufficiently consistent to provide representative integrated model results?

The peer review team answers these questions with a qualified yes—qualified in the sense that the uncertainties identified in Section 6.0 of this report presumably will be carefully addressed during the CADD/CAP stage. The modeling team's general approach is sound; their assumptions are logical; and the initial results of modeling are consistent with using the models as decision tools for meeting *Federal Facility Agreement and Consent Order* regulatory requirements.

The second question addressed by the peer review team is as follows:

2. Are the datasets and modeling results adequate for a transition to model evaluation studies in the CADD/CAP stage—the next stage in the UGTA strategy for the YF/CM corrective action unit?

The peer review team answers this question also with a qualified yes—qualified in the sense that the review team understands that considerably more data will be collected and more modeling will be done during the CADD/CAP stage. The N-I team has made a commendable effort in compiling available data and gleaning what they can from that sparse data. However, the peer review team was surprised to find that model developers were forced to draw data from distributions that were limited or non-existent, or that monitoring data were not routinely collected over the years of study and characterization efforts. Given the importance of the site and nature of the contamination, the peer review team expected a more consistent and thorough characterization effort to have been conducted to date. Therefore, because the site is, in the opinion of the peer review team, significantly undercharacterized, the next stage requires both more extensive field investigation and a broader uncertainty analysis to account for the many unknowns given the sparse data. The peer review team's recommendations regarding field investigations and uncertainty analysis are discussed in Section 6.0 of this report.

Section 5.0 addresses the questions asked of the peer review team, and Appendix H summarizes the recommendations.

***Table ES-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 1 of 5)*

| Key Uncertainty | Concerns | Recommendations |
|---|---|---|
| **Model Domain/ Boundary Conditions** | | |
| Section 6.1.1 | Western boundary | Expand the model domain to include Rainier Mesa, and use head and perched spring data from that area for calibration. |
| Section 6.1.2 | Southern boundary | Extend model domain to the south to capture contaminant boundaries that extend beyond the current model domain. |
| Section 6.1.3 | Northern boundary | Investigate inflow from the north with multi-well aquifer testing and water sampling. |
| Section 6.1.4 | AA/VA flow direction | Contour simulated water levels in the AA/VA; compare with available data; and include the resulting uncertainty in flux to the LCA in future modeling. |
| Section 6.1.5 | Hydraulic connection between aquifers | Evaluate uncertainty in flux to the LCA associated with the inconsistency of the boundary between the LCA and AA/VA models. Couple the AA/VA and LCA models, and use all the head data within the combined multi-aquifer system for calibration. |
| **Model Calibration** | | |
| Section 6.2.1 | Poorly posed calibration | Expand the model domain to couple the aquifer systems; extend the domain to the groundwater divide to the west; include more target data from the available dataset, as well as through additional data collection; and simplify the parameterization. |
| Section 6.2.2 | Lack of steady-state head data | Calibrate a coupled model of the aquifers; include more calibration targets; resurvey the well heads to ensure accuracy of the targets; and completely represent the data that were used to develop steady-state targets in the residual analysis. |
| Section 6.2.3 | Use of parameter bounds | Reduce the number of parameters through re-parameterization; remove bounds from the parameters; include more calibration targets; and adjust the model conceptualization and construction if the estimated parameter values are not reasonable. |
| Section 6.2.4 | Omission of available calibration data | Include as many calibration targets as possible (also use multiple targets at individual locations for the steady-state calibration to incorporate the transient nature of the data into the uncertainty of the steady-state calibration); include hydrogeologic features to facilitate a fit to those targets; and present residuals related to all of the measurements. Critically review all available calibration data. |
| Section 6.2.5 | Jacobian used to determine weights | Determine weights by evaluating the quality of the target data based on well construction and measurement procedures. |
| Section 6.2.6 | Field measurements of hydraulic conductivity not honored | After estimating parameters without bounds, compare the values to equivalent field values; if they are unreasonable, adjust the model conceptualization and/or construction. |

***Table ES-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 2 of 5)*

| Key Uncertainty | Concerns | Recommendations |
|---|---|---|
| **Hydraulic Properties and Pathways** | | |
| Section 6.3.1.1 | Limited characterization of country rock | Conduct MWATs in the central and western parts of Yucca Flat. |
| Section 6.3.1.2 | Model permeabilities inconsistent with field measurements | Use available hydraulic properties data to delineate permeability zones in the model. |
| | | Honor the measured hydraulic conductivities. Reevaluate the choice of the “fast” scenario. |
| Section 6.3.1.3 | Preferential flow not considered in uncertainty evaluation | Thoroughly evaluate existing data for indications of karst, and install new wells to investigate for karst. If karst features cannot be ruled out, include alternative models that have continuous high hydraulic conductivity pathways from the northern to the southern end of Yucca Flat and passing through source zones. |
| Section 6.3.2 | Representation of faults | Extend the range of permeability considered for modeling faults well above the highest measured value, and include alternative models without impermeable fault cores. |
| | | Assign increased permeability to the material that is currently simulated as country rocks near major faults in the analysis of uncertainty. |
| | | Explore greater fault permeability in the AA/VA model, and characterize AA/VA fault behavior. |
| | | Evaluate the contaminant boundary using an alternative flow model in which all faults in the volcanic rocks serve as permeable pathways to the LCA. |
| | | Include an alternative model that has no or many fewer minor faults; this may require allowing flow and transport to occur between the AA/VA and LCA via the TCU in addition to the major faults. |
| Section 6.3.3 | Potential for vertical flow through the TCU, other than by faults | Evaluate the uncertainty in the contaminant boundary due to flow across the TCU that is not impermeable, but rather honors the available data on hydraulic properties of the TCU. |
| | | Develop new data and field testing to determine the lateral continuity of the TCU as an effective hydraulic barrier to vertical transport. |
| Section 6.3.4 | Effective porosity | Evaluate uncertainty in the contaminant boundary due to effective fracture porosity of the TCU. |
| Section 6.3.5 | Surface water flow into fractures in the alluvium | Model faults as local zones of preferential flow through the unsaturated and saturated alluvium. Gather field data to ascertain the degree to which fissures contribute to enhanced local recharge. |
| Section 6.3.6 | Anisotropy and preferential flow in the unsaturated zone | Determine the maximum depth of recent infiltration along possible flow pathways to detonation cavities at craters with high rates of recharge, |

***Table ES-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 3 of 5)*

| Key Uncertainty | Concerns | Recommendations |
|---|---|---|
| **Source Term and Mass Flux to the LCA** | | |
| Section 6.4.1 | No uncertainty associated with RST | Include uncertainties in RST in modeling. |
| Section 6.4.2 | Uncertainties in partition factors not well defined | Develop support for partition factors used. |
| Section 6.4.3 | Water flow into cavities | Measure and monitor enhanced-recharge-driven transport in and below detonation craters. |
| Section 6.4.4 | Uncertainty in exchange volume not fully captured | Extend the uncertainty analysis to include exchange volumes of at least 5 $R_c$. |
| Section 6.4.5 | Chimney and cavity pathways to the LCA | Expand the uncertainty analysis to include a greater range of permeability enhancement assigned to the damage zone. Where possible, consider using post-shot holes to test field permeability of the damage zones. |
| **Transport** | | |
| Section 6.5.1 | Values for plutonium retardation not well supported and may be too high | Decrease Pu $K_d$ values used for modeling. Collect more data to understand Pu retardation, and further evaluate existing data. |
| Section 6.5.2 | Melt-glass dissolution largely neglected | Include melt-glass dissolution in UZ models. Consider additional processes affecting cavity-debris behavior in the LCA, and include an instant-release case. |
| **Simulating Critical Observations** | | |
| Section 6.6.1 | Field-measured $^3$H not simulated | Simulate sub-regions of the model with smaller mesh size and more particles to understand mismatches. |
| | | Incorporate processes that could lead to observed lateral transport of $^3$H in the AA/VA. |
| | | Evaluate whether timing of sampling or nature of completion of non-detect wells may be such the $^3$H occurrences were missed. |
| | | Gather field data to define the current extent of contamination, then adjust the model to better represent the field system. |
| Section 6.6.2 | Observed crater recharge not well matched in the model | Ensure that the crater-recharge model is conservative. |
| Section 6.6.3 | Geochemical and environmental isotope data not fully evaluated | Justify the choice of initial chlorine concentrations. Explain differences in interpretations of $^{14}$C in the Yucca Flat and Ash Meadows LCA flow systems. Avoid interpreting ages from dissolved organic $^{14}$C data. |
| Section 6.6.4 | Interpretation of temperature data | Explain temperature at the water table; use temperature data to inform calibration of the coupled flow model; and incorporate water fluxes indicated by temperature data into determination of the contaminant boundary. |

***Table ES-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 4 of 5)*

| Key Uncertainty | Concerns | Recommendations |
|---|---|---|
| **Simulating Critical Observations** (continued) | | |
| Section 6.6.5 | Missing some realistic geologic features | Incorporate more realistic geologic features as computational capabilities, software, and data improve. |
| Section 6.6.6 | Other sources of data available | Review and use data from surrounding DOE and DoD facilities to further constrain water levels, boundary fluxes, and estimates of hydraulic properties. |
| | | Build confidence in the Yucca Flat model by using the modeling approach to simulate single-test detonations outside Yucca Flat where there has been groundwater monitoring. |
| **Uncertainty Evaluation** | | |
| Section 6.7.1 | 95th percentile not captured | Generate flow models that represent combinations of values from the upper end of their parameter distributions, and explore whether calibration is successful. |
| Section 6.7.2 | Expected alternative flow models not included | Include alternative flow models with fast flow fields from many detonation locations. |
| Section 6.7.3 | Limited number (100) of NSMC realizations | Employ the approach described in Section 6.7.1 to capture fast flow fields without excessive numbers of simulations. |
| Section 6.7.4 | Limited number of calibrated flow models used to evaluate transport uncertainty | Include more fast flow field models coupled with transport parameter values from the end of the distribution that enhances transport. |
| Section 6.7.5 | Limited alternative models to evaluate relevant detonations | Include more flow fields in the uncertainty evaluation with bias to capture the 95th percentile, and include all sources with enhanced transport. |
| Section 6.7.6 | Limited range of transport parameters | Include Pu isotopes with combinations of lower $K_d$ values and higher mass in the source term; expand the evaluated uncertainty range of matrix diffusion; and include higher values of dispersivity. |
| Section 6.7.7 | Mesh refinement not necessarily conservative | Evaluate higher level meshes to determine definitively the mesh-refinement level for which there is no change in the contaminant boundary. |
| **Unforeseen Uncertainties** | | |
| Section 6.8.1 | New concerns and approaches anticipated | Engage external experts in periodic peer review. |
| Section 6.8.2 | Climate change | Evaluate whether long-term climate change and associated extreme weather events would have a significant impact on transport of radionuclides. |

***Table ES-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 5 of 5)*

| Key Uncertainty | Concerns | Recommendations |
|---|---|---|
| **Location of Radionuclide Plumes** | | |
| Section 6.9.1 | Extent of contamination poorly defined at present | Determine the bounds of contaminant migration in both the AA/VA and LCA. |
| Section 6.9.2 | Inadequate observation-well network | Conduct a comprehensive formal review of existing data quality, and maintain a groundwater monitoring program designed to evaluate model uncertainties and delineate contaminant boundaries. |
| | | General locations for new wells, aquifer tests, and sampling during the CADD/CAP stage, including samples from existing wells, are recommended in Section 6.9.2. |

AA = Alluvial aquifer
$^{14}C$ = Carbon-14
DoD = U.S. Department of Defense
$^{3}H$ = Tritium
$K_d$ = Distribution coefficient
LCA = Lower carbonate aquifer
MWAT = Multiple-well aquifer test
NSMC = Null Space Monte Carlo
Pu = Plutonium
$R_c$ = Cavity radius
RST = Radiological source term
TCU = Tuff confining unit
UZ = Unsaturated zone
VA = Volcanic aquifer

# 1.0 INTRODUCTION

This report documents the External Peer Review of the Yucca Flat/Climax Mine (YF/CM) Corrective Action Unit (CAU) 97 groundwater flow and contaminant transport model. The *Federal Facility Agreement and Consent Order* (FFACO) (1996, as amended) Underground Testing Area (UGTA) Activity is a four-stage corrective action strategy:

1. The Corrective Action Investigation Plan (CAIP) stage (DOE/NV, 2000a)
2. Corrective Action Investigation (CAI) stage
3. The Corrective Action Decision Document (CADD)/Corrective Action Plan (CAP) stage
4. The Closure Report (CR) stage

This external peer review is required before closing the CAI stage. The final step in the CAI stage will be a decision by the Nevada Division of Environmental Protection (NDEP) and the U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Field Office (NNSA/NFO) to determine whether the CAU model is acceptable for CADD/CAP studies. This external peer review report provides input to the decision.

The peer review was conducted between March and December 2014, and the peer review team was tasked with addressing the following questions:

1. Are the approaches, assumptions, and results consistent with the use of the models as decision tools for meeting FFACO regulatory requirements?

    a. Are the models of sufficient scale/resolution to adequately forecast contaminant transport in the YF/CM setting?

    b. Have the key processes been included in the models?

    c. Are the flow and transport modeling results and uncertainties technically sound and defensible?

    d. Are the conceptual models used in the different flow and transport models sufficiently consistent to provide representative integrated model results?

2. Are the datasets and modeling results adequate for a transition to model evaluation studies in the CADD/CAP stage—the next stage in the UGTA strategy for the YF/CM CAU?

The peer review team members are listed below, and short biographies are provided in Appendix A:

- John Klenke, Nuclear Waste Repository Project Office, Nye County, NV
- F. Joseph Pearson, Consulting Geochemist, New Bern, NC
- Eileen Poeter, Poeter Engineering and Colorado School of Mines, Golden, CO
- Jonathan Price, Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV
- Daniel Stephens, Daniel B. Stephens & Associates, Albuquerque, NM
- Scott Tyler, University of Nevada, Reno, NV

The peer review started with a five-day kickoff meeting in Las Vegas, Nevada, from April 7 to 11, 2014, after receiving the products to be reviewed in March 2014. Technical presentations and a site visit were conducted by project staff; topics included YF/CM site conditions, field experiments, data collection, and modeling activities (see Appendix B). Team members held periodic conference calls, and a team meeting was held on June 16 and 17, 2014, at the National Atomic Testing Museum in Las Vegas. The peer review team prepared a draft report on July 18, 2014, and discussed its initial findings with project staff at a meeting in Las Vegas on October 6 to 8, 2014. Based on these discussions, it was apparent that clarification was necessary to appropriately answer the questions posed above. The clarity was necessary to focus the review on the use of models at this point in the UGTA strategy and to define what is meant by “FFACO regulatory requirements” and “transition to model evaluation studies.” This clarification was provided in a letter from Bill R. Wilborn, NNSA/NFO UGTA Activity Lead, to Sam J. Marutzky, Navarro-Intera, LLC (N-I), UGTA Project Manager, on October 9, 2014. This clarification is attached as Appendix C.

This report is organized into seven sections, including this introduction section. Section 2.0 provides background information on YF/CM CAU, the radiological source terms (RSTs), and the calculated contaminant boundaries. Section 3.0 describes the basic YF/CM CAU geology and hydrogeology data reviewed by the peer review team. Section 4.0 is a general discussion on using mathematical models as regulatory decision tools to frame the peer review team’s opinions on the two review questions. Section 5.0 discusses the peer review team’s response to the two questions. Section 6.0 describes key uncertainties that the peer review team expects will be addressed during the CADD/CAP phase of the YF/CM CAU. Recommended approaches to address these key uncertainties during CADD/CAP are presented in Section 6.0 and are also summarized in Appendix H for convenience of the reader. Section 7.0 lists the documents reviewed by the peer review team and references cited in this report.

# 2.0 BACKGROUND

The Nevada National Security Site (NNSS), located in southern Nevada, was the primary U.S. site used for underground nuclear weapons testing. Underground testing in deep vertical shafts and tunnels was conducted from 1951 to 1992. The DOE initiated the UGTA Activity to assess and evaluate radiologic groundwater contamination resulting from underground nuclear testing at the NNSS and vicinity. Contaminated groundwater is defined as groundwater that exceeds the *Safe Drinking Water Act* (SDWA) (CFR, 2013a) radiological maximum contaminant level (MCL) for any radionuclide.

The UGTA Activity assesses the public risk from groundwater contaminated from nuclear testing. The primary assessment method is to develop groundwater flow and radionuclide transport models to forecast the potential extent of contaminated groundwater in the next 1,000 years. The modeling forecasts provide estimated three-dimensional (3-D) groundwater volumes that may be contaminated within the next 1,000 years, and are referred to as “contaminant boundaries.” The contaminant boundaries must show the groundwater volume that has at least a 5 percent chance of exceeding the MCLs.

Model forecasts provide the basis for negotiations between NDEP and NNSA/NFO on use restrictions and regulatory boundaries. The regulatory boundary represents a regulatory-based distinction between possibly contaminated or not contaminated groundwater.

## 2.1 YF/CM Corrective Action Unit

The YF/CM CAU is located about 140 kilometers (km) northwest of Las Vegas, Nevada. Between 1957 and 1992, 747 underground nuclear detonations were conducted within the CAU. Yucca Flat is a topographically closed basin with a playa at its southern end. The basin is bounded by the Halfpint Range on the east, by Rainier Mesa and the Belted Range on the north, by the Eleana Range and Mine Mountain on the west, and by the CP Hills and Massachusetts Mountain on the south (Figure 2-1).

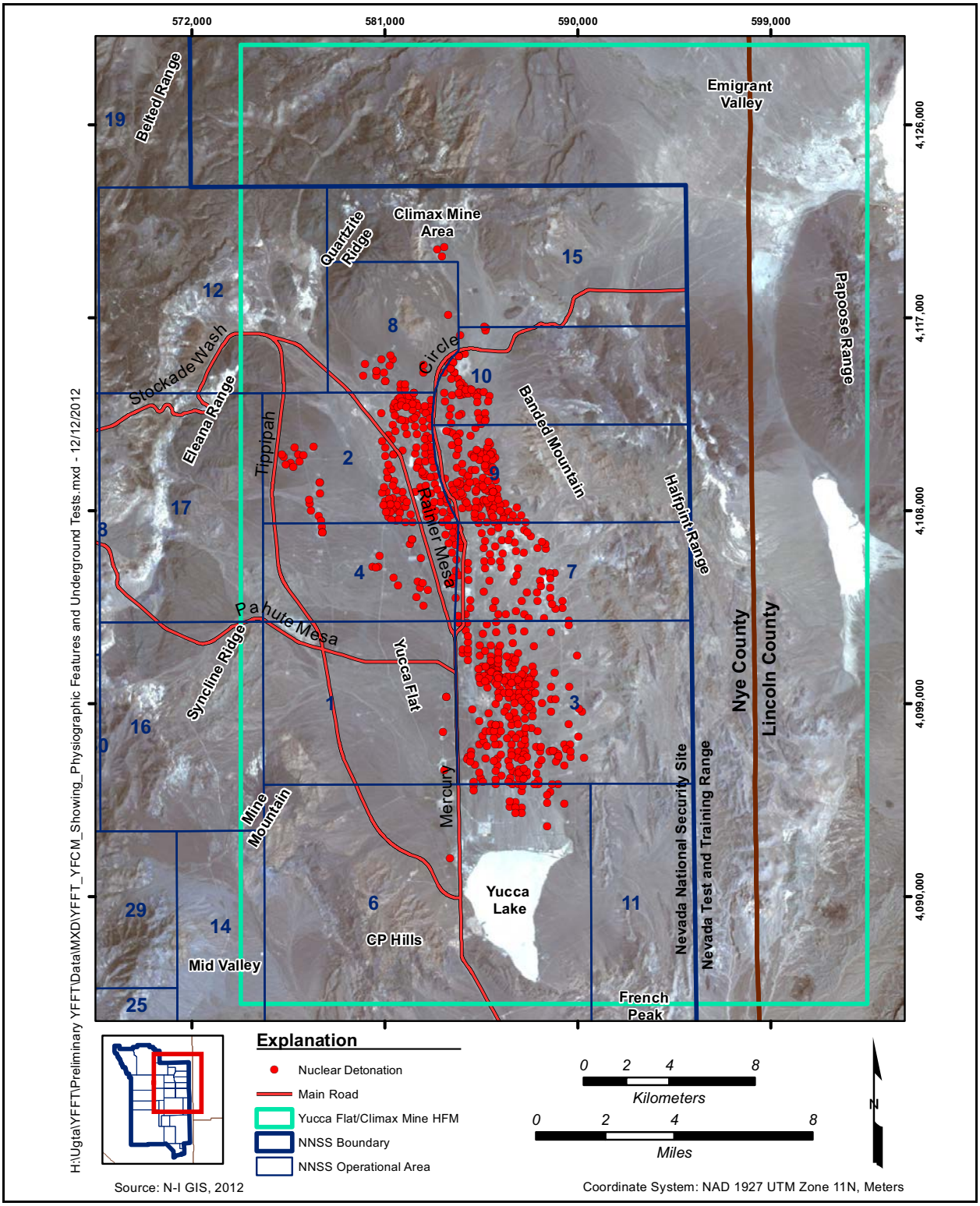



***Figure 2-1***
***Satellite Image and Physiographic Features of the YF/CM CAU***
Source: N-I, 2013, Fig. 1-3

The general geologic setting in the YF/CM area includes a thick Cenozoic volcanic and sedimentary section that overlies carbonate and clastic rocks of Precambrian and Paleozoic age (BN, 2006). The Precambrian and Paleozoic carbonate and clastic rocks crop out in the bedrock hills surrounding the basin (Figure 2-2). The hydrostratigraphic sequence in the CAU is summarized in the hydrostratigraphic framework model (HFM) (BN, 2006).

The CAU and surrounding areas were affected by two opposing tectonic deformations: mid-Mesozoic through Eocene compressive deformation, and a subsequent phase of mid-to-late Cenozoic extension. The HFM includes 178 normal faults with displacements greater than 60 meters (m) (200 feet [ft]) (BN, 2006).

The hydrostratigraphic units (HSUs) identified in the HFM have been grouped into confining units and aquifers depending on their general hydraulic characteristics (BN, 2006). The CAU groundwater depth depends on location, but generally the water table is about 500 m (1,640 ft) beneath the ground surface. A map of the HSUs at the water table is shown in Figure 2-3. A representative west–east cross section through the HFM is illustrated in Figure 2-4. The map and cross section show that the water table is in carbonate rocks or clastic confining units throughout much of Yucca Flat, with saturated volcanic rocks and alluvium occurring in the deepest parts of the basin east of the Carpetbag-Topgallant fault system.

Depending on their extent and degree of interconnection, the aquifers in the CAU vicinity have been classified as either regional or local flow systems (Fenelon et al., 2010). Regional flow systems allow groundwater to move freely over long distances. Poorly connected, less extensive aquifers make up local flow systems that can provide a source of diffuse leakage or local drainage to the underlying regional flow system. The Cenozoic alluvial aquifer (AA) and volcanic aquifers (VAs) have been grouped into a local groundwater flow system (the AA/VA system) whose flow is constrained to the Yucca Flat basin (Fenelon et al., 2010). The only regional groundwater flow system in the CAU is the LCA. The LCA is a regionally extensive aquifer that extends from north of Yucca Flat to the discharge area in Ash Meadows.

Recharge to the AA/VA system is generally limited to local inflow from deep percolation through the unsaturated zone with little opportunity for lateral inflow or outflow due to the restricted nature of these saturated units in the basin. Recharge to the LCA occurs in the highland areas to the north and east of Yucca Flat and by local infiltration along the margins of the basin as well as vertical recharge

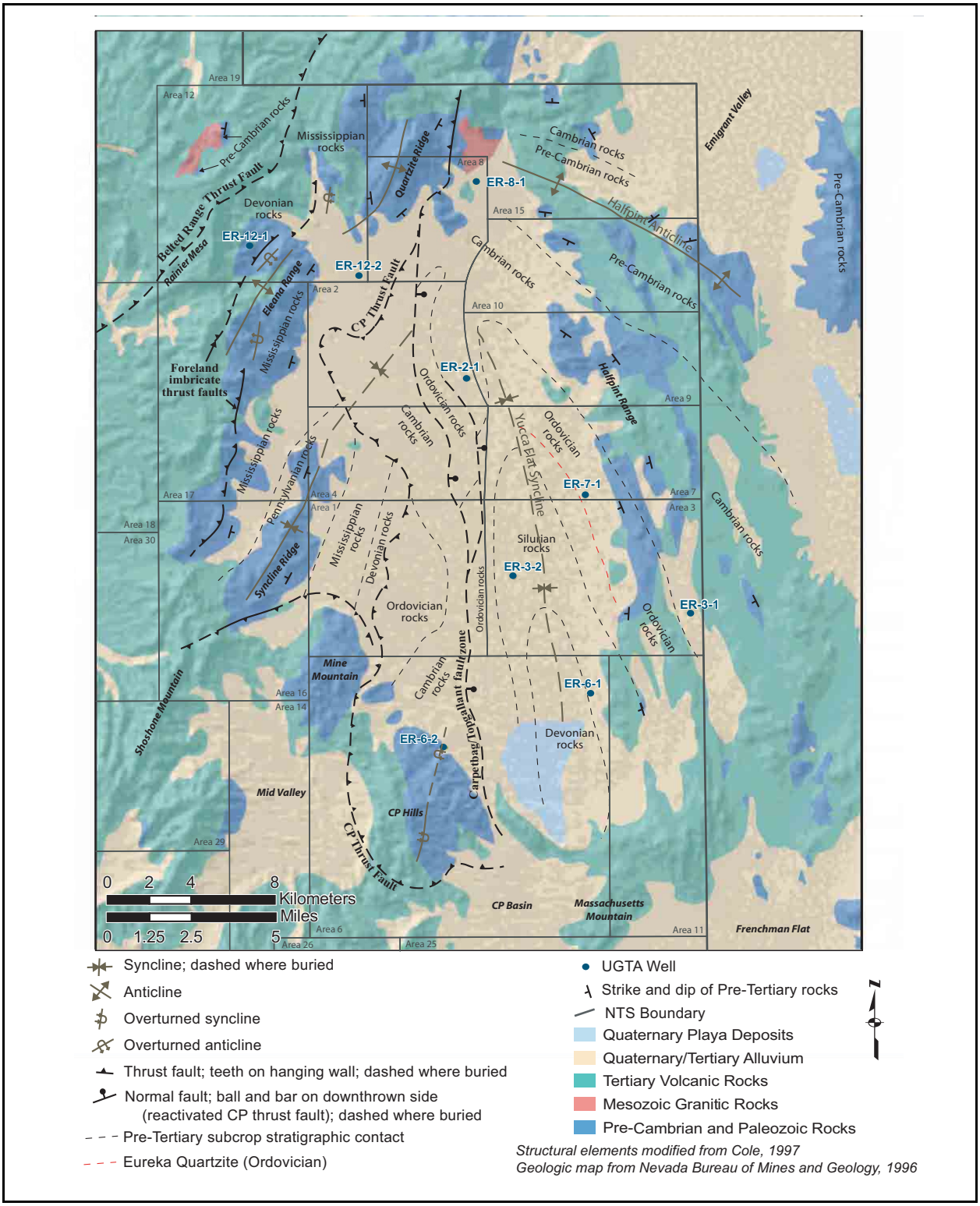



***Figure 2-2***
***Generalized Geologic Map of the YF/CM Region and Associated Physiographic Features***
Source: BN, 2006, Fig. 3-1

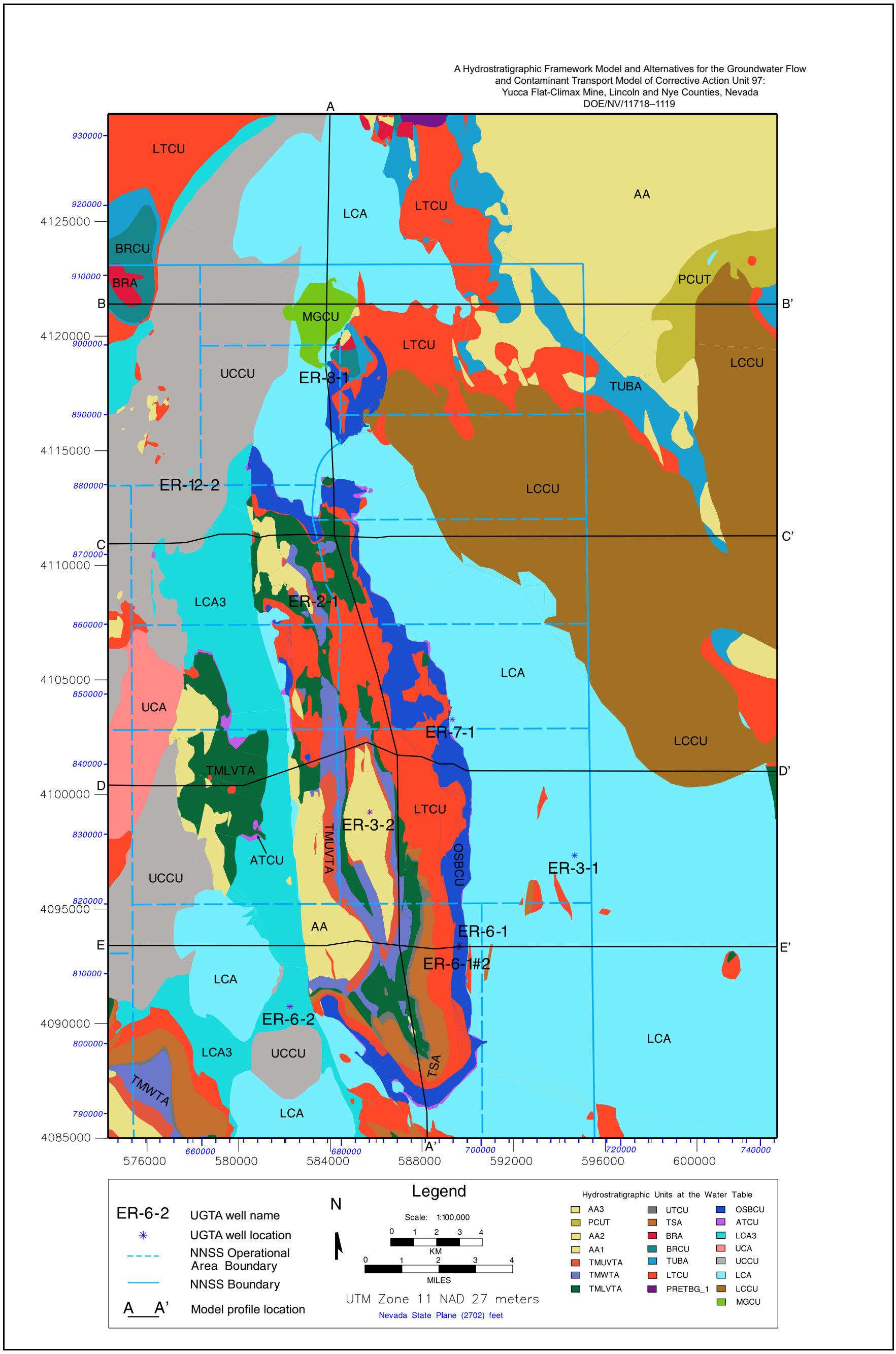



***Figure 2-3***
***Distribution of HSUs at the Water Table for the YF/CM CAU Model Area***
Source: Modified from BN, 2006

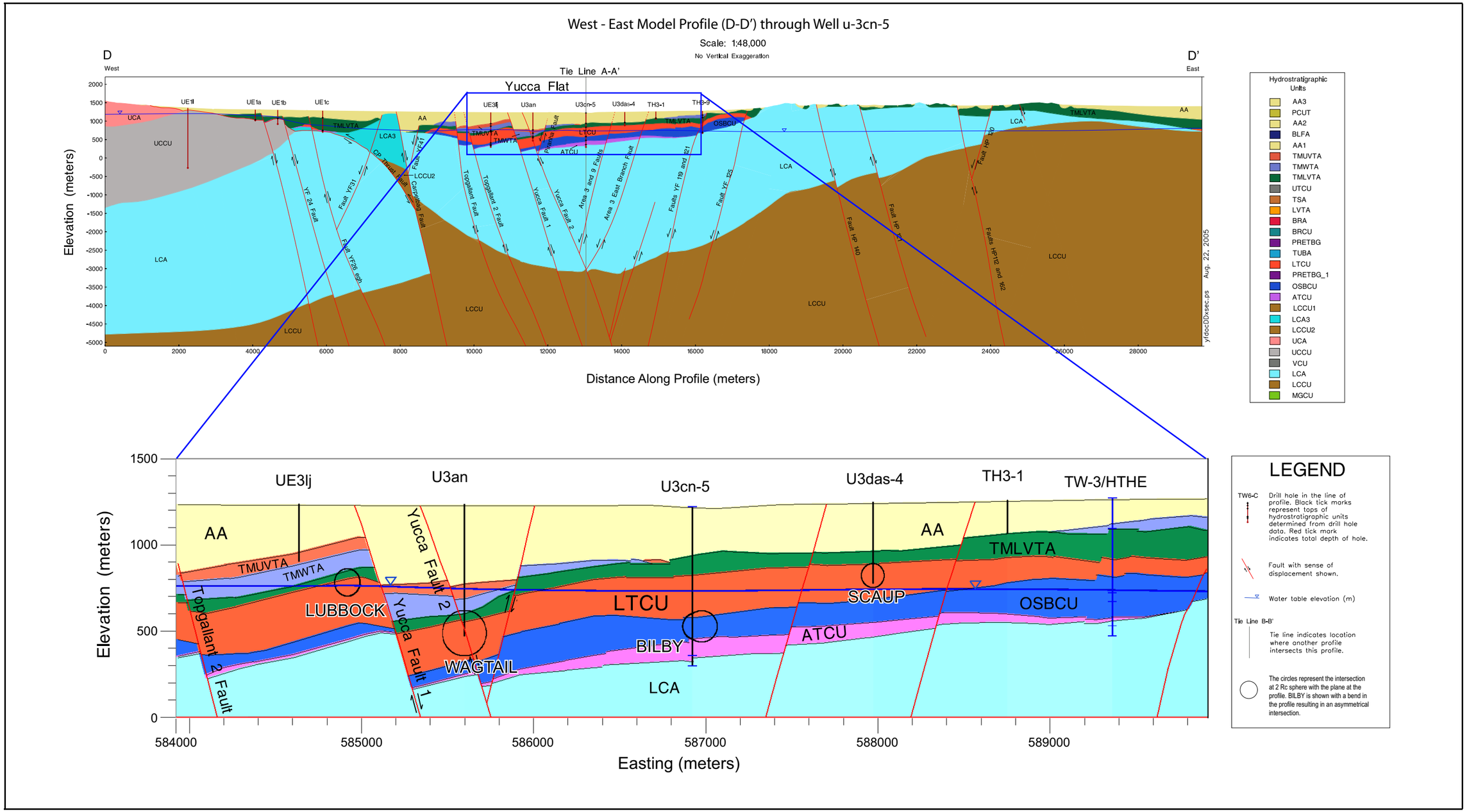



***Figure 2-4***
***West–East Profile of HSUs for the YF/CM CAU Model Area***
Source: Modified from BN, 2006, and SNJV, 2006b
Note: Cavity radius is calculated using the maximum of the announced yield range in DOE/NV (2000b) and the equation in Pawloski (1999).

from the overlying unsaturated zone and AA/VA system within Yucca Flat. The general groundwater flow regime in the LCA regional flow system is illustrated in Figure 2-5.

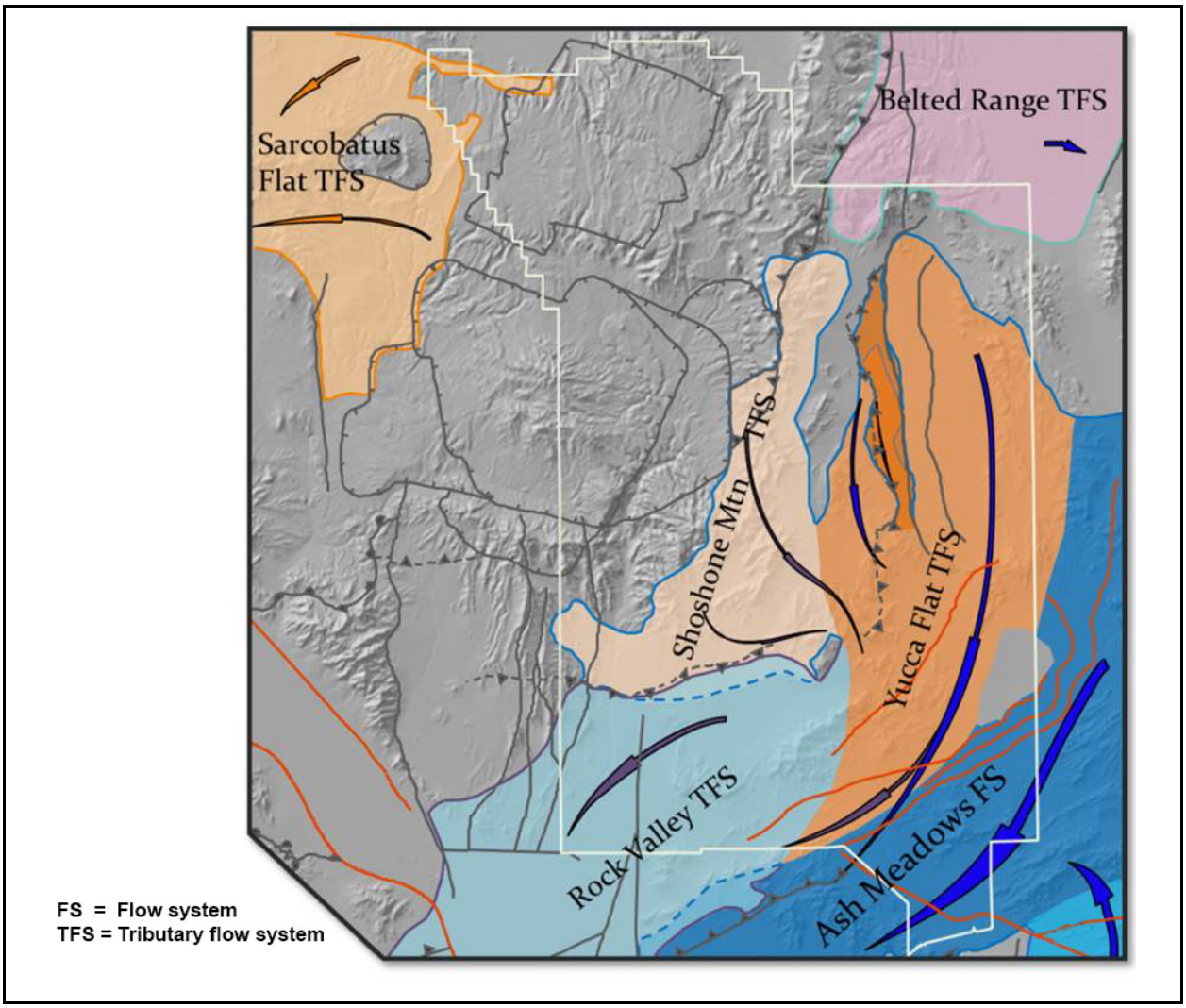



***Figure 2-5***
***General Groundwater Flow Paths in the LCA in Yucca Flat***
Source: Modified from Fenelon et al., 2010

## *2.2 Contaminant Sources*

The CAU contains residual contamination from 747 underground nuclear detonations. Three were in the granite stock at Climax Mine, and the remaining 744 were in the alluvium, volcanic tuffs, or carbonate rocks in Yucca Flat. The detonations are summarized in the U.S. Department of Energy, Nevada Operations Office (DOE/NV) document (2000b), and the locations are illustrated in Figure 2-1.

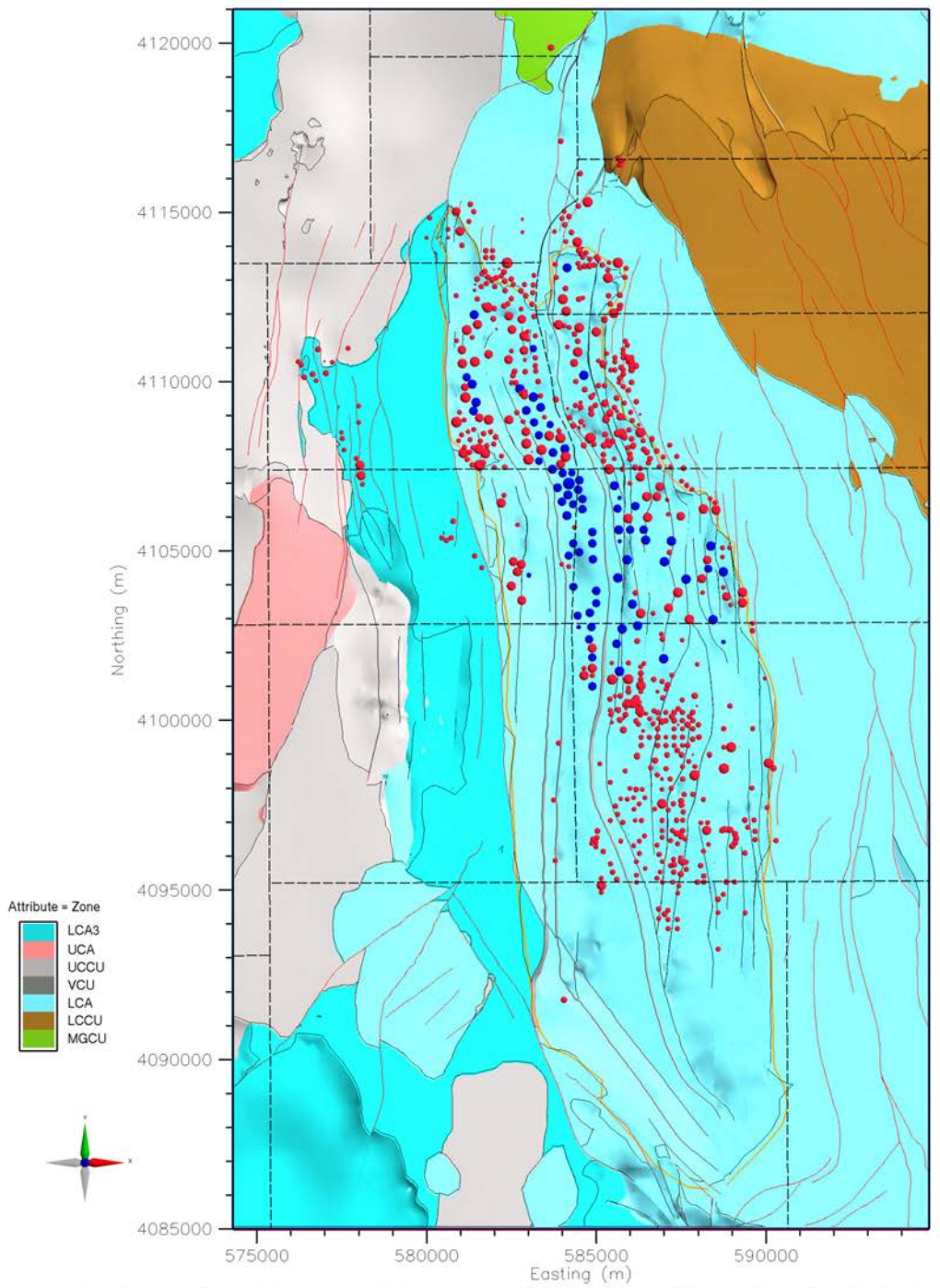
The relationship of the 747 underground nuclear detonations to the regional water table surface are illustrated in Figure 2-6. Of the 747 detonations, 668 had working points above the water table (shown as red circles), and 76 were below the water table (shown as blue circles). The circle diameters are drawn to equal two times the yield-dependent cavity diameters based on the relationship presented in Pawloski (1999) and the maximum reported yield in DOE/NV (2000b). There were 39 detonations within 3 cavity radii ($R_c$) of the saturated LCA (Figure 2-7).

The relevant unclassified radionuclide contaminant source is presented in Bowen et al. (2001), where the CAU inventory has been divided into detonations with working points greater than and less than 100 m above the regional water table. Bowen et al. (2001) identified 43 radionuclides of potential concern (could exceed 0.1 times the SDWA MCL). The decay-corrected (to September 22, 1992) total inventory activity is presented in Table 2-1 and illustrated in Figure 2-8. Table 2-1 also summarizes other relevant information, including (1) half-life, (2) specific activity, (3) SDWA MCL, (4) representative initial cavity concentration normalized to the SDWA MCL, and (5) whether the radionuclide was screened out by more detailed source term modeling documented in Appendix C of N-I (2013). Different normalized concentrations were developed for silicic rock and carbonate rock cavities because of different cavity size relationships to yield and different sorption behavior of several key radionuclides (notably strontium-90 [$^{90}$Sr] and cesium-137 [$^{137}$Cs]).

The initial radionuclide inventory is dominated by tritium ($^{3}$H), as well as $^{90}$Sr and $^{137}$Cs for the initial representative cavity concentrations normalized to the SDWA MCL without considering the effects of sorption in both silicic and carbonate detonation cavities (Figure 2-9). These radionuclides have relatively short half-lives. As a result, the total inventory and the initial representative cavity concentration decrease with time. Figure 2-10 illustrates the representative cavity concentrations normalized to the SDWA MCL when considering the effects of sorption.

## 2.3 Groundwater Flow and Contaminant Transport Models

Groundwater flow and contaminant transport models were developed as part of the corrective action investigation to identify the lateral and vertical extent of contaminant migration over the next 1,000 years. Based on the desire to capture the effects of different processes and features in the different hydrogeologic settings and the resulting different source term environments, the CAU flow




Note: Red circles represent detonations with working points above the water table and blue circles represent detonations with working points below the water table.
Cavity radius is based on maximum yield range reported in DOE/NV--209 (Pawloski, 1999).
Positive Y is North; Positive X is East.

Distribution of HSUs at the water table with volcanic rocks and alluvium HSUs removed to show detonation locations.

***Figure 2-6***
***YF/CM CAU Underground Nuclear Detonations Ranked by Size of Maximum Yield-Weighted Cavity Size***
Source: N-I, 2013, Fig. 1-14

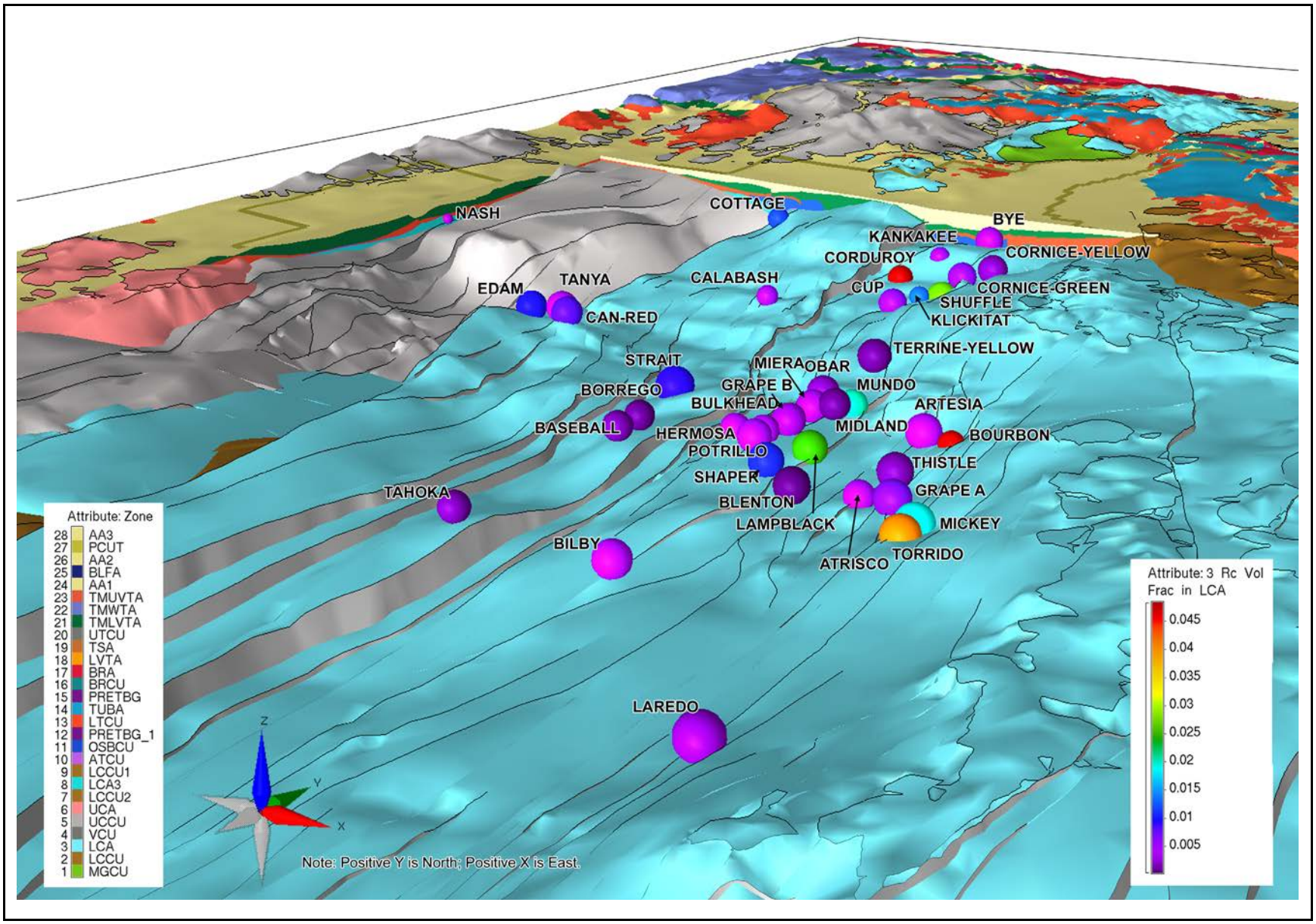



***Figure 2-7***
***Underground Nuclear Detonations at Yucca Flat with Exchange Volumes That Intersect the Saturated LCA When an Exchange Volume Radius of 3 $R_c$ Is Assumed***

Source: N-I, 2013, Fig. 2-2

Note: Cavity radius is calculated using the maximum of the announced yield range in DOE/NV (2000b) and the equation in Pawloski (1999).

## *Table 2-1*
## *Initial Radionuclide Inventory and Representative Cavity Concentrations for YF/CM CAU*
*(Page 1 of 2)*

| Element | Radionuclide | Half-Life (Years) | Specific Activity (Ci/g) [a] | Initial Inventory Curies (μg for U) | | SDWA MCL [d] | Representative Concentrations Normalized to SDWA MCL [e] | |
|---|---|---|---|---|---|---|---|---|
| | | | | Above Water Table [b] | Below Water Table [c] | pCi/L (μg/L for U) | Silicic Rock Cavity | Carbonate Cavity |
| Hydrogen | $^{3}$H | 1.23E+01 | 9,800 | 1.472E+07 | 3.316E+07 | 20,000 | 16,000 | 49,000 |
| Carbon | $^{14}$C | 5.73E+03 | 4.5 | 1.137E+03 | 8.389E+02 | 2,000 | 7 | 20 |
| Aluminum | $^{26}$Al | 7.17E+05 | 0.019 | 5.573E-02 | 3.595E-02 | Screened out | | |
| Chlorine | $^{36}$Cl | 3.01E+05 | 0.033 | 1.163E+02 | 2.309E+02 | 700 | 2 | 5 |
| Argon | $^{39}$Ar | 2.69E+02 | 34 | 3.204E+02 | 9.551E+02 | Screened out | | |
| Potassium | $^{40}$K | 1.27E+09 | 7.1E-06 | 8.219E+01 | 2.422E+02 | Screened out | | |
| Calcium | $^{41}$Ca | 1.03E+05 | 0.085 | 8.545E+02 | 1.661E+03 | 7,800 | <0.1 | 2 |
| Nickel | $^{59}$Ni | 7.51E+04 | 0.082 | 2.139E+01 | 4.265E+01 | Screened out | | |
| | $^{63}$Ni | 1.00E+02 | 60 | 2.334E+03 | 5.229E+03 | 50 | 50 | 160 |
| Krypton | $^{85}$Kr | 1.07E+01 | 400 | 1.137E+04 | 5.805E+04 | Screened out of Source Term | | |
| Strontium | $^{90}$Sr | 2.91E+01 | 140 | 1.499E+05 | 7.479E+05 | 8 | 500 | 2,200,000 |
| Zirconium | $^{93}$Zr | 1.53E+06 | 0.0025 | 6.852E+00 | 2.607E+01 | Screened out | | |
| Niobium | $^{93m}$Nb | 1.61E+01 | 290 | 6.246E+02 | 6.730E+03 | Screened out | | |
| | $^{94}$Nb | 2.03E+04 | 3.9E+04 | 2.296E+01 | 1.975E+02 | Screened out | | |
| Technetium | $^{99}$Tc | 2.13E+05 | 0.017 | 6.153E+01 | 1.875E+02 | 900 | 0.4 | 1 |
| Palladium | $^{107}$Pd | 6.50E+06 | 0.00051 | 7.634E-01 | 9.226E-01 | Screened out | | |
| Cadmium | $^{113m}$Cd | 1.41E+01 | 240 | 1.566E+02 | 4.994E+02 | Screened out | | |
| Tin | $^{121m}$Sn | 5.50E+01 | 54 | 6.738E+02 | 1.918E+03 | Screened out | | |
| | $^{126}$Sn | 1.00E+05 | 0.029 | 3.402E+00 | 9.161E+00 | | | |
| Iodine | $^{129}$I | 1.57E+07 | 0.00018 | 2.079E-01 | 5.422E-01 | 1 | 2 | 8 |
| Cesium | $^{135}$Cs | 2.30E+06 | 0.0012 | 6.926E+00 | 1.970E+01 | 200 | <0.1 | 0.6 |
| | $^{137}$Cs | 3.02E+01 | 88 | 2.919E+05 | 9.299E+05 | 200 | 0.7 | 120,000 |
| Samarium | $^{151}$Sm | 9.00E+01 | 27 | 1.388E+04 | 3.189E+04 | Screened out | | |
| Europium | $^{150}$Eu | 3.60E+01 | 70 | 1.354E+04 | 1.099E+02 | Screened out | | |
| | $^{152}$Eu | 1.35E+01 | 180 | 3.634E+04 | 7.083E+04 | | | |
| | $^{154}$Eu | 8.59E+00 | 270 | 2.968E+04 | 5.480E+04 | | | |
| Holmium | $^{166m}$Ho | 1.20E+03 | 1.8 | 2.665E+01 | 5.514E+01 | Screened out | | |

## *Table 2-1*
## *Initial Radionuclide Inventory and Representative Cavity Concentrations for YF/CM CAU*
*(Page 2 of 2)*

| Element | Radionuclide | Half-Life (Years) | Specific Activity (Ci/g) [a] | Initial Inventory Curies (µg for U) | | SDWA MCL [d] | Representative Concentrations Normalized to SDWA MCL [e] | |
|---|---|---|---|---|---|---|---|---|
| | | | | Above Water Table [b] | Below Water Table [c] | pCi/L (µg/L for U) | Silicic Rock Cavity | Carbonate Cavity |
| Thorium | $^{232}$Th | 1.40E+10 | 1.1E-07 | 5.969E+00 | 1.752E+01 | Screened out | | |
| Uranium (Inventory in µg and MCL in µg/L) | $^{232}$U | 6.89E+01 | 22 | 4.081E+00 | 1.671E+01 | 30 | Screened out | |
| | $^{233}$U | 1.59E+05 | 0.0098 | 1.247E+04 | 1.583E+04 | | | |
| | $^{234}$U | 2.46E+05 | 0.0063 | 1.373E+04 | 2.408E+04 | | | |
| | $^{235}$U | 7.04E+08 | 2.2E-06 | 1.183E+06 | 1.490E+06 | | <0.1 | <0.1 |
| | $^{236}$U | 2.34E+07 | 6.5E-05 | 1.410E+04 | 5.345E+04 | | Screened out | |
| | $^{238}$U | 4.47E+09 | 3.4E-07 | 2.580E+07 | 4.672E+07 | | <0.1 | 0.1 |
| Neptunium | $^{237}$Np | 2.14E+06 | 0.00071 | 1.140E+00 | 1.072E+01 | 15 | <0.1 | 0.8 |
| Plutonium | $^{238}$Pu | 8.77E+01 | 17 | 1.774E+04 | 1.115E+04 | 15 | 2 | <0.1 |
| | $^{239}$Pu | 2.41E+04 | 0.063 | 9.997E+04 | 2.746E+04 | 15 | 10 | 0.3 |
| | $^{240}$Pu | 6.56E+03 | 0.23 | 2.523E+04 | 7.045E+03 | 15 | 3 | <0.1 |
| | $^{241}$Pu | 1.44E+01 | 100 | 3.415E+05 | 1.034E+05 | 15 | Screened out | |
| | $^{242}$Pu | 3.75E+05 | 0.0040 | 7.485E+00 | 4.621E+00 | 15 | | |
| Americium | $^{241}$Am | 4.33E+02 | 3.5 | 2.309E+04 | 6.088E+03 | 15 | Screened out | |
| | $^{243}$Am | 7.37E+03 | 0.20 | 2.682E+00 | 3.416E+00 | 15 | | |
| Curium | $^{244}$Cm | 1.81E+01 | 82 | 1.586E+03 | 2.506E+03 | 15 | Screened out | |
| **Total** | | | -- | **1.578E+07** | **3.523E+07** | -- | -- | -- |

Source: Modified from Bowen et al., 2001, and Table 2-4 of N-I (2013).

Note: Inventories are decay corrected to September 23, 1992 (the date of the last underground nuclear test at the NNSS).

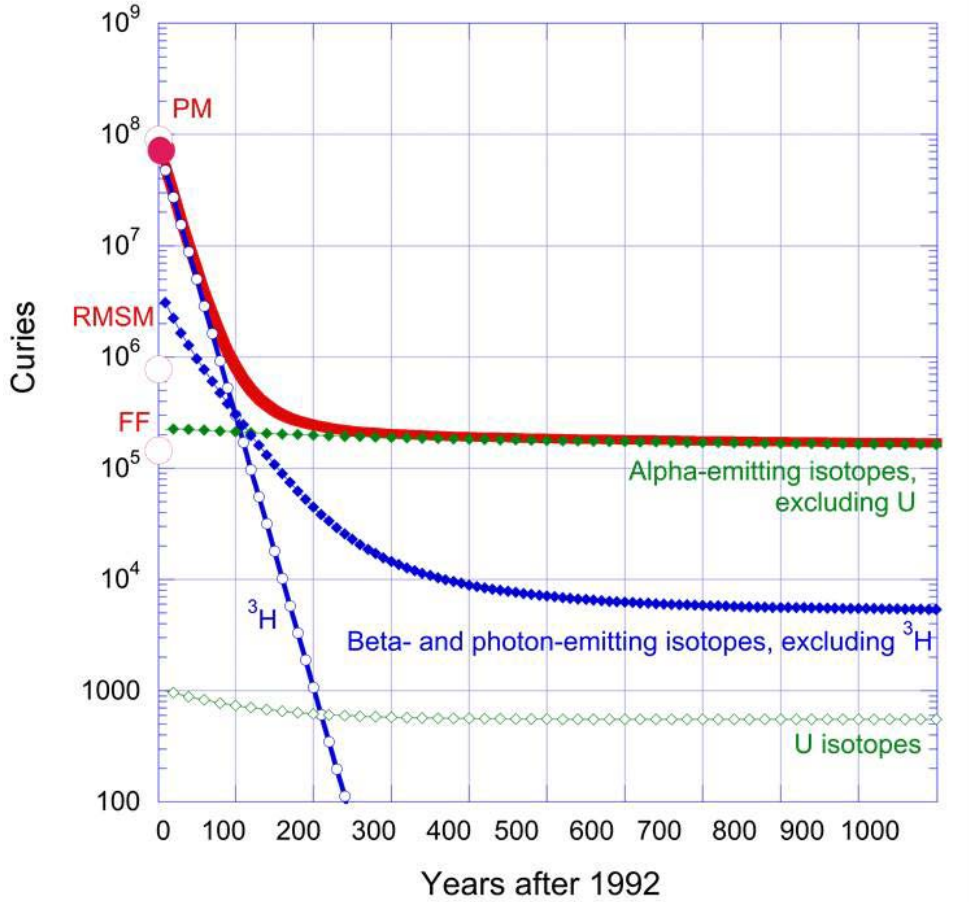
[a] Specific activities derived from Argonne National Laboratory (2007) or CFR (2013b).

[b] Total inventory for detonations with working points more than 100 m above the water table based on Bowen et al. (2001).
[c] Total inventory for detonations with working points below or within 100 m of the water table based on Bowen et al. (2001).

[d] Maximum contaminant levels for beta/photon emitters are concentrations that result in a dose of 4 mrem/yr; for gross alpha particles it is 15 pCi/L, and for U it is 30 µg/L. The MCLs are provided in EPA (2002) *Radionuclides in Drinking Water: A Small Entity Compliance Guide*.

[e] Representative concentrations derived using assumptions presented in Section 2.3 of N-I, (2013). These assumptions include cavity radius based on either Pawloski (1999) for silicic rock cavities or Boardman (1970) for carbonate rock cavities; $K_d$ values that are means of $K_d$ distributions for silicic rock or carbonate rock as presented in Table 2-5 of N-I (2013), mean melt glass fractions for either silicic rock or carbonate rock. These assumptions are the same as those used to develop Fig. 2-8 of N-I (2013).

CFR = *Code of Federal Regulations*
Ci/g = Curies per gram
EPA = U.S. Environmental Protection Agency
$K_d$ = Distribution coefficient
mrem/yr = Millirem per year
pCi/L = Picocuries per liter
µg = Microgram
µg/L = Micrograms per liter




Note: Open circles represent 1992 total inventory for the following CAUs:
PM = Central and Western Pahute Mesa (CAUs 101 and 102)
RMSM = Rainier Mesa/Shoshone Mountain (CAU 99)
FF = Frenchman Flat (CAU 98)

***Figure 2-8***
***YF/CM CAU Total Radionuclide Inventory Decay***
Source: Bowen et al., 2001

and transport modeling was divided into the following four separate modeling domains, with links providing water and contaminant flux to the downgradient domain:

- Climax Mine (3 detonations)
- Yucca Flat unsaturated zone (668 unsaturated-zone detonations)
- Yucca Flat saturated AA/VA system (76 saturated-zone detonations)
- Yucca Flat saturated LCA (LCA and lower carbonate aquifer thrust plate [LCA3]; 12 and 39 detonations within 2 or 3 $R_c$ exchange volumes, respectively)

The domain's spatial relationships are illustrated in Figures 2-11 and 2-12.

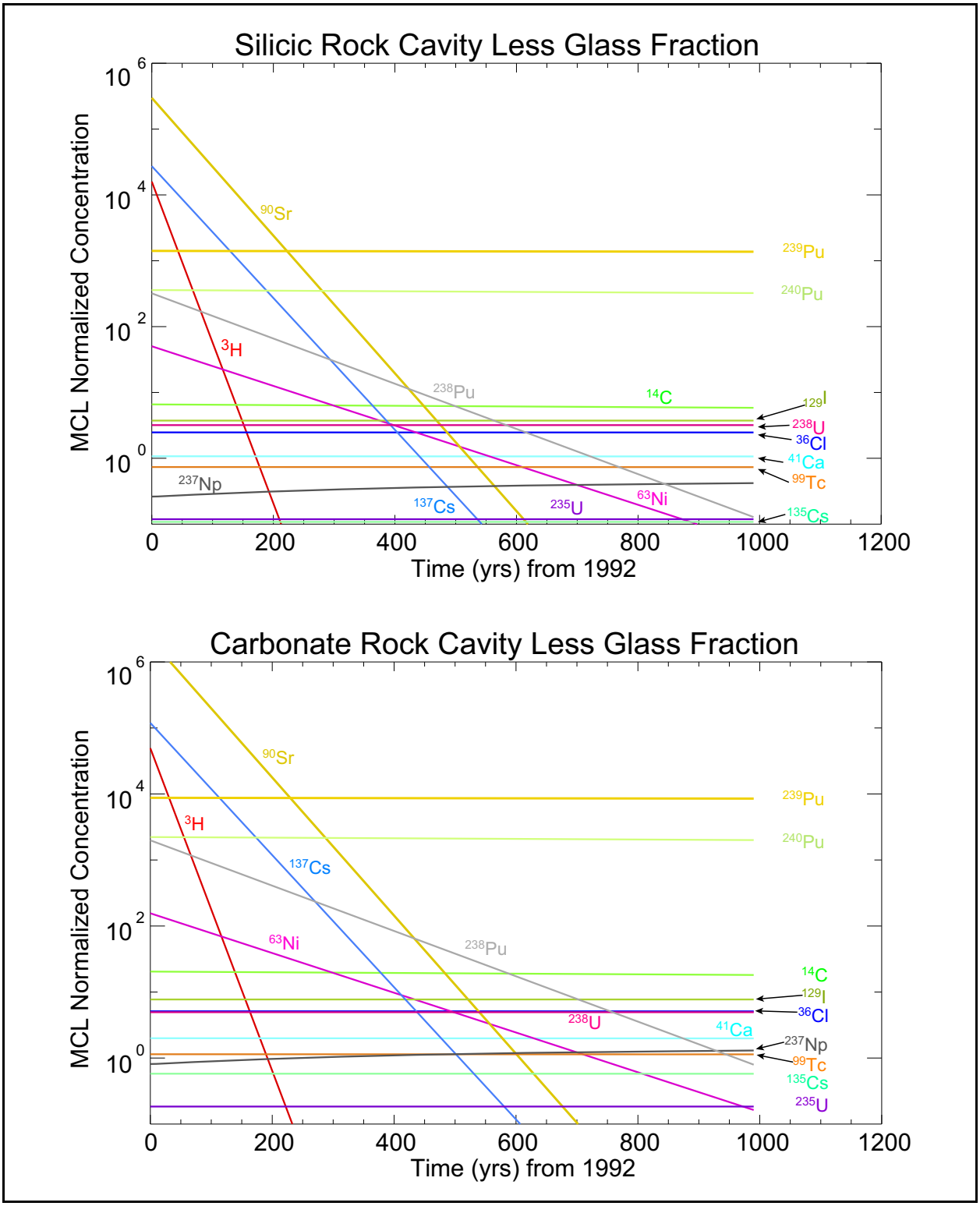



***Figure 2-9***
***MCL-Normalized Cavity Concentration versus Time Less Melt-Glass Inventory***
Source: N-I, 2013, Fig. 2-7

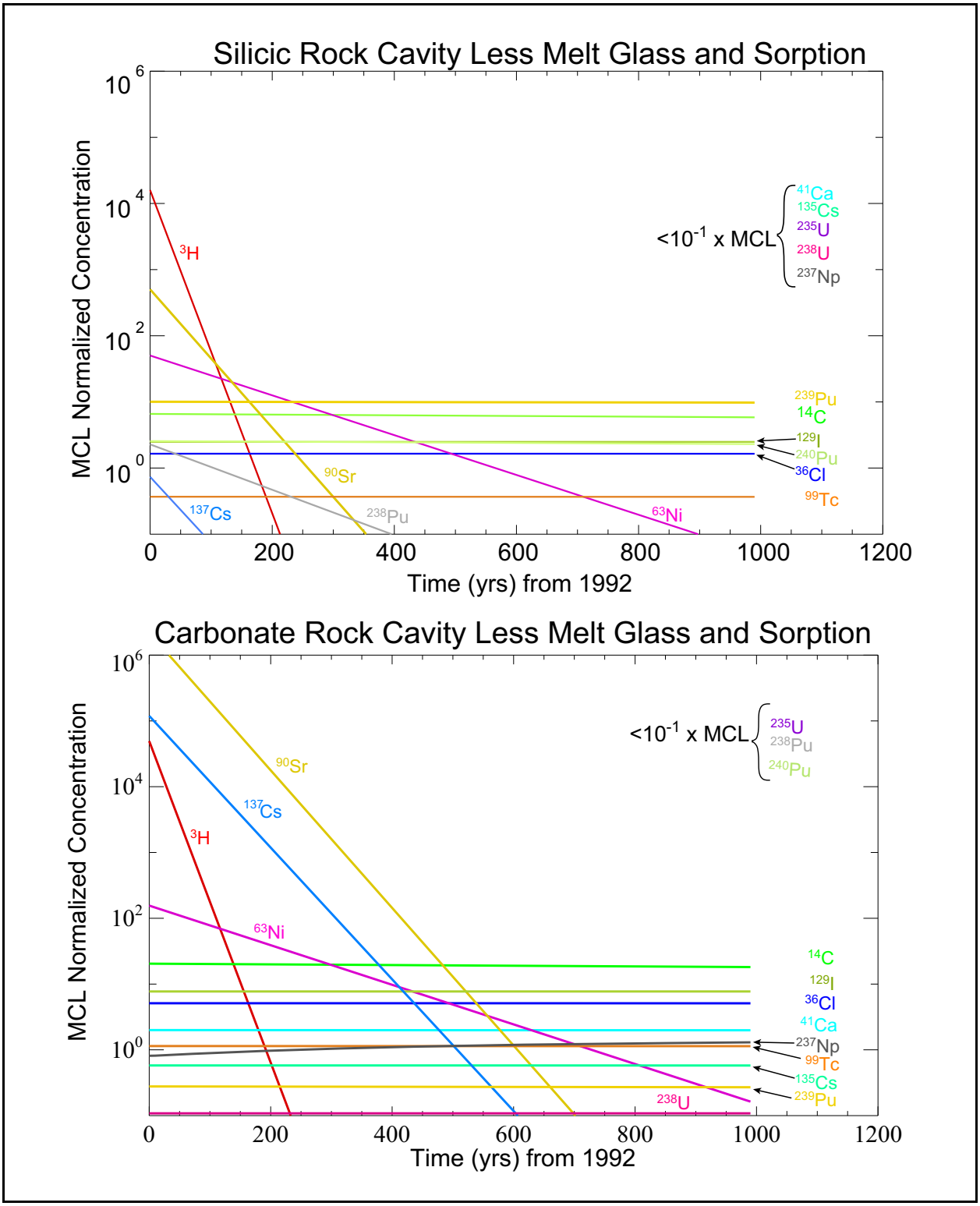



***Figure 2-10***
***MCL-Normalized Cavity Concentration versus Time***
***Less Melt-Glass Inventory Considering Sorption***
Source: N-I, 2013, Fig. 2-8

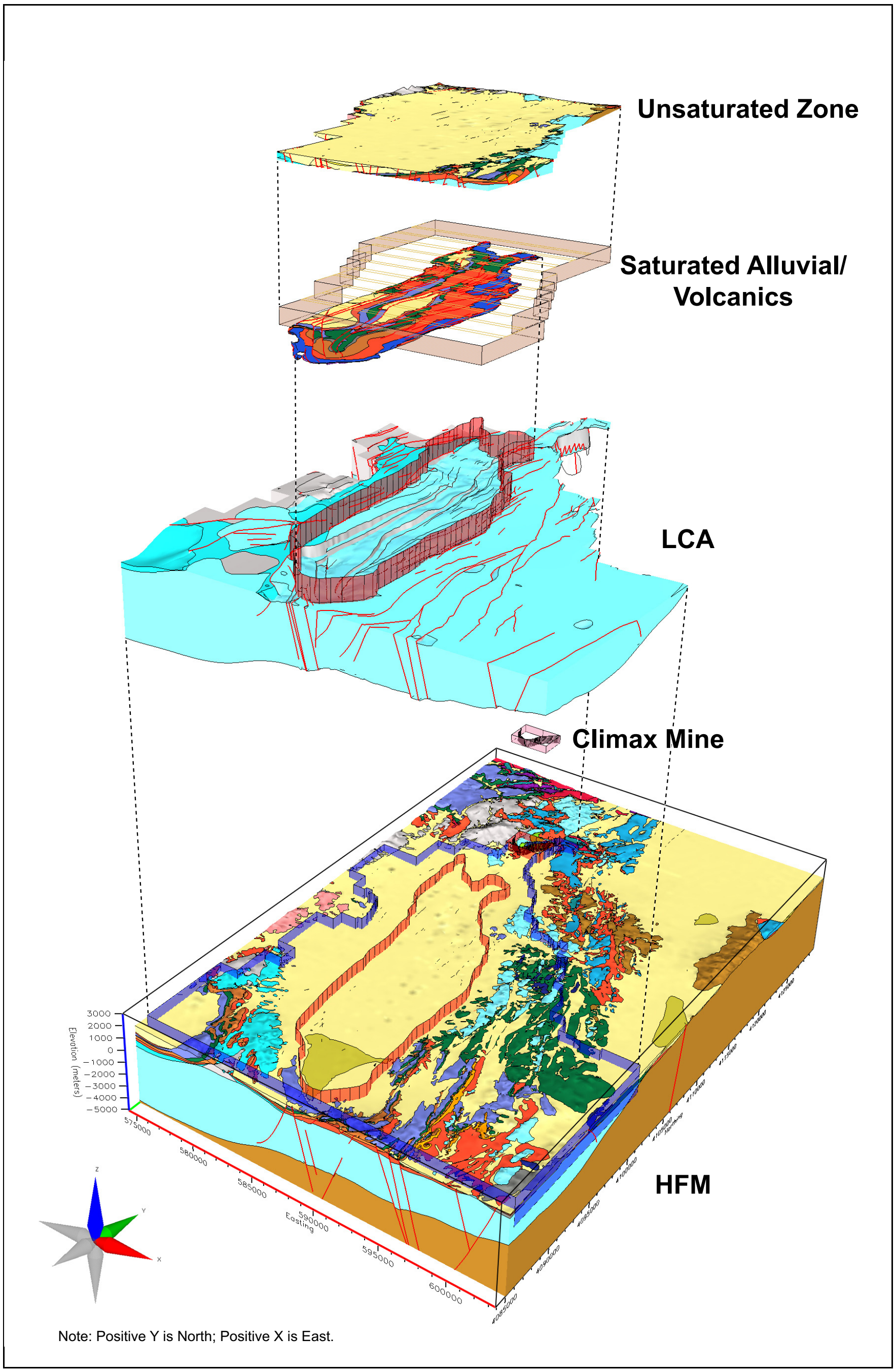



***Figure 2-11***
***Relationships between the YF/CM CAU Model Domains in 3-D Perspective***
Source: N-I, 2013, Fig. 1-16

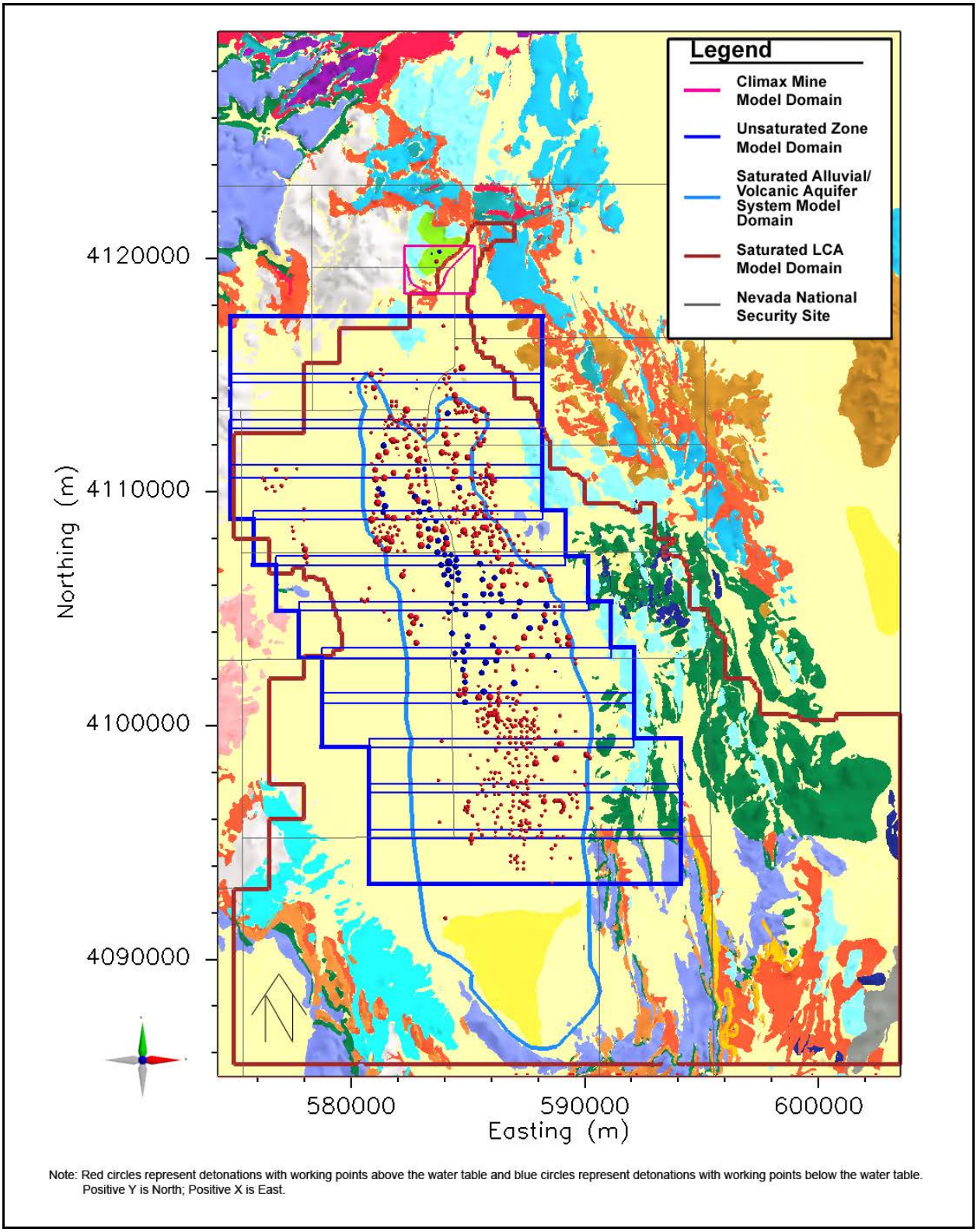



***Figure 2-12***
***Lateral Boundaries of the YF/CM CAU Model Domains***

Source: N-I, 2013, Fig. 1-17

Note: Cavity radius is calculated using the maximum of the announced yield range in DOE/NV (2000b) and the equation in Pawloski (1999).

The Climax Mine, Yucca Flat unsaturated zone, and Yucca Flat saturated AA/VA system flow and transport were used to calculate the possible range of contaminant fluxes to the saturated LCA regional aquifer. These models evaluated the effect of uncertain features, processes, and parameters, including ranges of infiltration rates, vertical to horizontal permeability anisotropy ratios, effective porosity of confining units, magnitude of crater recharge, exchange volume extents, and tuff confining unit (TCU) overpressures. The transport of contaminants from these sources to the LCA was determined to be insignificant in comparison to the initial contamination from the detonations that were assumed to have exchange volumes that intersect the saturated LCA (Pohlmann et al. [2007] and N-I [2013]).

The Yucca Flat LCA groundwater flow and transport conceptual and numerical models, parameter distributions and bases, assumptions, and results (including sensitivity and uncertainty analyses) are presented in Sections 5.0 and 6.0 of N-I (2013). The LCA models use the water and contaminant fluxes calculated using the overlying unsaturated zone and saturated AA/VA system flow and transport models as well as contamination assumed to be initially in place in the LCA from those detonations within 3 $R_c$ of the saturated LCA.

## 2.4 Forecast Contaminant Boundaries

The LCA transport model forecasts contaminant boundaries. The forecast contaminant boundaries focus on the LCA because it represents (1) the lower HSU boundary that delineates the possible extent of contaminated groundwater and (2) the only regional aquifer in the CAU, and (3) is a regional groundwater source for use on and off the NNSS. To represent the uncertainty in the contaminant boundaries, multiple alternative flow and transport models were used. The base-case model was chosen as the most conservative of the alternative representations in order to ensure that the potential extent of contamination was not underestimated. Each alternative model represented a separate and distinct contaminant boundary forecast. Collectively, the forecasts are termed an ensemble of contaminant boundaries. The CAU ensemble of contaminant boundaries is presented in Figure 2-13.

The seven alternative models were as follows:

- Northern Flux = 1 kilogram per second (kg/s), alternate fault fracture porosity distribution and alternative $K_d$ for Sr, Cs, C, and Ni
- Northern Flux = 1 kg/s
- Lower Bound Null Space Monte Carlo (NSMC)
- Alternative Fault Fracture Porosity
- Scale-Dependent Matrix Diffusion
- Alternative Matrix Sorption for Sr, Cs, C, and Ni
- Alternative Hydrologic Source Term (HST)

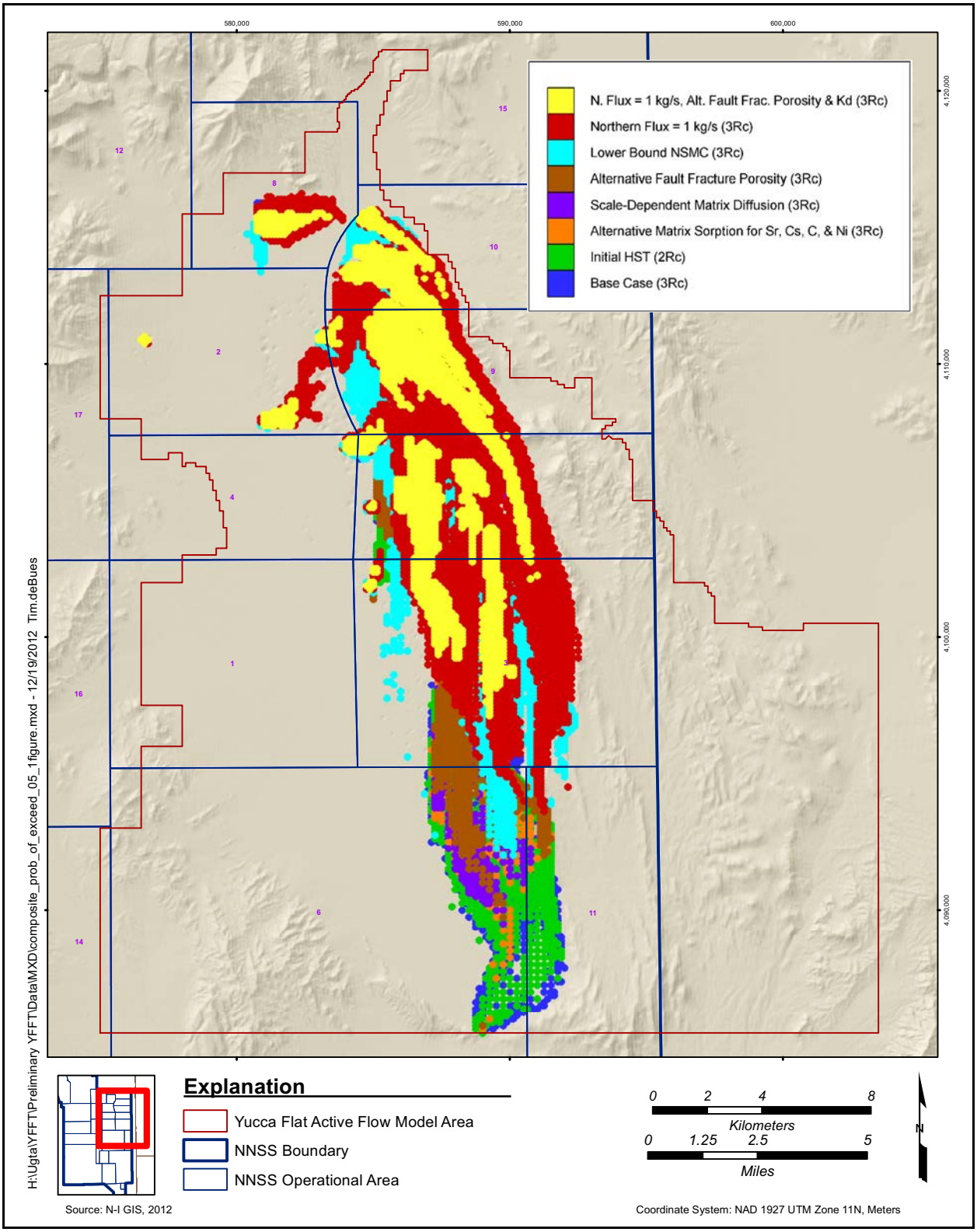



***Figure 2-13***
***Ensemble of Contaminant Boundaries in the LCA for LCA Contaminant Sources***

# 3.0 DATA REVIEWED

The peer review team reviewed the geologic data, water-level data, water-budget data, hydraulic properties data, water-quality data, and radionuclide concentration data from the YF/CM CAU. This basic understanding of the hydrogeologic system in the Yucca Flat basin was essential for evaluating the groundwater flow and contaminant transport models. It provided a foundation for answering the questions posed to the peer review team, specifically question 2. This section summarizes these data.

## 3.1 Geologic Data

The CAU geologic data were used as the scientific basis for the HFM presented in Bechtel Nevada (BN) (2006). The HFM was in turn used as the framework for the groundwater flow and contaminant transport models for YF/CM described in Pohlmann et al. (2007) and N-I (2013), respectively.

The dataset defining the CAU geologic and hydrostratigraphic setting contains geological and geophysical studies conducted over the last six decades. In general, these studies include the following:

- Direct observations of surface geologic exposures
- Detailed geologic maps at a scale of 1:24,000
- About 3,000 boreholes drilled in the model area, of which 529 were included in the HFM
- Surface geophysical surveys (gravity, magnetic, resistivity, and seismic)

In Yucca Flat stratigraphic units at land's surface can be traced below the surface with the numerous borehole observations. The geologic and geophysical observations made in the boreholes (Figure 3-1) include drill cuttings every 10 ft; about 13 km of continuous core samples; geophysical logs (density, resistivity, spectral gamma-ray, neutron, caliper, borehole image, acoustic, temperature and fluid flow); and laboratory analyses (chemical, including X-ray fluorescence [XRF]; mineralogic, including X-ray diffraction [XRD]; and petrographic).

Geophysical surveys included gravity data used to define the basin shape, locate major faults, and estimate the Paleozoic basement depth. Ground magnetic and aeromagnetic surveys were used to define the extent of the Climax Stock and to locate buried faults. Electrical resistivity data determined the Yucca Flat playa deposit thickness. Natural source magnetotelluric data were used to define the

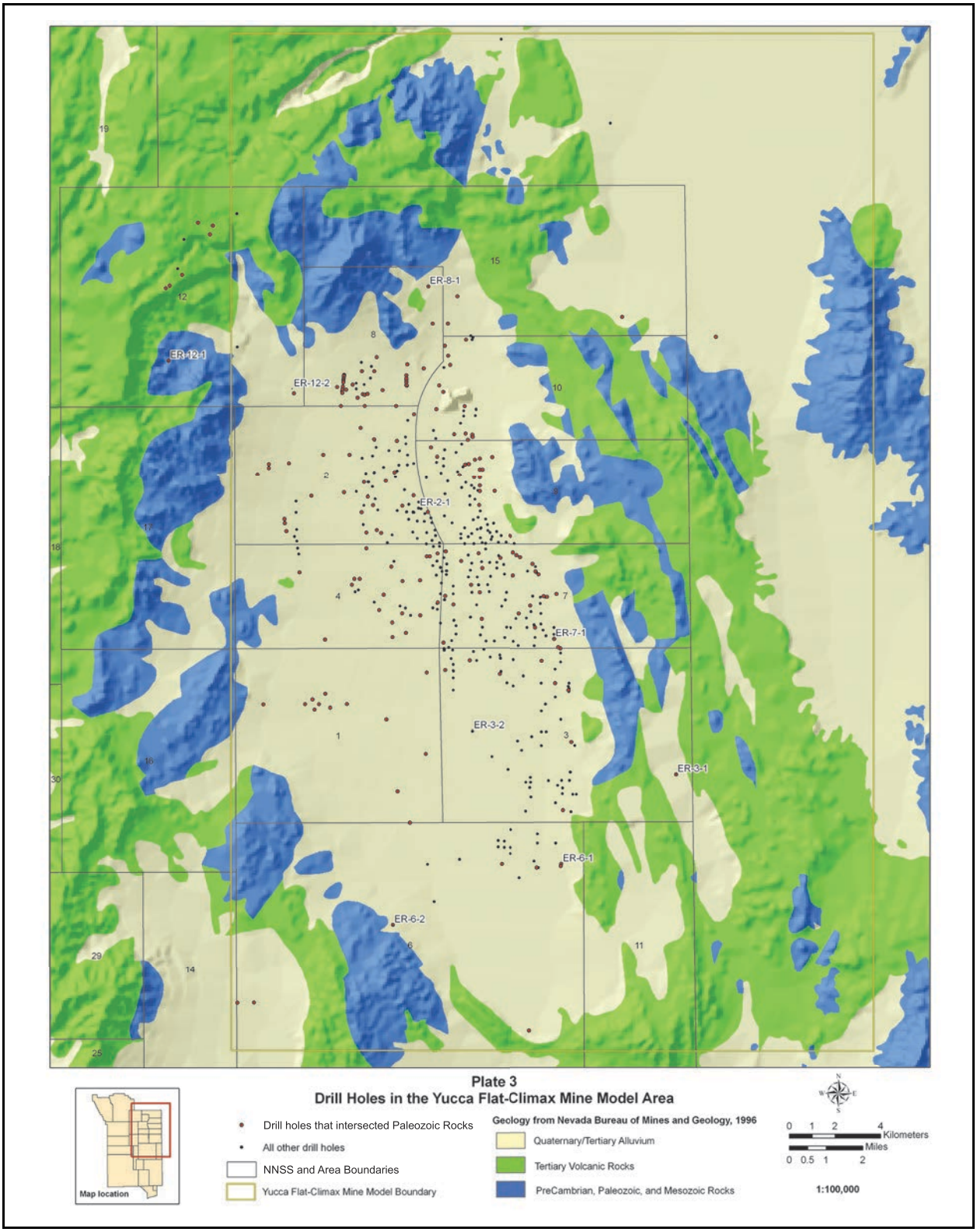



***Figure 3-1***
***Drill Holes in the YF/CM Model Area***
Source: Modified from BN, 2006, Fig. 3-1

pre-Tertiary stratigraphy and structure. Finally, about 140 miles (mi) of two-dimensional (2-D) seismic reflection lines have helped locate major faults.

The above data sources and datasets were used to define the 3-D hydrostratigraphic framework, HSU conceptual models, and other important geologic features (i.e., faults, fractures and alteration zones) for groundwater flow and contaminant transport. This information is summarized in BN (2006).

## 3.2 Water-Level Data

Water-level data have been collected since the earliest water-supply wells were drilled in the CAU area in the 1950s. The early data were used by Winograd and Thordarson (1975) to develop a regional potentiometric surface of the aquifers (Figure 3-2). More recent data were tabulated by Fenelon et al. (2012) and were used to develop potentiometric surface maps for the local AA/VA flow system (Figure 3-3) and the regional carbonate aquifer (Figure 3-4).

The water-level data maps and predevelopment potentiometric surface reflect an assumed steady-state condition. Transient water-level responses in the tuffs of the AA/VA flow system as the result of underground nuclear testing have been recognized and were used to calibrate the AA/VA flow system model (Figures 3-5 and 3-6). Long-term natural responses in the carbonate aquifer have been observed (Figure 3-7). Finally, water-level responses to large-scale multiple-well aquifer tests (MWATs) support the LCA groundwater flow-model calibration (Figure 3-8).

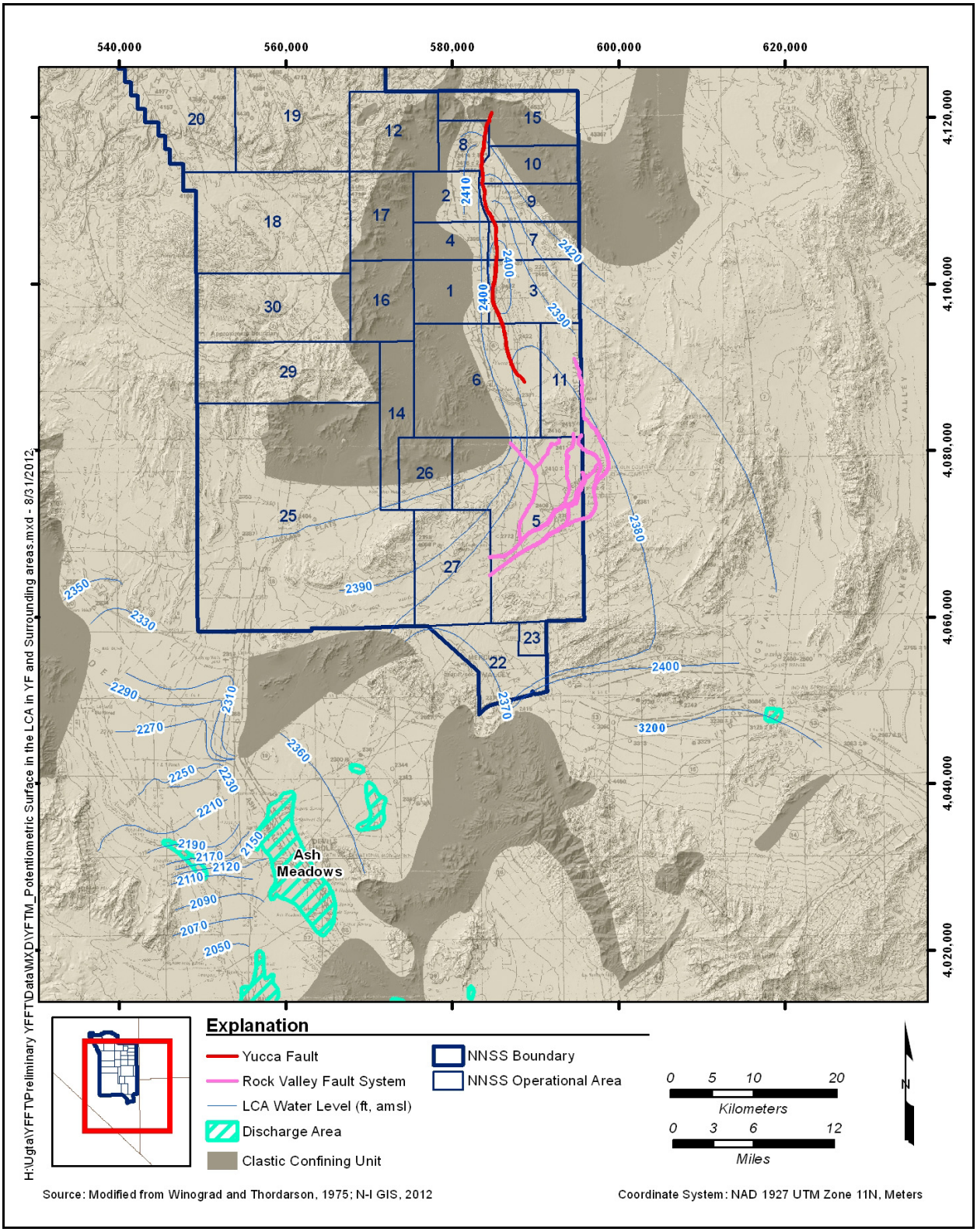



***Figure 3-2***
***Potentiometric Surface in the LCA in Yucca Flat and Surrounding Areas, Including Ash Meadows***

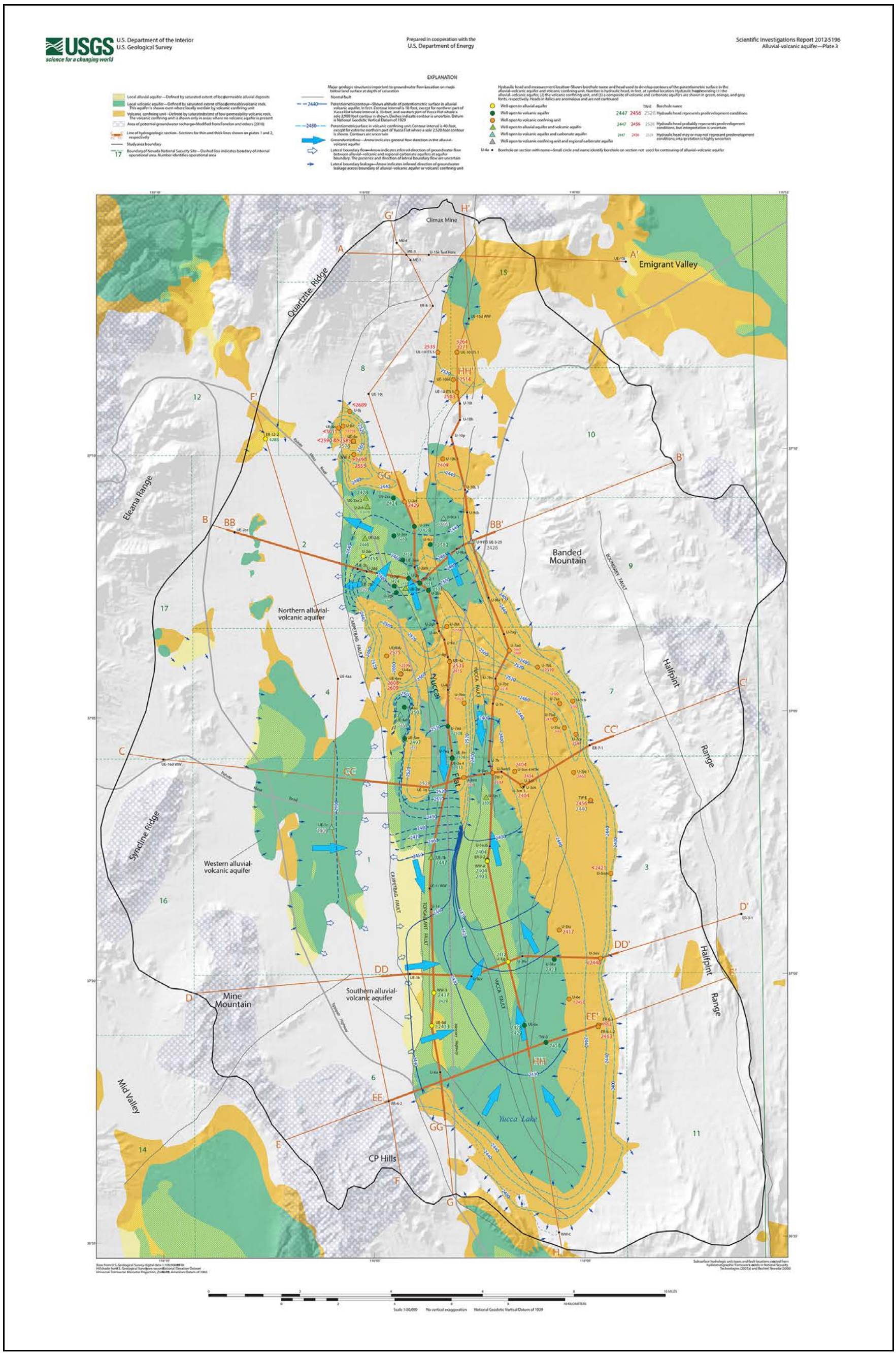



**Figure 3-3**
**Predevelopment Hydraulic Heads and Potentiometric Surface for the AA/VA System**
Source: Fenelon et al., 2012

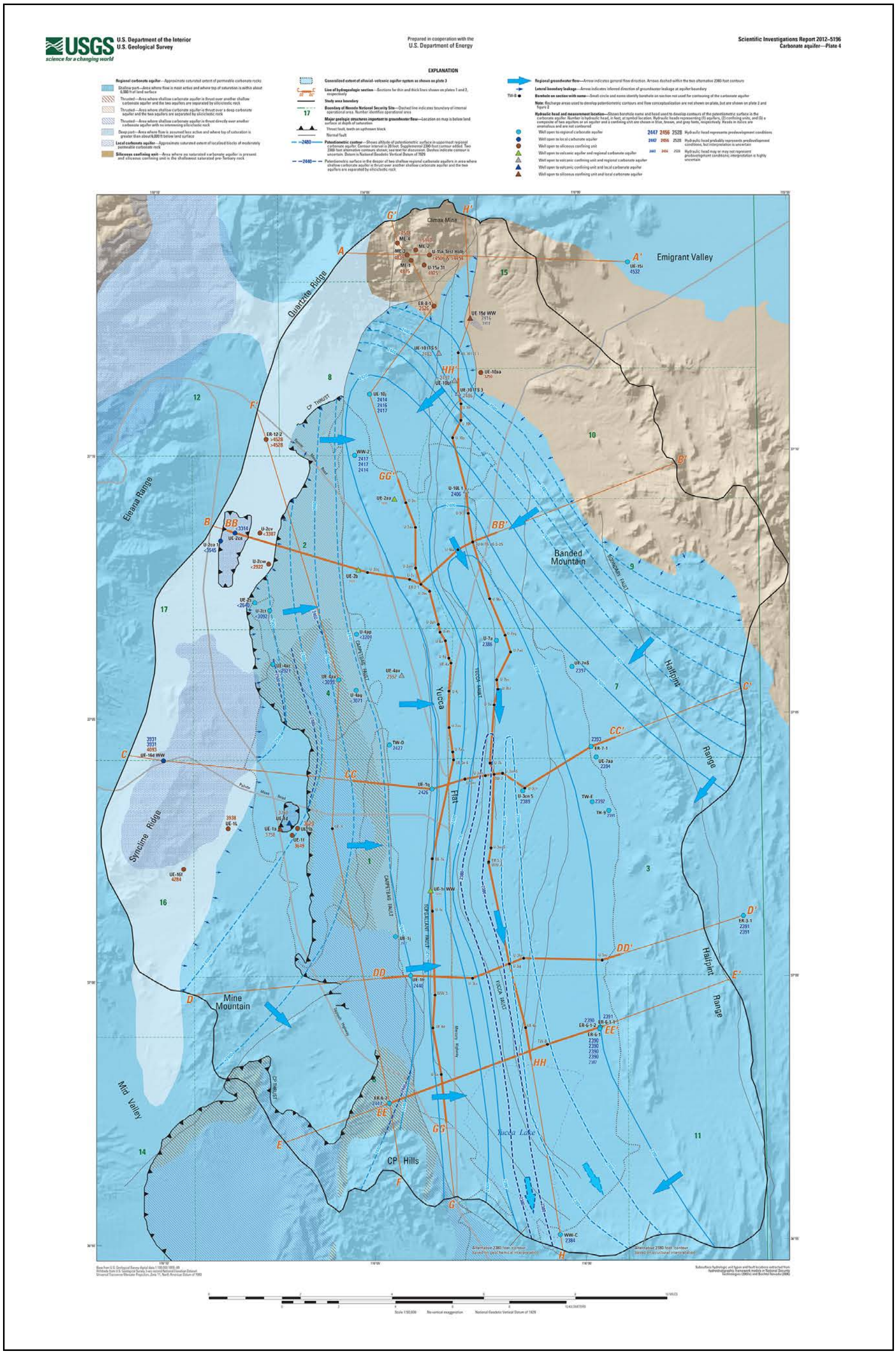



**Figure 3-4**
**Predevelopment Hydraulic Heads and Potentiometric Surface for the Carbonate Aquifer**
Source: Fenelon et al., 2012

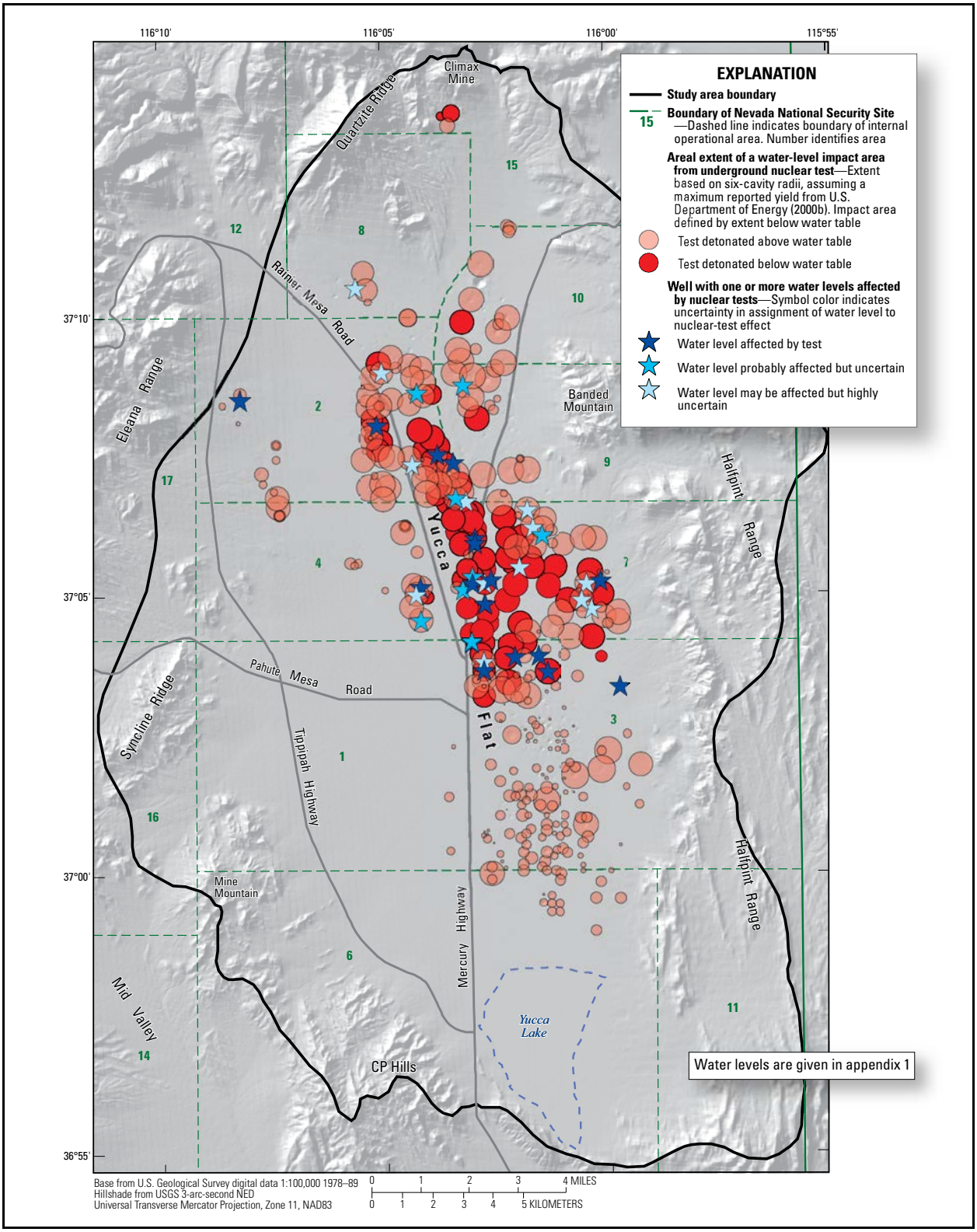



***Figure 3-5***
***Wells in the TCUs with Transient Water-Level Responses from Underground Nuclear Testing***
Source: Fenelon et al., 2012

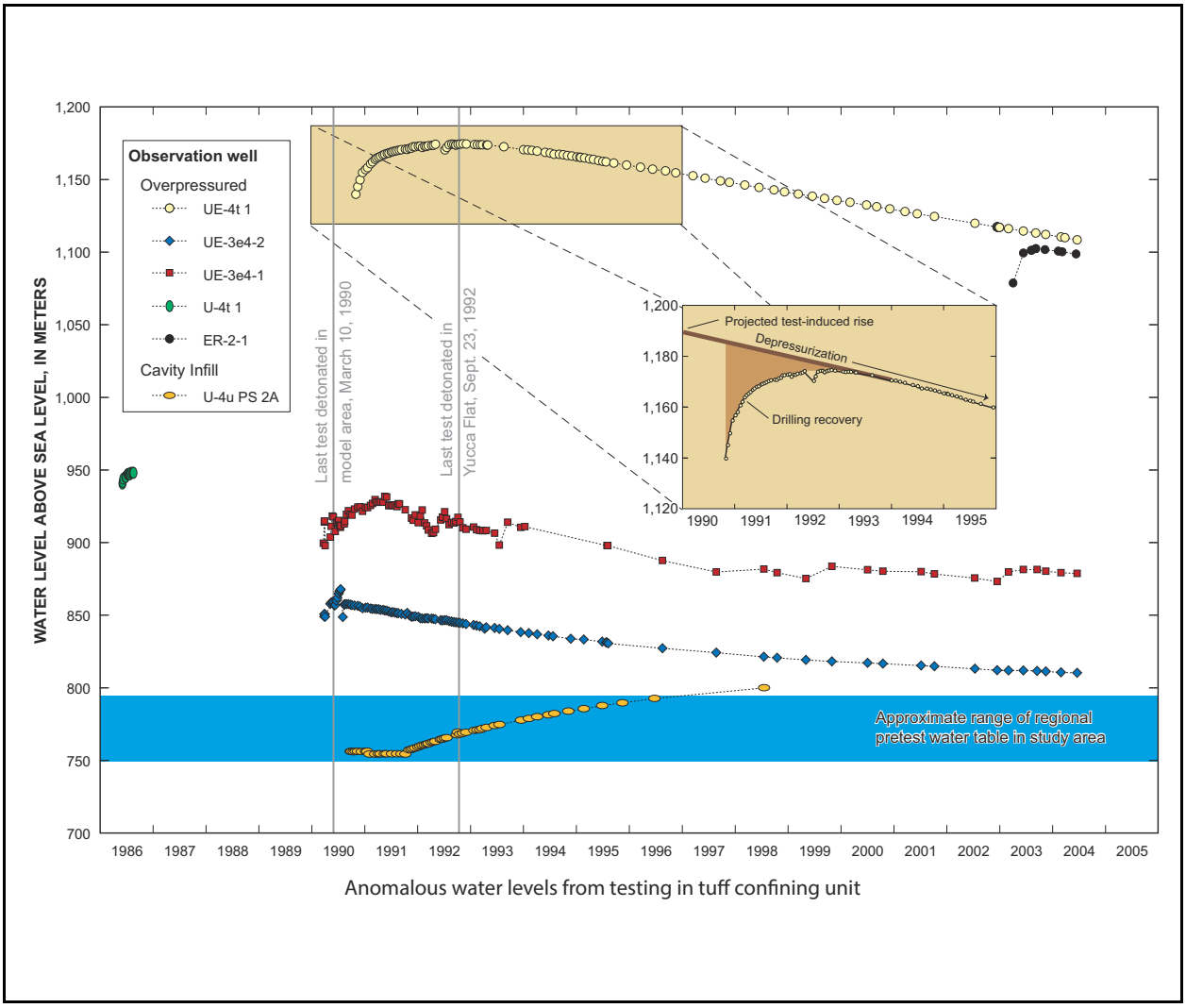



***Figure 3-6***
***Transient Water-Level Response in Yucca Flat from Underground Nuclear Testing***
Source: Halford et al., 2005

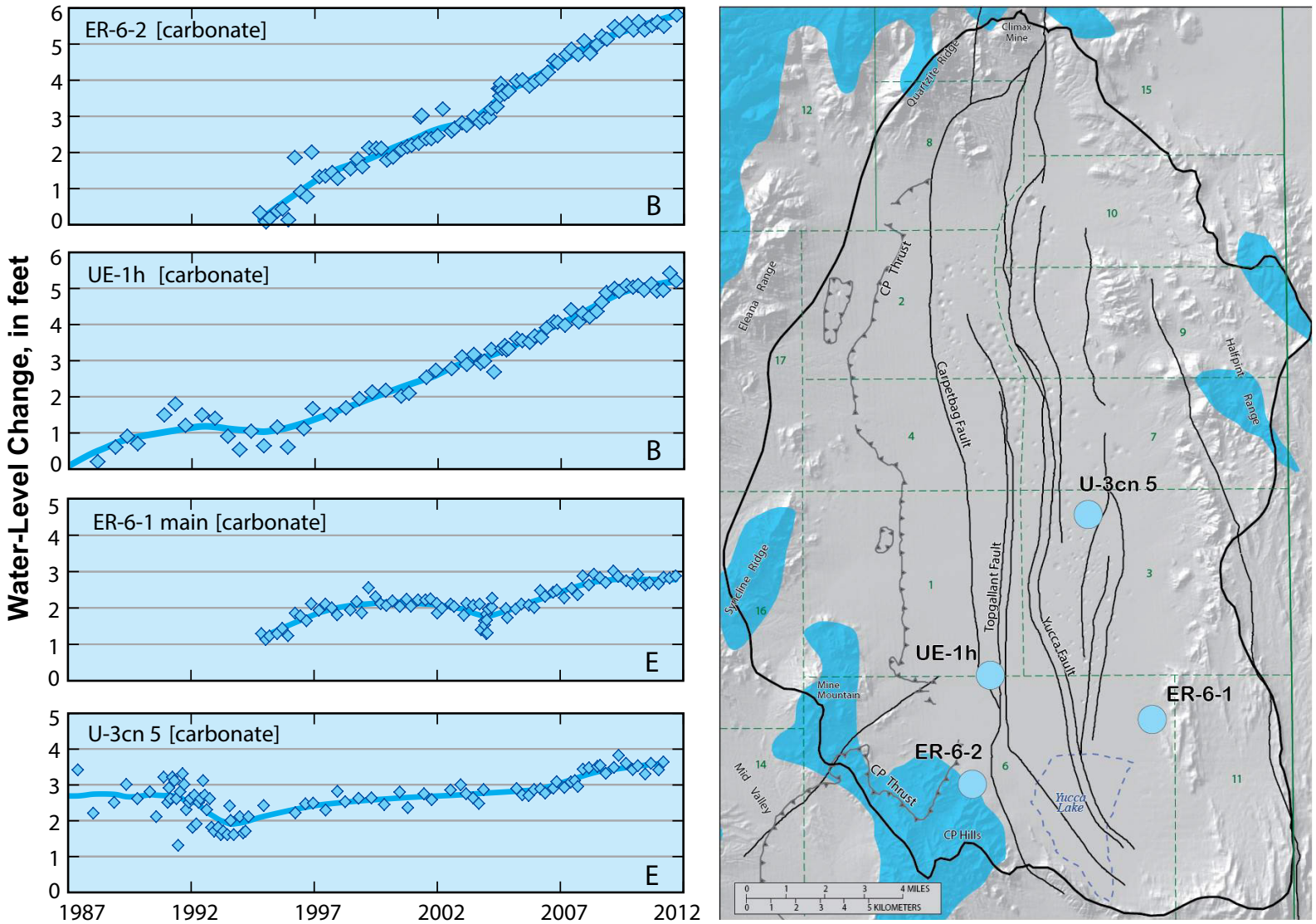



***Figure 3-7***
***Water-Level Transients in Selected Carbonate Aquifer Wells***
Source: Fenelon et al., 2012

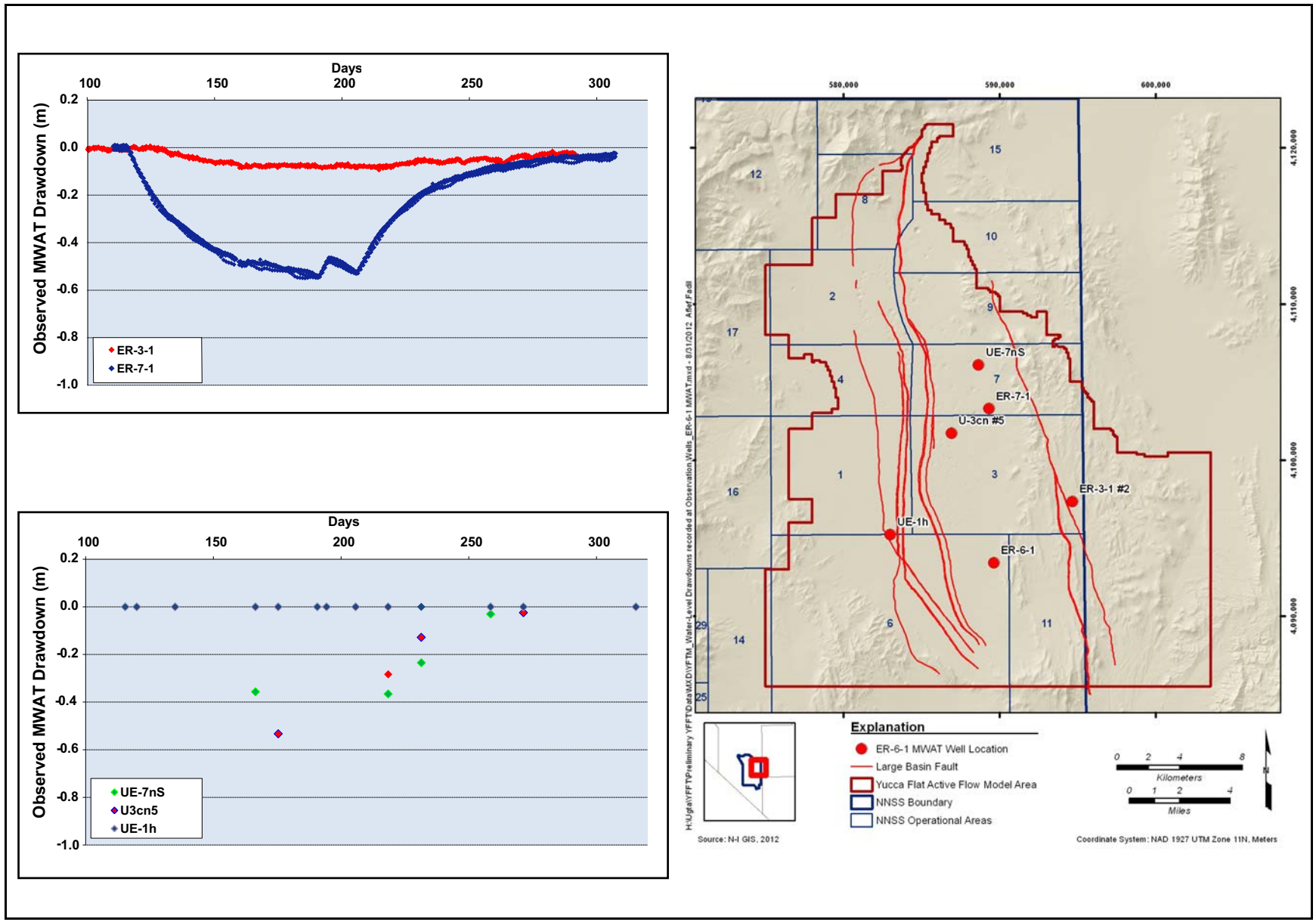



***Figure 3-8***
***Water-Level Responses from MWAT at ER-6-1 #2***
Source: N-I, 2013, Fig. 5-10

### 3.3 Water Budget Data

The local AA/VA system lies totally within the CAU boundaries, and is recharged by infiltration from the central portion of the basin and potentially from the higher elevation hills that border the basin (Figure 3-9).

The regional carbonate aquifer system is part of the larger regional aquifer system that contributes to the Ash Meadows Flow System, This system includes the Belted Range Tributary Flow System to the north of Yucca Flat and the Yucca Flat Tributary Flow System (Figure 2-5) (Fenelon et al., 2010). Water budget data for the regional groundwater flow system is available for the natural and anthropogenic discharge in the Death Valley Regional Flow System (DVRFS) model (Belcher et al., 2004), and these data, along with inferred infiltration distributions and estimated underflow from other groundwater flow basins, were used to calibrate the DVRFS model.

### 3.4 Hydraulic Properties Data

Hydraulic properties, notably permeability and hydraulic conductivity, have been measured for the AA, the TCUs, the tuff aquifers, and the carbonate aquifers. These measurements are summarized in the hydrologic data document (SNJV, 2006b).

Unsaturated zone alluvium permeability examples are illustrated in Figure 3-10. TCUs and tuff aquifer permeabilities are summarized in Figure 3-11. The range of hydraulic conductivities derived from aquifer-scale testing of the LCA is illustrated in Figure 3-12.

### 3.5 Water-Quality and Temperature Data

The groundwater quality (i.e., geochemistry and stable isotope concentrations) and temperature have been measured, and the data are summarized in Stoller-Navarro Joint Venture (SNJV) documents (2006a, 2006b, and 2007).

The geochemical and stable isotopic data were used to define the probable groundwater flow paths in the LCA (Figure 3-13). Radiocarbon data were used to estimate groundwater ages and infer LCA groundwater velocities (Figure 3-14). The temperature data constrain the general groundwater flow in the center of Yucca Flat (Figure 3-15). These data have been used to corroborate the general groundwater flow in the LCA.

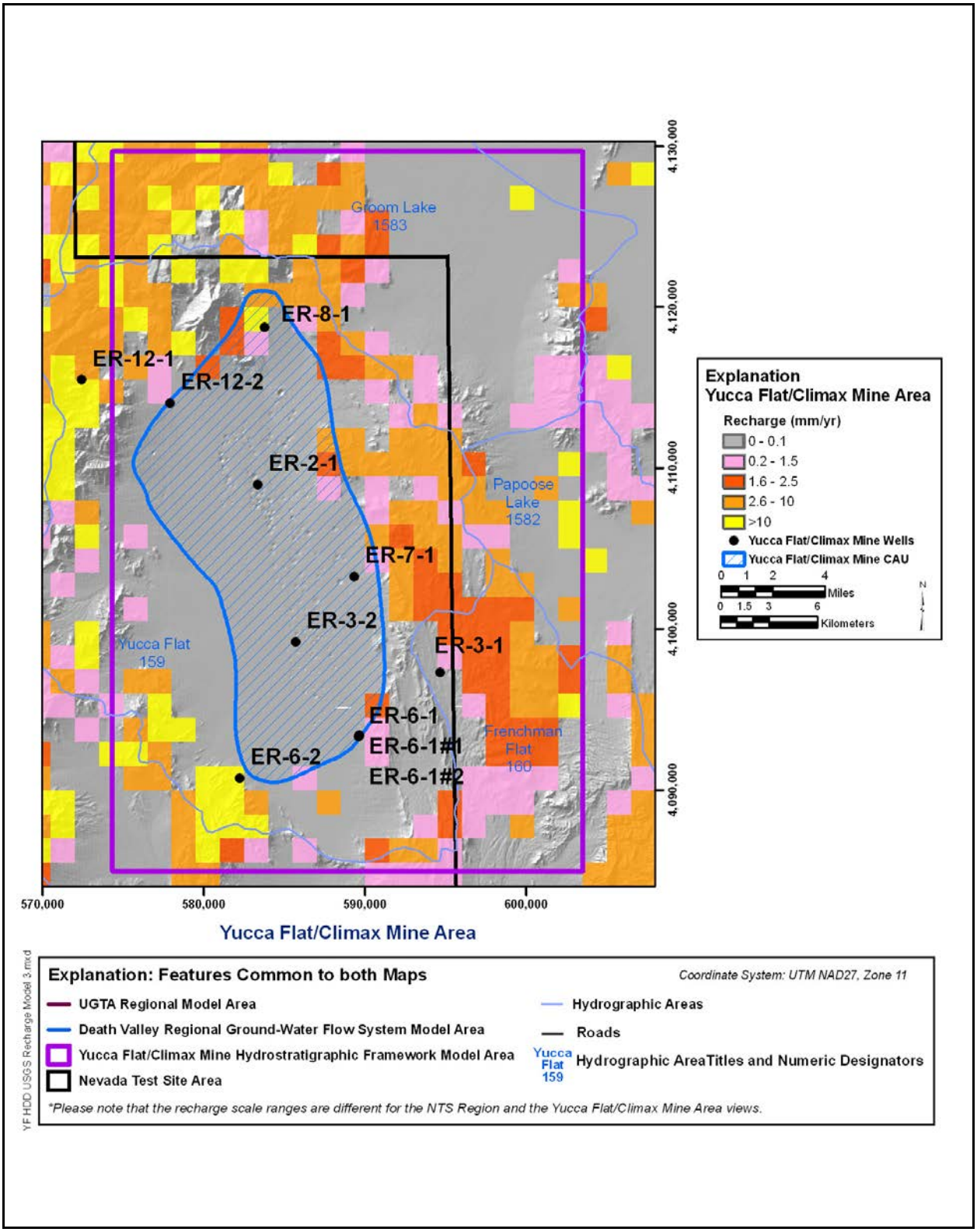
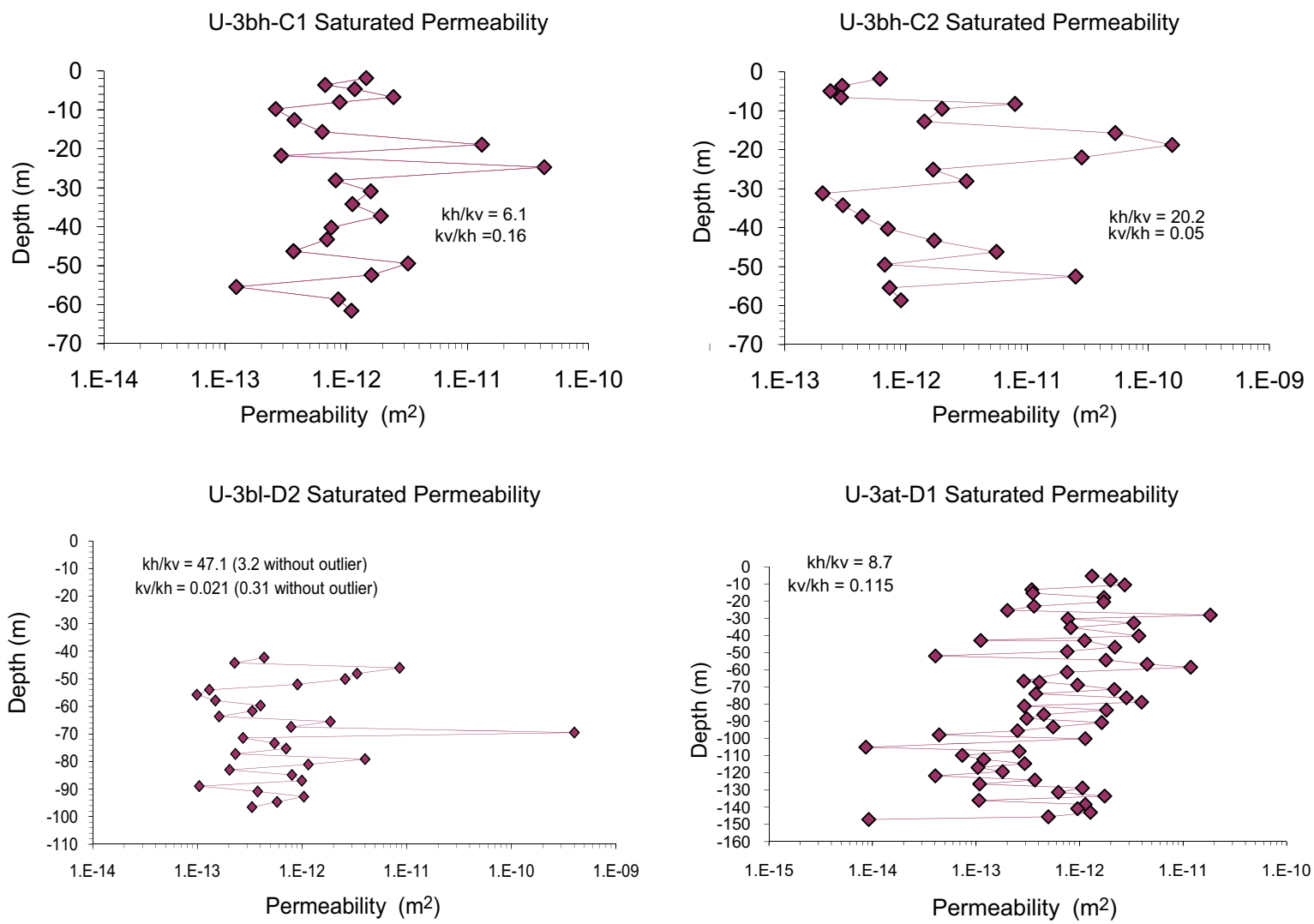



***Figure 3-9***
***Estimated Net Infiltration in the Vicinity of the YF/CM CAU***
Source: SNJV, 2006b




Note: Boreholes U-3bh-C1 and U-3bh-C2 are vertical holes drilled entirely within the U-3bh collapse crater. Boreholes U-3-bl-D2 and U-3at-D1 are angle holes that begin in undisturbed areas but penetrate the collapse zones beneath the U-3bl and U-3at craters at depth.

***Figure 3-10***
***Representative Permeability Measurements of the Alluvium in the Unsaturated Zone***
Source: N-I, 2013, Fig. 3-24

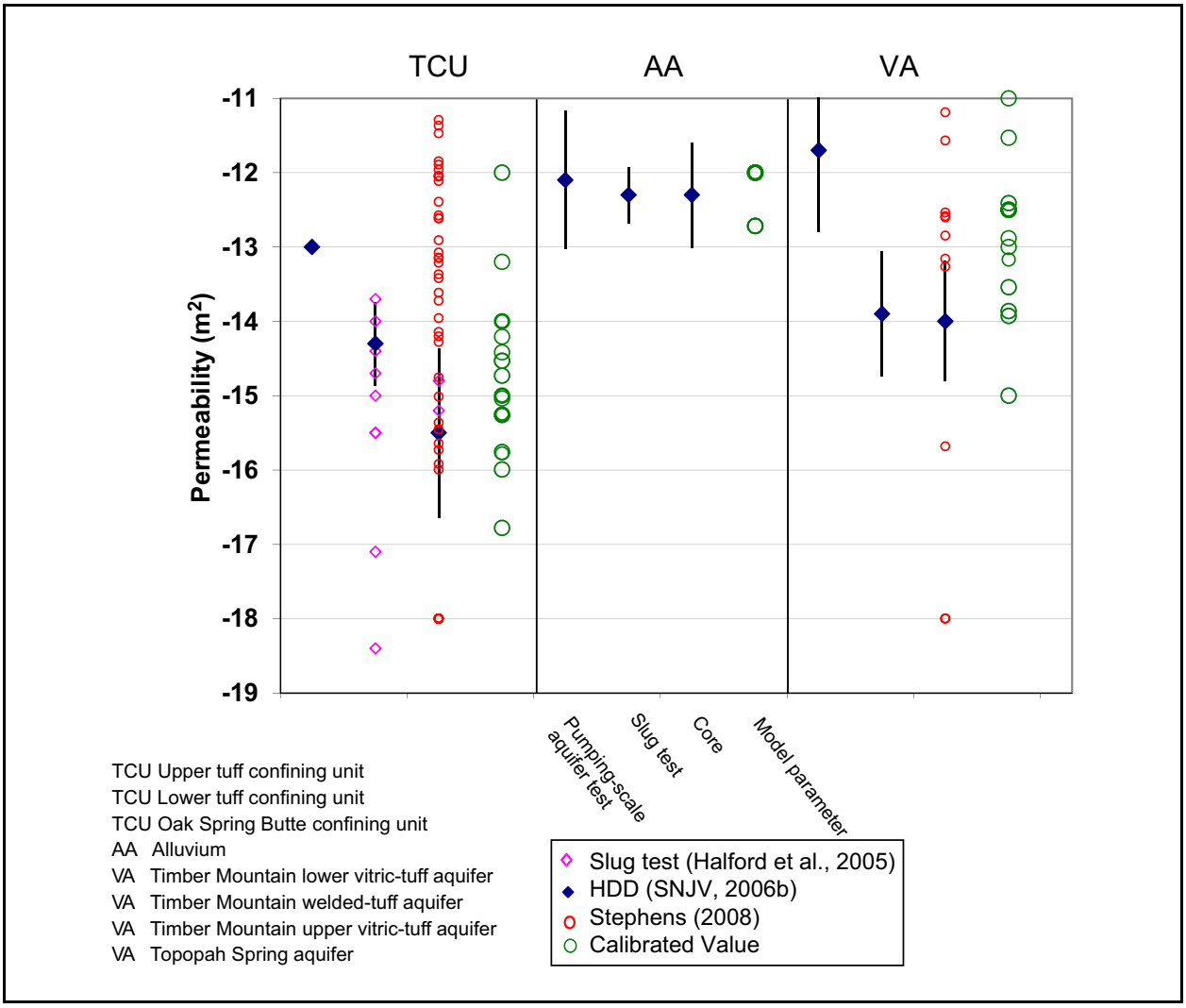



***Figure 3-11***
***Range of Measured Permeability of the TCU, AA, and VAs***
Source: N-I, 2013, Fig. 4-12

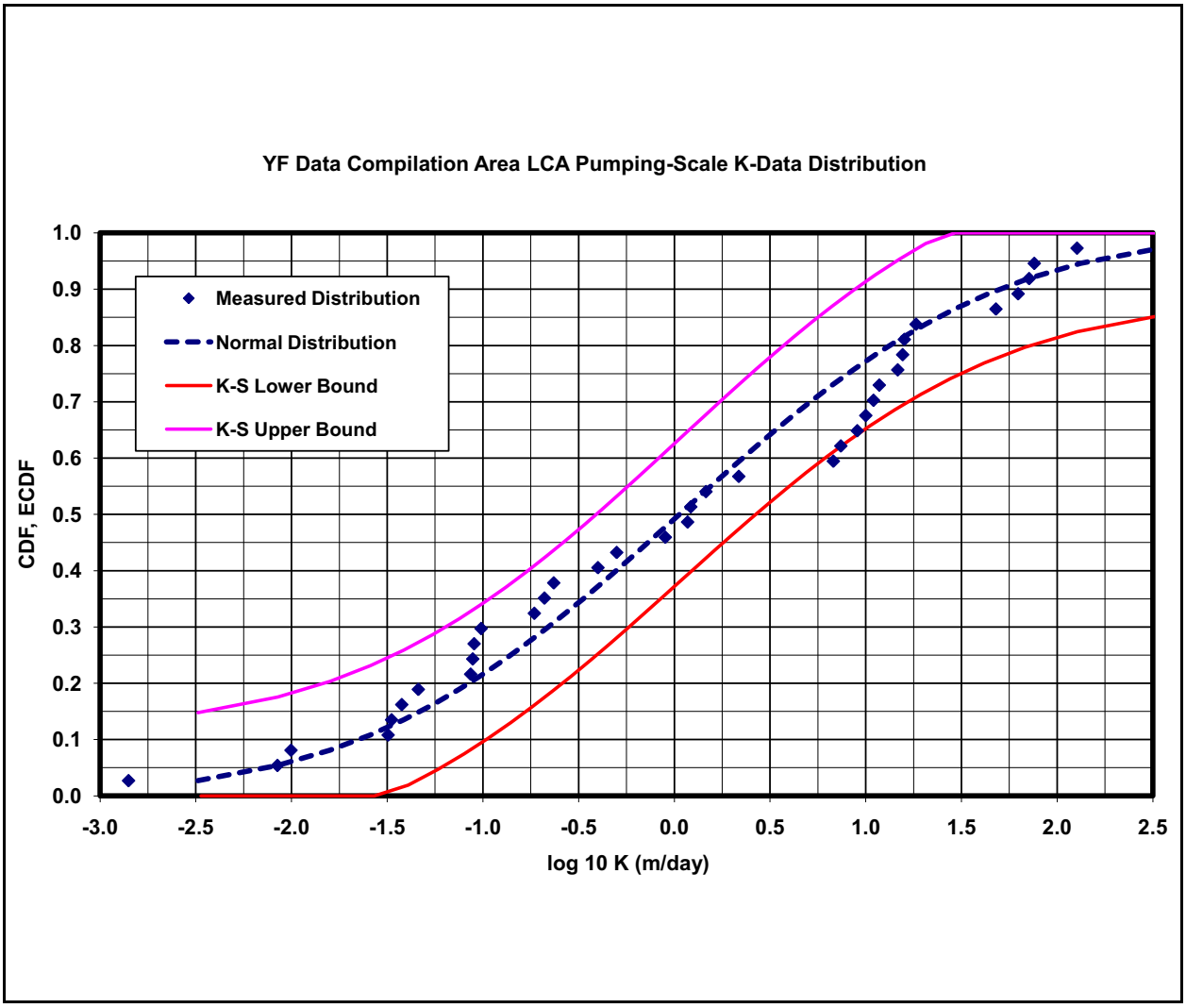



***Figure 3-12***
***Range of Hydraulic Conductivity from Aquifer Tests in the LCA***
Source: SNJV, 2006b, Fig. 6-19

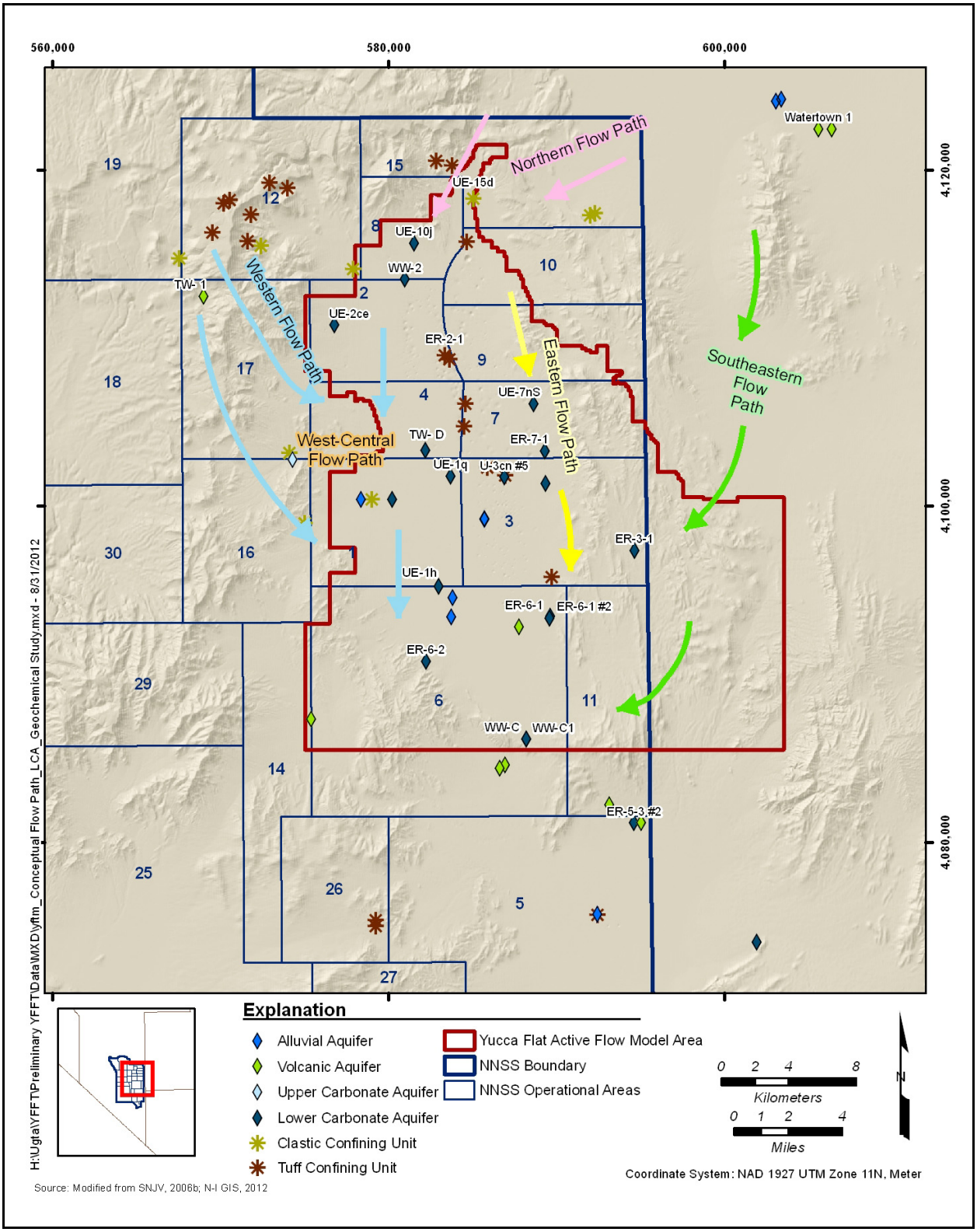



***Figure 3-13***
***Interpreted Groundwater Flow Paths in the LCA Inferred from Geochemical Data***
Source: SNJV, 2006b, Fig. 12-12

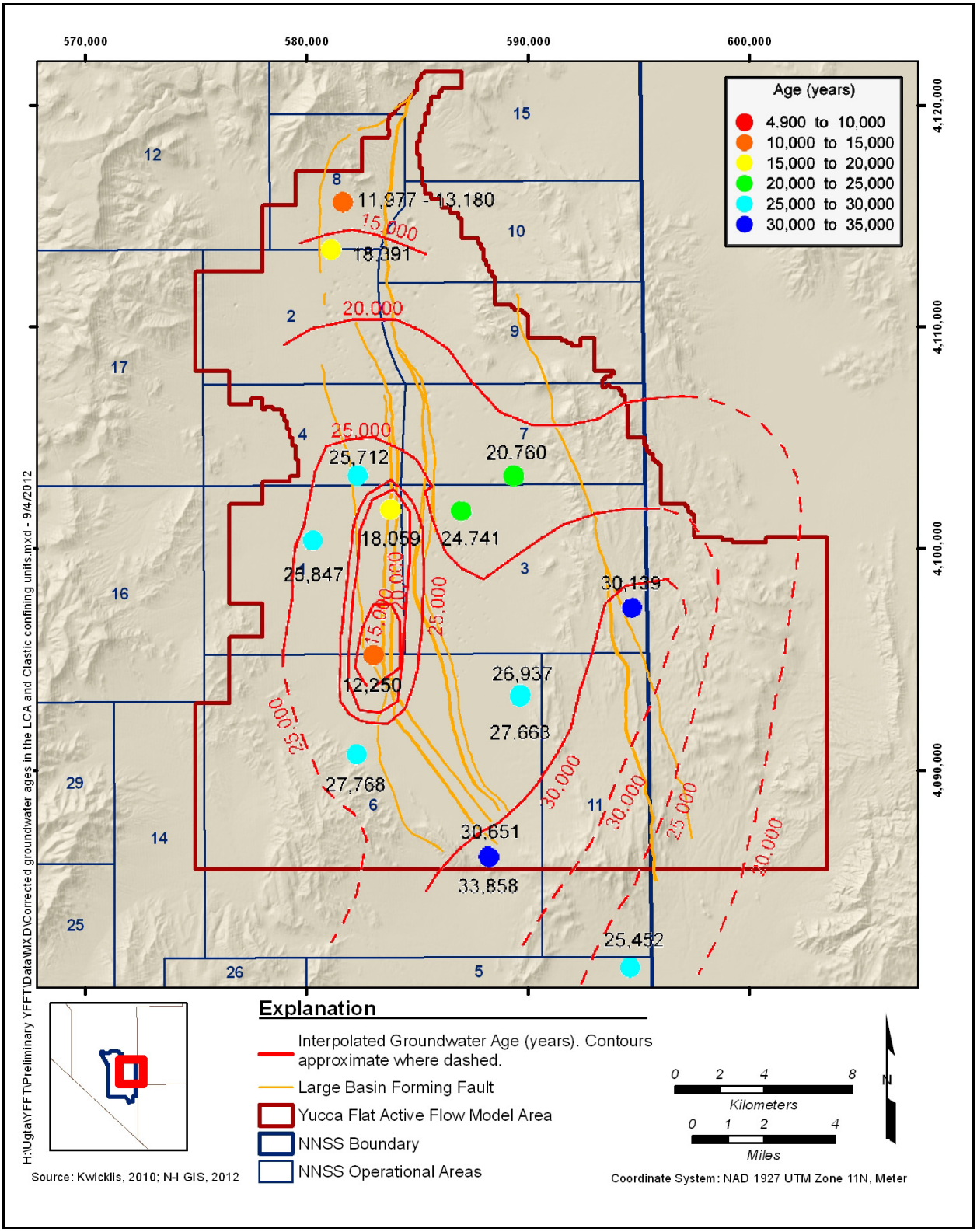



***Figure 3-14***
***Groundwater Ages in the LCA Inferred from $^{14}C$ Data***
Source: N-I, 2013, Fig. 5-14

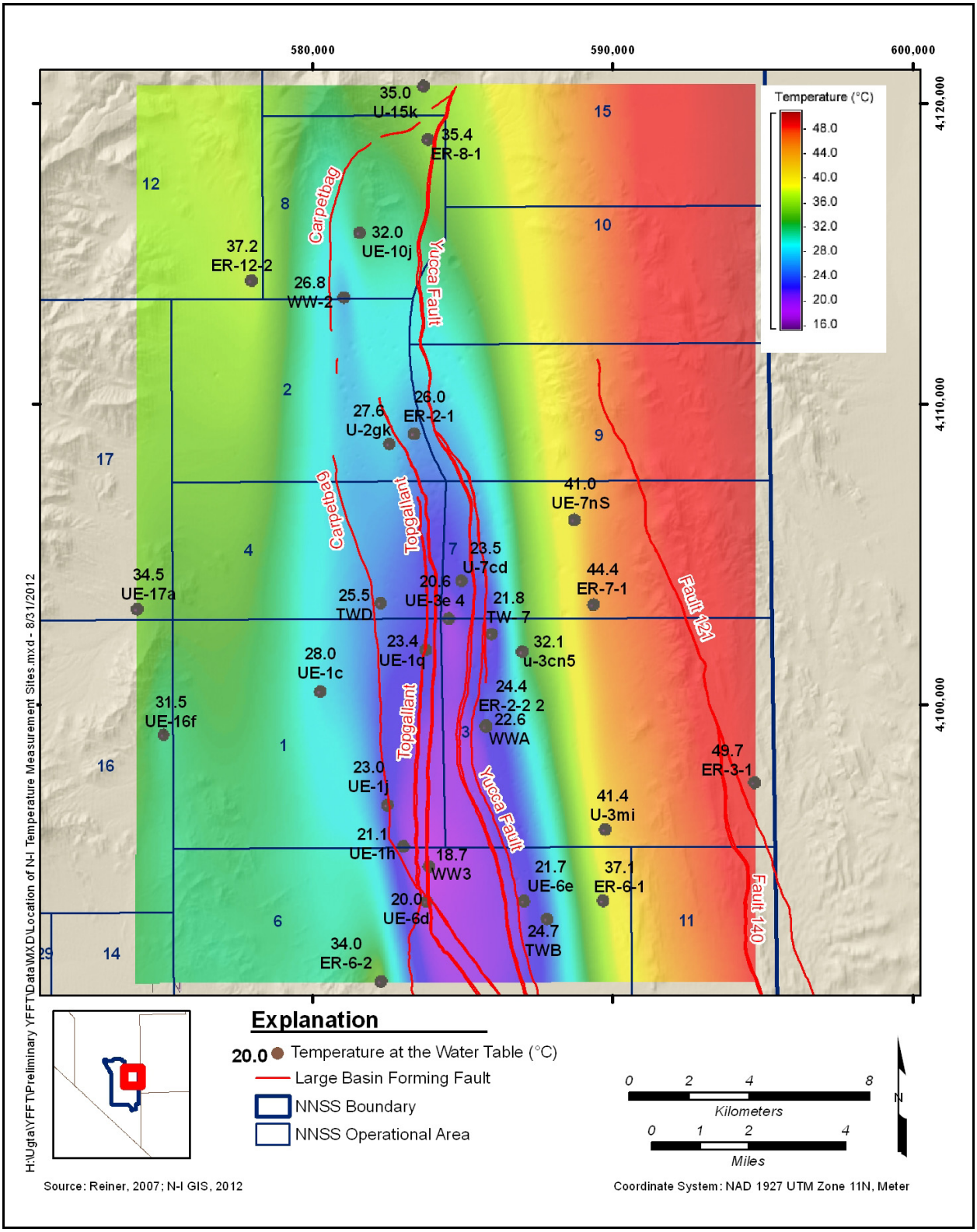



***Figure 3-15***
***Temperature at 1,500 ft (457 m) below Land Surface in the Yucca Flat Area***
Source: N-I, 2013, Fig. 5-16

## 3.6 Radionuclide Transport Parameter Data

Radionuclide transport parameter data used to define parameter distributions for the radionuclide transport models are summarized in the transport parameter document (SNJV, 2007) and included the following:

- Field tracer tests to define the LCA fracture porosity
- Permeability field measurements to develop fracture aperture estimates
- Fracture spacing borehole observations
- Matrix porosity and tortuosity laboratory measurements to define the matrix diffusion parameters
- Laboratory measurements of radionuclide sorption on fracture surfaces and the matrix
- Laboratory measurements of colloid sorption/desorption parameters

An *in situ* tracer test was performed as part of the ER-6-1 #2 MWAT conducted in the LCA. The test used different tracers in two injection zones in the ER-6-1 well upgradient of the ER-6-1 #2 pumping well. The results are illustrated in Figure 3-16. The time of peak tracer arrival was used to define the LCA fracture porosity.

Examples of matrix sorption coefficents ($K_d$) for key sorbing radionuclides are illustrated in Figure 3-17. These data along with similar data for other relevant HSUs were used to exclude several radionuclides in the source term inventory summarized in Table 2-1 and from the unsaturated zone and saturated AA/VA system transport models (N-I, 2013).

## 3.7 Radionuclide Contamination Data

Several wells in the CAU have been sampled over the last decades during and after underground nuclear testing. These wells were used for a variety of purposes and sampling for radionuclide contamination had varied objectives. Sampling locations are identified in Figures 3-18 and 3-19 for the alluvial/tuff aquifer system wells and the LCA/LCA3 wells, respectively. Radionuclide concentrations in “near-field” or “hot wells” were used to develop the HST. The more distal or “far-field” well radionuclide concentrations were compared to modeled radionuclide concentrations. Table 3-1 summarizes the sampling results at the various CAU wells.

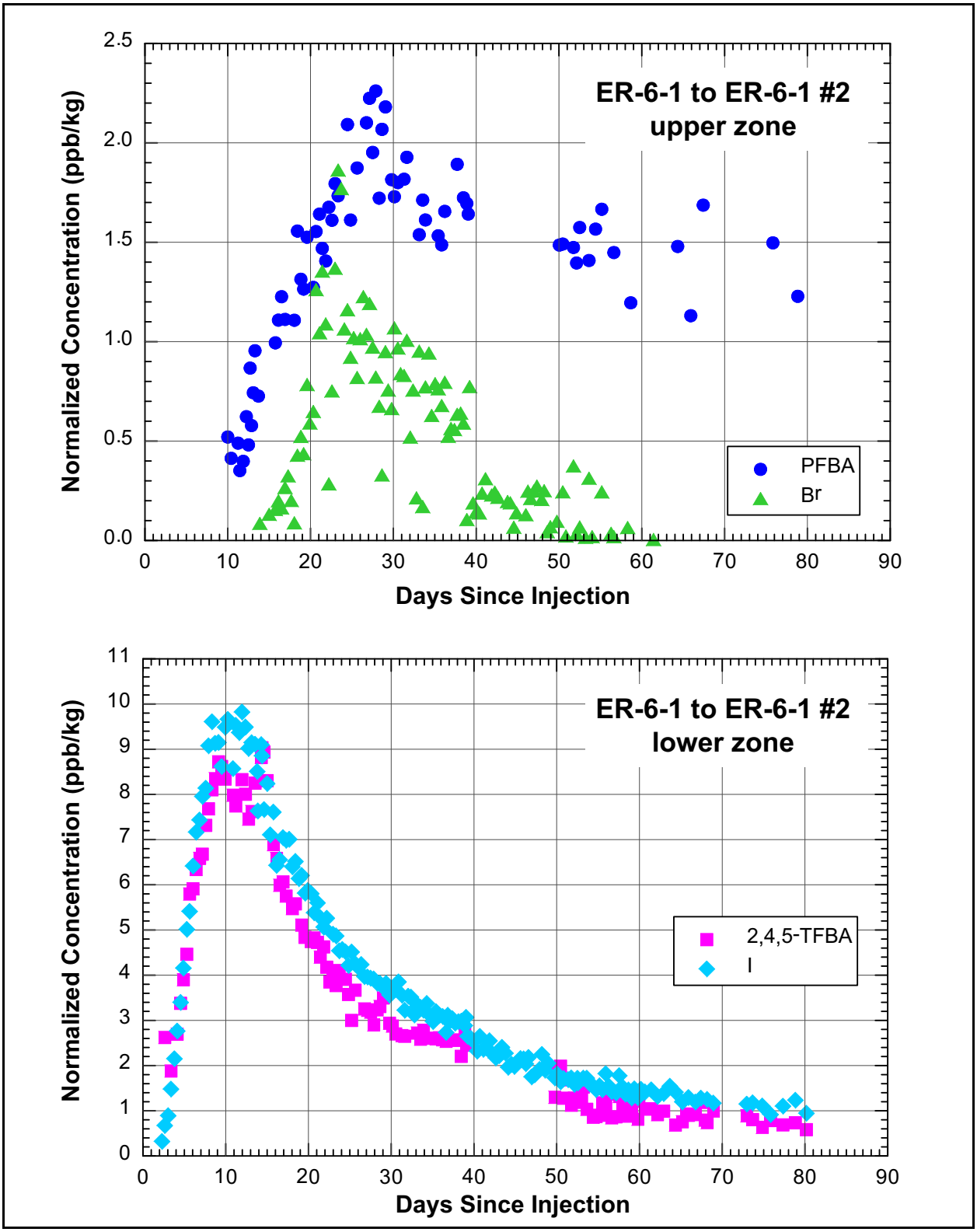



***Figure 3-16***
***Tracer Recovery from ER-6-1 #2 MWAT Tracer Test***
Source: Modified from SNJV, 2006d

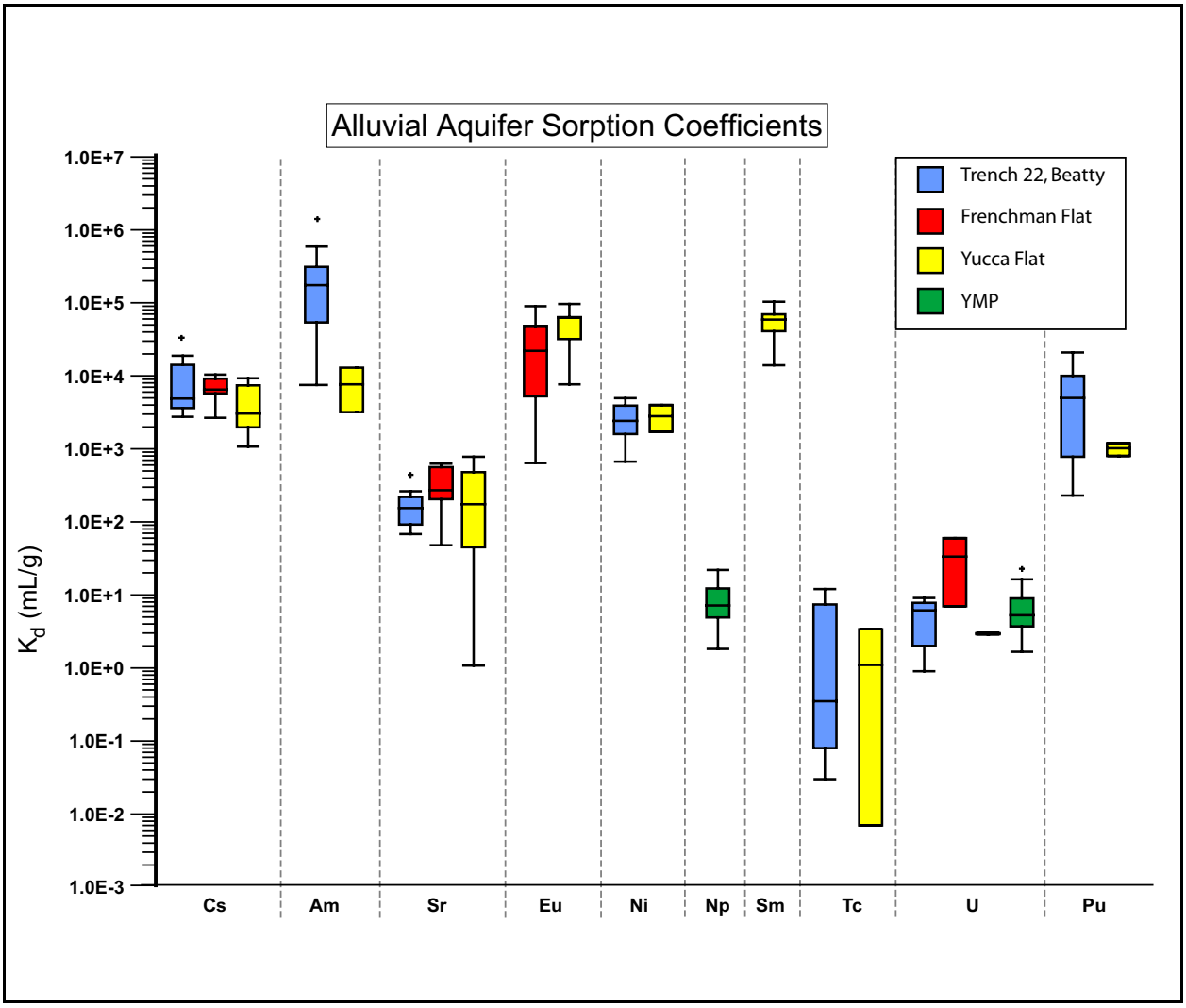



***Figure 3-17***
***Laboratory Sorption Coefficients for the AA***
Source: SNJV, 2007

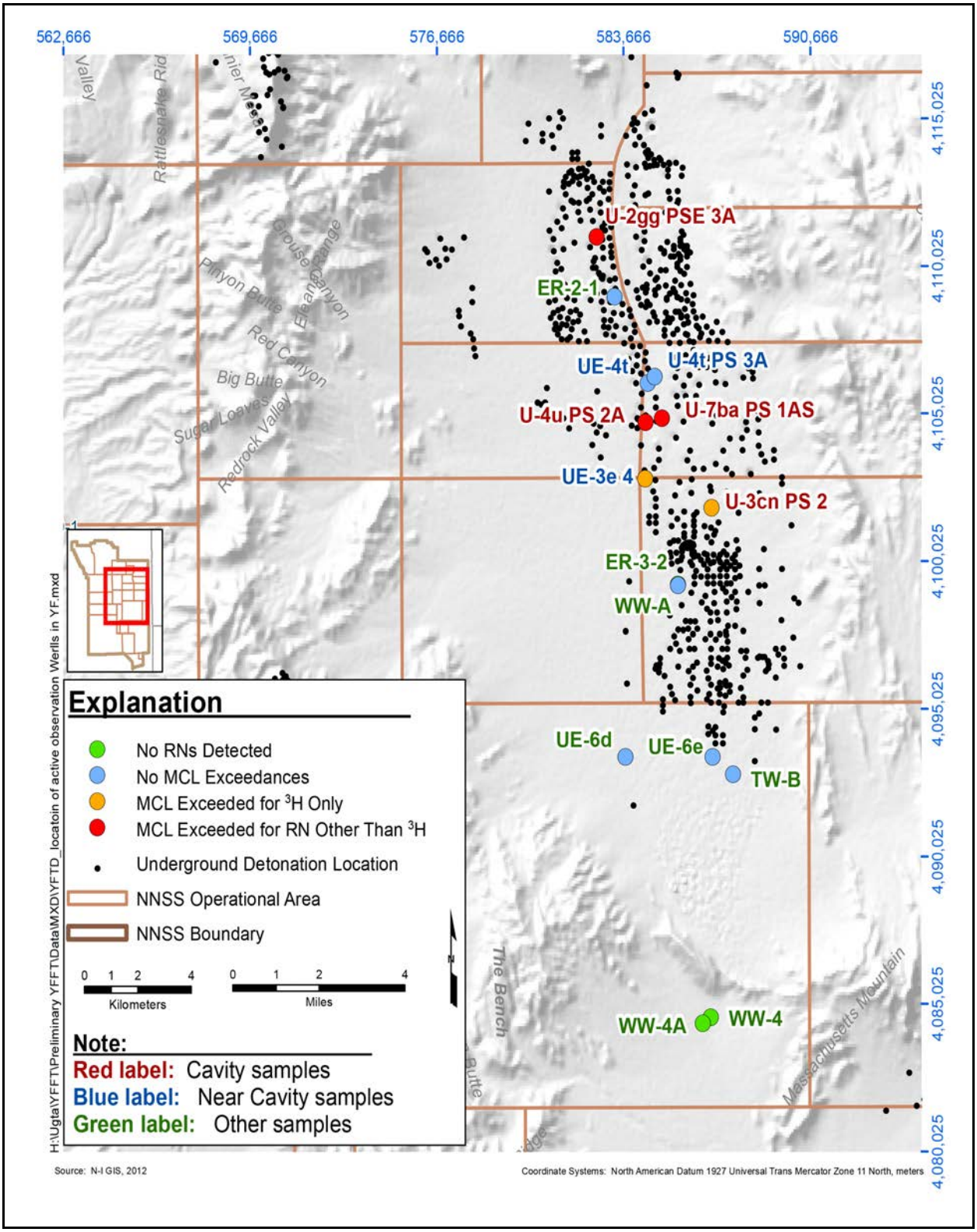



***Figure 3-18***
***Location of Observation Wells Used for Groundwater Sampling in the AA/VA System***
Source: Modified from N-I, 2013, Fig. D-1

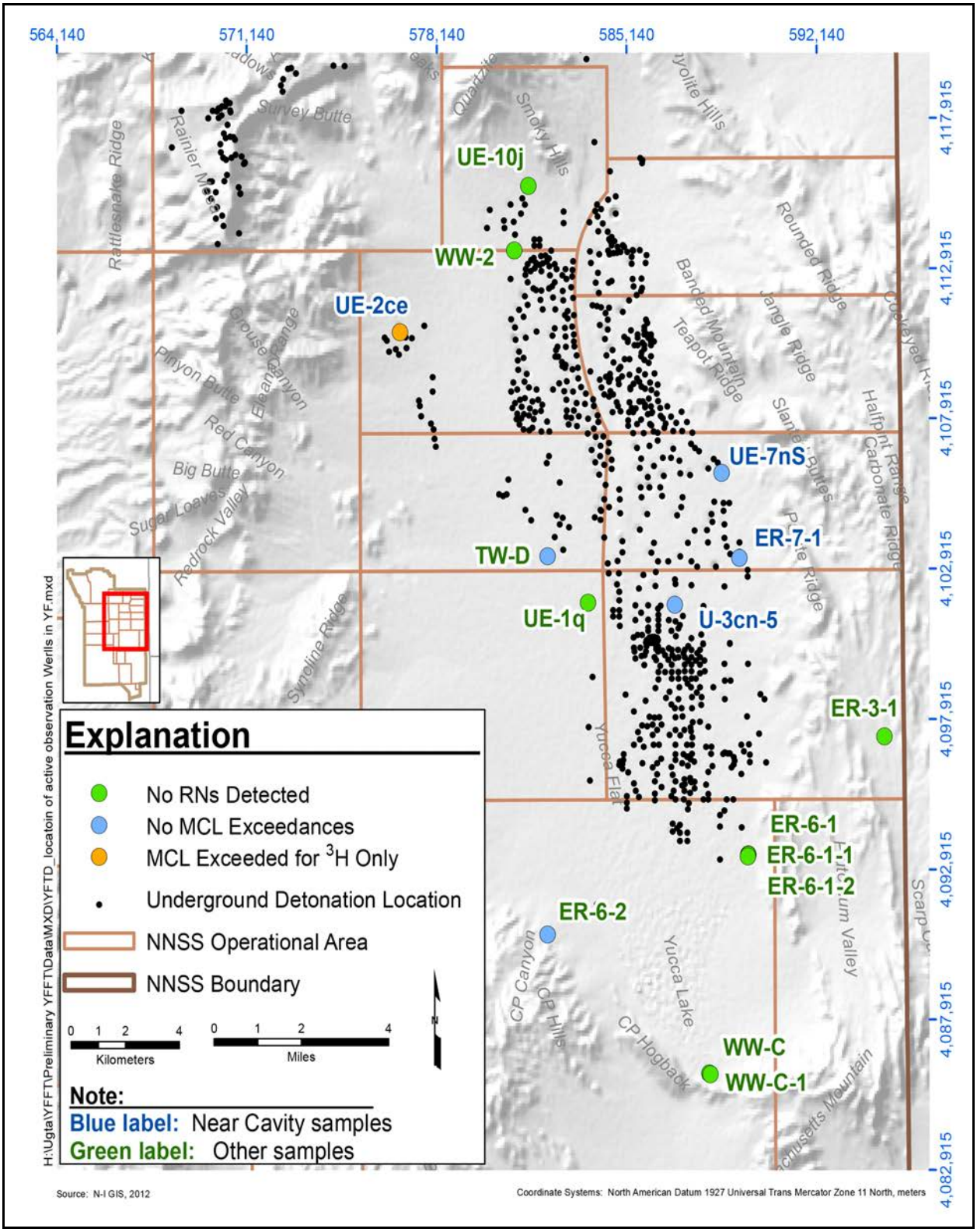



***Figure 3-19***
***Location of Observation Wells Used for Groundwater Sampling in the LCA and LCA3***
Source: Modified from N-I, 2013, Fig. D-1

***Table 3-1***
***Summary of Radionuclide Data from Sampled Observations Wells in Yucca Flat***
*(Page 1 of 6)*

| Well | NNSS Area | HSU Open to Well | Sample Dates | Radioisotopes Analyzed and Corresponding Results |
|---|---|---|---|---|
| **Near-Field Wells Completed in the AA/VA System** | | | | |
| U-2gg PSE 3A | 2 | TMLVTA | 09/21/1994 (597 m bgs bailed), 09/22/1994 (587 m bgs bailed) (see Section D.2.5 of N-I [2013] for more details) | • For the 09/21/1994 sample, $^{3}$H was reported as 5.4E+03 and 7.6E+03 pCi/L,$^{14}$C as 6.0E+03 pCi/L, $^{137}$Cs as 2.7 pCi/L, and Pu as <2.7E-03 pCi/L.<br>• For the 09/22/1994 sample, $^{3}$H was reported as 6,490 pCi/L, $^{14}$C as 19,900 pCi/L, and $^{137}$Cs as 0.9 pCi/L, and Pu as <3.1E-03 pCi/L. |
| U-3cn PS 2 | 3 | OSBCU | Samples were collected frequently during 1964 to 1966 hydraulic testing, 1977, 1981, 1982, 1983, 1985, 1997, 2001, 2004, and 2007 (see Section D.3.1 of N-I [2013] for more details). | • During 1964–1966 hydraulic tests, $^{3}$H ranged from 2.1E+08 to 2.7E+08 pCi/L, $^{90}$Sr was reported as 0.4 pCi/L, and $^{137}$Cs ranged from 3 to 5 pCi/L at 579–792 m; $^{3}$H ranged from 9.8E+05 to 9.5E+07 pCi/L at 512–527 m (no $^{137}$Cs or $^{90}$Sr results were reported for this sampling interval).<br>• $^{3}$H in subsequent samples ranged from 7.7E+06 pCi/L (2007) to 4.6E+07 pCi/L (1981), $^{14}$C from 171 pCi/L (1997) to 372 pCi/L (2004), $^{36}$Cl from 0.3 pCi/L (1997) to 63 pCi/L (2004), $^{90}$Sr from 0.06 pCi/L (1983) to 2.4 pCi/L (1997), $^{99}$Tc from 36 pCi/L (2007) to 80 pCi/L (1997), $^{129}$I from 0.2 pCi/L (2007) to 0.5 pCi/L (1997), $^{137}$Cs from 1.1 pCi/L (1997) to 3.7 pCi/L (1977), and Pu from 2E-03 pCi/L (1985) to 6E-02 pCi/L (2007). |
| U-4t PS 3A | 7 | LTCU | 1993 and 2008 (bailed; see Section D.2.4 of N-I [2013] for more details). | • For the 1993 samples (311 and 322 m), a high variability in $^{3}$H (1.1E+03 to 6.7E+04 pCi/L) was observed.<br>• For the 2008 sample, $^{3}$H was reported as 3.0E+03 pCi/L, $^{14}$C as 0.87 pCi/L, $^{36}$Cl as <4.9E-03 pCi/L, $^{129}$I as 2.5E-04, and Pu as <1.5E-03 pCi/L. |
| U-4u PS 2A | 7 | LTCU | 1992, 1993, 1997, 1998, 1999, 2003, 2008 (bailed at 472-, 484-, and 504-m depths; see Section D.2.3 of N-I [2013] for more details). | • For the 1992 samples, $^{3}$H was reported as 5.8E+07 pCi/L (504 m).<br>• For the 1993 samples, $^{3}$H ranged from 4.9E+07 pCi/L (533 m) to 5.3E+07 pCi/L (484 m), $^{137}$Cs from 2.0 pCi/L (533 m) to 600 pCi/L (504 m), and Pu was 0.14 pCi/L (533 m).<br>• For the 1997 samples, $^{3}$H was reported as 1.6E+07 pCi/L (472, 484, and 512 m); $^{14}$C was reported as 47 pCi/L, $^{90}$Sr as 3.1 pCi/L, $^{137}$Cs as 66 pCi/L, and $^{239/240}$Pu as 0.2 pCi/L for samples collected at 512 m.<br>• For the 1998 samples, $^{3}$H was reported as 1.5E+07 to 2.2E+07 pCi/L, $^{14}$C as 238 pCi/L, $^{36}$Cl as 8.5 pCi/L, $^{99}$Tc as 16 pCi/L,$^{137}$Cs as 43 to 75 pCi/L, and $^{239/240}$Pu as 0.12 pCi/L.<br>• For the 1999 samples, $^{3}$H was reported as 1.6E+07 pCi/L,$^{14}$C as 229 pCi/L, $^{36}$Cl as 8.5 pCi/L, and $^{239/240}$Pu as 1.2 pCi/L.<br>• For the 2003 samples, $^{3}$H was reported as 2.7E+07 pCi/L, $^{14}$C as 326 pCi/L, $^{36}$Cl as 29 pCi/L, $^{129}$I as 0.13 pCi/L, $^{99}$Tc as 35 pCi/L, and $^{239/240}$Pu as 0.32 pCi/L.<br>• For the 2008 samples, $^{3}$H was reported as 2.4E+07 pCi/L, $^{14}$C as 402 pCi/L, $^{36}$Cl as 19 pCi/L, $^{129}$I as 0.15 pCi/L, $^{99}$Tc as 26 pCi/L, and $^{239/240}$Pu as 0.44 pCi/L. |
| U-7ba PS 1AS | 7 | LTCU | 07/19/1995 (bailed at 366-, 427-, 488-, 549-, and 584-m depths; see Section D.2.2 of N-I [2013] for more details). | • $^{3}$H increased with depth (5.5E+06 pCi/L to 4.3E+07 pCi/L).<br>• $^{137}$Cs was reported as 65 pCi/L (366 m), 4.7E+04 pCi/L (427 m), 6.9E+04 pCi/L (488 m), 3.4E+04 pCi/L (549 m), and 1.3E+05 pCi/L (584 m). |

***Table 3-1***
***Summary of Radionuclide Data from Sampled Observations Wells in Yucca Flat***
*(Page 2 of 6)*

| Well | NNSS Area | HSU Open to Well | Sample Dates | Radioisotopes Analyzed and Corresponding Results |
|---|---|---|---|---|
| **Near-Field Wells Completed in the AA/VA System** (continued) | | | | |
| UE-3e 4 P1 | 3 | LTCU | 1990, 1991, 1992, 1993, 1998, and 2009 (bailed; see Section D.2.1 of N-I [2013] for more details). | • $^{3}$H ranged from 3.3E+05 to 1.8E+07 pCi/L.<br>• For the 1993 samples, $^{14}$C and $^{239,240}$Pu were reported below the MDL (3,200 and 0.06 pCi/L, respectively).<br>• For the 2009 samples, $^{14}$C was reported as 1.3 pCi/L, $^{36}$Cl as 0.73 pCi/L, $^{99}$Tc as 2.1 pCi/L, $^{129}$I as 6.8E-03 pCi/L, and $^{239,240}$Pu as <3.1E-04 pCi/L. |
| UE-3e 4 P2 | 3 | LTCU | 1990, 1991, 1992, 1993, 1998, and 2009 (bailed; see Section D.2.1 of N-I [2013] for more details). | • $^{3}$H decreased from 3.3E+06 to 2.2E+03 pCi/L from 1990 to 2009.<br>• For the 1993 sample, $^{14}$C, $^{137}$Cs, and $^{239,240}$Pu were reported below the MDL (3,200, 0.28, and 0.08 pCi/L, respectively).<br>• For the 2009 sample, $^{14}$C was reported as 0.012 pCi/L, $^{36}$Cl as 3.6E-04 pCi/L, $^{99}$Tc as 1.9 pCi/L, and $^{129}$I as 1.7E-04 pCi/L. |
| UE-3e 4 P3 | 3 | TMLVTA | 1990, 1991, 1992, 1993, 1998, and 2009 (bailed; see Section D.2.1 of N-I [2013] for more details). | • $^{3}$H decreased from 3.3E+06 to 1.4E+05 pCi/L from 1990 to 2009.<br>• For the 1993 sample, $^{14}$C was reported as 4.8E+03 pCi/L; and $^{137}$Cs and $^{239,240}$Pu were reported below the MDL (0.47 and 0.08 pCi/L, respectively).<br>• For the 2009 samples, $^{14}$C was reported as 0.11 pCi/L, $^{36}$Cl as 6.6E-02 pCi/L, $^{129}$I as 5.6E-04 pCi/L, and $^{239,240}$Pu as <3.1E-04 pCi/L. |
| UE-4t 1 | 7 | LTCU | 1990, 1992, 2000, and 2008 (bailed; see Section D.2.4 of N-I [2013] for more details). | • $^{3}$H was reported below or near MDLs (8.4 to 1,080 pCi/L) for the 1990, 1992, and 2000 samples.<br>• For the 2008 sample, $^{3}$H was reported as 68 pCi/L, $^{14}$C as 0.097 pCi/L, $^{36}$Cl as 2.7E-04 pCi/L, and $^{129}$I as 3.4E-05 pCi/L. |
| UE-4t 2 | 7 | LTCU | 2000 and 2008 (bailed; see Section D.2.4 of N-I [2013] for more details). | • For the 2000 sample, $^{3}$H activities was reported below the MDL (10.4 pCi/L).<br>• For the 2008 sample, $^{3}$H was reported as 1.7E+03 pCi/L, $^{14}$C as 0.061 pCi/L, $^{36}$Cl as 5.1E-04 pCi/L, and $^{129}$I as 4.2E-04 pCi/L. |

## *Table 3-1*
## *Summary of Radionuclide Data from Sampled Observations Wells in Yucca Flat*
*(Page 3 of 6)*

| Well | NNSS Area | HSU Open to Well | Sample Dates | Radioisotopes Analyzed and Corresponding Results |
|---|---|---|---|---|
| **Near-Field Wells Completed in the LCA/LCA3** | | | | |
| ER-7-1 | 7 | LCA | 07/02/2003 (719 m bgs bailed), 07/17/2003 (pumped) | • For the 07/02/2003 sample, $^{3}$H, $^{14}$C, $^{137}$Cs, and Pu were reported below the MDL.<br>• For the 7/17/2003 sample, $^{3}$H was reported as ≤117 pCi/L, $^{14}$C as 1.6E-02 pCi/L and $^{36}$Cl as 1.2E-04 pCi/L; $^{90}$Sr, $^{99}$Tc, $^{129}$I, $^{137}$Cs, and Pu were reported below the MDL. |
| U-3cn 5 | 3 | LCA | Samples were collected frequently during 1965 to 1973 hydraulic testing. Additional sampling in 1980, 1981, 1997, 1998, 2000, 2011 (see Section D.3.1 of N-I [2013] for more details). | • During 1965-1973 hydraulic tests, $^{3}$H ranged from less than 1.3E+03 to 1.3E+08 pCi/L (671–727 m); 1.6E+06 to 3.2E+06 pCi/L (604–655 m); 1.6E+06 to 8.5E+06 pCi/L (560–604 m); and <1.3E+03 to 9.4E+04 pCi/L (863–893 m).<br>• $^{3}$H was reported below the MDL (10.9 to 1,200 pCi/L) for most samples following the hydraulic tests; $^{3}$H was reported as 2.9 pCi/L for 1980 sample and as 10.4 pCi/L for 1981 sample. $^{137}$Cs was reported as 0.003 pCi/L for the 1980 sample and below the MDL (0.001 to 101 pCi/L) for subsequent samples (1981 to 2000); $^{90}$Sr was reported as 7.0E-04 pCi/L for the 1980 sample, as 4.6E-04 pCi/L for the 1981 sample, and below the MDL (0.29 and 0.59 pCi/L, respectively) for 1997 and 2000 samples; $^{99}$Tc was reported below the MDL (2.1 pCi/L) for 1997 sample; and Pu was reported as 2.3E-04 pCi/L for 1980 sample and below the MDL (0.07 and 0.01 pCi/L, respectively) for 1997 and 2000 samples.<br>• For the 2011 sample, $^{3}$H was reported below the MDL (192 pCi/L), $^{14}$C as 0.033 pCi/L, $^{129}$I as 1.1E-06 pCi/L, and $^{137}$Cs as <0.04 pCi/L. |
| UE-2ce | 2 | LCA3 | Frequent pumped samples between 1977 to 1984; bailed in 1993, 2001, 2005; pumped in 2008 (see Section D.3.3 of N-I [2013] for more details). | • $^{3}$H ranged from 1.6E+04 to 3.4E+07 pCi/L, $^{90}$Sr ranged from 0.08 to 5.1 pCi/L, and $^{137}$Cs ranged from <4.5E-03 to 1.7 pCi/L in early samples (1977 to 1984).<br>• $^{3}$H ranged from 9.3E+04 to 1.5E+05 pCi/L, and Pu was below the MDL (0.04 to 0.09 pCi/L) in 1993, 2001, and 2005 bailed samples; $^{137}$Cs was <0.3 pCi/L in 1993 sample; and $^{14}$C, $^{36}$Cl, $^{99}$Tc, $^{129}$I were 0.8, 0.4, <0.002, 0.02 pCi/L, respectively in the 2005 sample.<br>• For the 2008 samples, $^{3}$H ranged from 1.2E+5 to 2.7E+5 pCi/L; $^{14}$C ranged from 0.88 to 1.11 pCi/L; and $^{36}$Cl, $^{99}$Tc, $^{129}$I were 1.3, 0.002, 0.01 pCi/L, respectively. |
| UE-7nS | 7 | LCA | Samples were collected between 1977 and 1984 at multiple depths (sampling information incomplete). Samples were collected at 620 m bgs by RREMP annually between 1994 and 2010, and in 1993, 2001, and 2005 by LLNL and LANL (see Section D.3.2 of N-I [2013] for more details). | • A general increasing trend in $^{3}$H activities (13 pCi/L to 2,850 pCi/L) was reported for samples collected between 1977 and 1984; sampling information including depth was not reported for the earliest samples.<br>• RREMP analyses included $^{3}$H, $^{14}$C, $^{90}$Sr, $^{99}$Tc, $^{137}$Cs, and Pu. $^{3}$H decreased from 550 pCi/L in 1995 to 41 pCi/L in 2010. All other radionuclides were below the MDL.<br>• For the 1993 samples, $^{3}$H was reported as 457 pCi/L, $^{14}$C as <3,200 pCi/L, $^{137}$Cs as <0.2 pCi/L, and $^{239,240}$Pu as <0.04 pCi/L.<br>• For the 2001 samples, $^{3}$H was reported as 4,600 pCi/L, $^{14}$C as 0.14 pCi/L, $^{36}$Cl as 1.4E-03 pCi/L, $^{129}$I as 6.1E-04 pCi/L, and $^{239,240}$Pu as <0.04 pCi/L by LLNL. LANL reported $^{3}$H as 386 to 3,320 pCi/L.<br>• For the 2005 samples, $^{3}$H was reported as 132 pCi/L, $^{14}$C as 0.14 pCi/L, $^{36}$Cl as 2.4E-04 pCi/L, $^{99}$Tc as <0.04 pCi/L, $^{129}$I as 4.1E-05 pCi/L, and $^{239,240}$Pu as <0.04 pCi/L. |

## *Table 3-1*
## *Summary of Radionuclide Data from Sampled Observations Wells in Yucca Flat*
*(Page 4 of 6)*

| Well | NNSS Area | HSU Open to Well | Sample Dates | Radioisotopes Analyzed and Corresponding Results |
|---|---|---|---|---|
| **Far-Field Wells Completed in the AA/VA System** | | | | |
| ER-2-1 | 2 | TMWTA, TMLVTA, LTCU | 09/03/2003 (pumped), 09/05/2003 (564 m bgs bailed) | • For the 09/03/2003 sample, $^{3}$H was reported as 228 pCi/L, $^{14}$C as 0.04 pCi/L, and $^{36}$Cl as 1.0E-04 pCi/L; $^{137}$Cs, $^{90}$Sr, $^{129}$I, and Pu were below the MDL; $^{99}$Tc was reported as 12 ± 4 pCi/L and 8 ± 4 pCi/L for duplicates (these values are near the 6 pCi/L MDL and considered highly uncertain).<br>• For the 09/05/2003 sample, $^{3}$H, $^{14}$C, $^{137}$Cs, and Pu were reported below the MDL. |
| ER-3-2 | 3 | AA | 1995, 1999, 2000 (451 and 774 m bgs bailed) | • $^{3}$H was reported below the MDL (10–164 pCi/L) for all samples.<br>• Pu was only analyzed in the 02/25/1999 sample and was reported below the MDL (0.05 pCi/L). |
| TW B | 6 | TSA | 1963, 1965, bailed monthly from 1976 to 1987, 1990, 1993, 1998 | • $^{90}$Sr was reported below the MDL (0.4 pCi/L) for the 1963 sample and $^{3}$H was reported as a nondetect for the 1965 sample.<br>• $^{3}$H was reported to decrease from 260 pCi/L to 158 pCi/L for the monthly samples, and was reported as 109 and 44 pCi/L for the 1990 and 1998 samples, respectively.<br>• For the 1993 sample, $^{36}$Cl, $^{99}$Tc, and $^{137}$Cs were reported as 6.8E-04, <5, and <0.7 pCi/L, respectively. |
| TW-7 (HTH) | 3 | LTCU | 1994 | • $^{3}$H was reported below the MDL (55 pCi/L). |
| UE-6d | 6 | PCUT, ATCU | 1994, 1995 | • $^{3}$H was reported as 710 pCi/L (1994) and 670 pCi/L (1995). |
| UE-6e | 6 | LTCU, OSBCU | 1994, 1995 | • $^{3}$H was reported as 12.5 pCi/L (1994) and 16 pCi/L (1995). |
| WW 4 | 6 | TMWTA | 1983 to 2010 (monthly to biannually) (pumped) | • For a 1993 sample, $^{3}$H was reported as 0.96 pCi/L, $^{36}$Cl as 3.1E-4 pCi/L, and $^{99}$Tc as <5 pCi/L.<br>• $^{3}$H, $^{14}$C, $^{90}$Sr, $^{99}$Tc, $^{137}$Cs, and Pu were reported below or near the MDL (values reported near the MDL are likely to be nondetects). Samples were primarily analyzed for $^{3}$H; other radionuclides were analyzed less frequently. The $^{3}$H MDLs ranged from 10 to 900 pCi/L. |
| WW 4A | 6 | TMWTA | 1994 and 1995 to 2010 (quarterly) (pumped) | • $^{3}$H, $^{14}$C, $^{90}$Sr, $^{99}$Tc, $^{137}$Cs, and Pu were reported below or near the MDL (values reported near the MDL are likely to be nondetects). Samples were primarily analyzed for $^{3}$H; other radionuclides were analyzed less frequently. The $^{3}$H MDLs ranged from 1.5 to 754 pCi/L. |
| WW A | 3 | AA | 1961, 1962, monthly between 1972 and 1987, 1990, and annually from 2000 to 2010 | • For the 1961 and 1962 samples, $^{90}$Sr was reported below the MDL (0.4 pCi/L).<br>• $^{3}$H was reported near or below the MDL for the majority of the monthly 1972 to 1987 samples. $^{3}$H was reported as 37 pCi/L for the final 1987 sample and as 170 pCi/L for the 1990 sample.<br>• $^{3}$H decreased from 573 to 342 pCi/L between 2001 and 2010. Gamma emitters, $^{14}$C, $^{90}$Sr, $^{99}$Tc, and $^{239,240}$Pu were reported near or below the MDL indicating their absence (values reported near the MDL are likely to be nondetects). |

## *Table 3-1*
## *Summary of Radionuclide Data from Sampled Observations Wells in Yucca Flat*
*(Page 5 of 6)*

| Well | NNSS Area | HSU Open to Well | Sample Dates | Radioisotopes Analyzed and Corresponding Results |
|---|---|---|---|---|
| **Far-Field Wells Completed in the LCA/LCA3** | | | | |
| ER-3-1 | 3 | LCA | 1995, 1996 (pumped) | • $^{3}$H was reported below the MDL (181–283 pCi/L) for both samples.<br>• Pu was analyzed in both samples and $^{137}$Cs was analyzed in the 11/09/1995 sample. Reported results were below the MDL.<br>• For the 11/09/1995 sample, $^{90}$Sr and $^{99}$Tc were reported below the MDL (0.6 and 25 pCi/L, respectively), and as 0.27 ± 0.13 and 3.2 ± 1.4 pCi/L, respectively for the 10/16/1996 sample; values are near the MDLs (0.2 and 2.2 pCi/L, respectively) and considered highly uncertain. |
| ER-6-1 | 6 | LCA | 10/09/1992, 11/23/1992, 1999 to 2004 (bailed annually), 01/28/2004 (pumped) | • $^{3}$H was reported below the MDL (0.96–360 pCi/L) for all samples.<br>• $^{14}$C, $^{90}$Sr, $^{99}$Tc, $^{129}$I, $^{137}$Cs, and Pu were reported below the MDL throughout the sampling period; these radionuclides were not analyzed in all samples.<br>• $^{36}$Cl was reported as 1.3E-04 pCi/L for the 11/23/1992 sample. |
| ER-6-1-2 | 6 | LCA | 2003 (pumped), 2004 (701 m bgs bailed) | • For the 2003 sample, $^{3}$H was reported as ≤30.8 pCi/L; $^{14}$C as 7.4E-03 pCi/L $^{36}$Cl as 1.4E-04 pCi/L; and $^{90}$Sr, $^{99}$Tc, $^{129}$I, $^{137}$Cs, $^{237}$Np, and Pu were reported below the MDL.<br>• For the 2004 sample, $^{3}$H, $^{14}$C, $^{137}$Cs, and Pu were reported below the MDL. |
| ER-6-2 | 6 | LCA3 | 07/20/2004 (823 m bgs bailed), 08/04/2004 (pumped) | • For the 07/20/2004 sample, $^{3}$H, $^{14}$C, $^{137}$Cs, and Pu were reported below the MDL.<br>• For the 08/04/2004 sample, $^{3}$H was reported as 92 pCi/L, $^{14}$C as 8.1E-03 pCi/L, and $^{36}$Cl as 1.6E-04 pCi/L; $^{90}$Sr, $^{99}$Tc, $^{129}$I, $^{137}$Cs, and Pu were reported below the MDL. |
| HTH 2 | 8 | LCA | 1962, 1989 to 2006 (monthly to annually) | • For a 2006 sample, $^{3}$H and $^{36}$Cl were reported as <1 and 1.5E-04 pCi/L, respectively.<br>• Gamma emitters, $^{3}$H, $^{14}$C, $^{90}$Sr, $^{99}$Tc, and Pu were reported below or near the MDL (values reported near the MDL are likely to be nondetects). Samples were primarily analyzed for $^{3}$H; other radionuclides were analyzed less frequently. The $^{3}$H MDLs ranged from 1 to 900 pCi/L. |
| TW D | 4 | LCA | 1965, bailed 1973 to 1987 (biannually) and 1993 to 2010 (annually) | • $^{3}$H, $^{14}$C, $^{90}$Sr, $^{99}$Tc, $^{90}$Sr, $^{137}$Cs, and Pu were reported below or near the MDL (values reported near the MDL are likely to be nondetects). Samples were primarily analyzed for $^{3}$H; other radionuclides were analyzed much less frequently.<br>• For a 1993 sample, $^{3}$H was reported as 3.8±1.3 pCi/L and $^{99}$Tc was reported as <5. |
| UE-10j | 10 | LCA | 05/25/1965 (bailed 728 m), 04/30/1993 (680–796 m) 03/17/1997 (760–796 m; Zone 1) 03/20/1997 (721–741 m; Zone 2) 03/24/1997 (680–700 m; Zone 3) | • For the 1965 sample, $^{90}$Sr was reported below the MDL (0.3 pCi/L).<br>• For the 1993 sample, $^{3}$H, $^{90}$Sr, $^{99}$Tc, and $^{137}$Cs, were reported below MDLs (2, 0.5, 4.5, and 0.6 pCi/L, respectively); and $^{36}$Cl was reported as 2E-04 pCi/L.<br>• For the 1997 samples, $^{3}$H and $^{137}$Cs were reported below MDLs (90 to 190 and 6.8 pCi/L, respectively). |
| UE-1q | 1 | LCA | 1992 and bailed annually from 1999 to present | • $^{3}$H was reported near or below the MDL (1–34 pCi/L) for all samples indicating its absence (values reported near the MDL are likely to be nondetects).<br>• Gamma emitters, $^{14}$C, $^{90}$Sr, $^{99}$Tc, and Pu were reported below the MDL throughout the sampling period; these radionuclides were not analyzed in all samples.<br>• $^{36}$Cl was reported as 1.4E-04 pCi/L in 1992 samples. |

## *Table 3-1*
## *Summary of Radionuclide Data from Sampled Observations Wells in Yucca Flat*
*(Page 6 of 6)*

| Well | NNSS Area | HSU Open to Well | Sample Dates | Radioisotopes Analyzed and Corresponding Results |
|---|---|---|---|---|
| **Far-Field Wells Completed in the LCA/LCA3** (continued) | | | | |
| WW C | 6 | LCA | 1961, 1962, nearly monthly between 1972 and 1995 (pumped) | • For the 1961 and 1962 samples, $^{90}$Sr was reported below the MDL (0.4 and 0.5 pCi/L, respectively).<br>• $^{3}$H ranged from approximately 100 pCi/L in 1972 to less than 50 pCi/L in 1987; the initial elevated $^{3}$H was attributed to a 1964 tracer test (Lyles, 1990).<br>• For the 1993 sample, $^{3}$H was reported as 11.5 pCi/L, $^{36}$Cl as 2.4E-04 to 2.6E-04 pCi/L, and $^{99}$Tc as <5 pCi/L.<br>• $^{90}$Sr and Pu was reported below the MDL for samples collected between 1989 and 1995 (these radionuclides were not reported for earlier samples). |
| WW-C-1 | 6 | LCA | 1962, pumped 1973 to 1987 (biannually) and 1989 to 2010 (monthly) | • $^{3}$H decreased from about 100 pCi/L in 1973 samples to less than the MDL in the 1987 samples. Initial high $^{3}$H was attributed to a $^{3}$H tracer introduced into this well in the early 1960s (Lyles, 1990). $^{3}$H was reported below MDLs (10 to 30 pCi/L) for subsequent analyses.<br>• $^{14}$C, $^{90}$Sr, $^{99}$Tc, $^{137}$Cs, and Pu were reported below or near the MDL for samples collected between 1989 and present (values reported near the MDL are likely to be nondetects).<br>• For the 1993 sample, $^{36}$Cl was reported as 2.4E-04 pCi/L. |

Note: Concentrations reported with a "<" are less than the MDL (the MDL follows the "<").

ATCU = Argillic tuff confining unit
bgs = Below ground surface
LANL = Los Alamos National Laboratory
LLNL = Lawrence Livermore National Laboratory
LTCU = Lower tuff confining unit
MDL = Minimum detection limit
OSBCU = Oak Spring Butte confining unit
PCUT = Playa confining unit
RREMP = Routine Radiological Environmental Monitoring Program
TMLVTA = Timber Mountain lower vitric-tuff aquifer
TMWTA = Timber Mountain welded-tuff aquifer
TSA = Topopah Spring aquifer

# 4.0 MODELS AS REGULATORY DECISION TOOLS

This section provides a general discussion on using mathematical models as regulatory decision tools based on the comprehensive report published by the National Research Council (NRC) (2007). The report identifies model development steps as defining the model purpose, modeling context specifics, conceptual model formulation, computational model development, model evaluation, and model use in regulatory context. While interested readers are referred to the original report for detailed information (NRC, 2007), the following paragraphs provide key point summaries.

## 4.1 Model Purpose

It is imperative to have a clear goal for any model, as it drives all the decisions in subsequent phases. A model is a simplification of reality and should never be expected to fully match the real system; rather, it should be used to fulfill defined tasks (NRC, 2007). Thus, for the YF/CM model, it is critical that it fulfills the goal as a tool to support regulatory decision making.

## 4.2 Modeling Context

This task involves identifying the following:

- Temporal and spatial scale
- Intended model users and required expertise
- Input data and sources
- Model evaluation data availability
- Desired outputs (deterministic or probabilistic)
- Need for additional outputs to enhance model transparency and flexibility
- Required reliability
- Model applicability evaluation criteria

Documenting these in a systematic and consistent manner can contribute significantly to the model success. The documentation for this step was paramount in the peer review team's answer to question 1.a-d.

## 4.3 Conceptual Model Formulation

A conceptual model is a qualitative, and often graphical, description of a 3-D groundwater flow system. It depicts the general system structure and the relationships within the system that are known or hypothesized to be important. A clear and effective conceptual model is key to successful model development and application. However, the conceptual model needs to be revisited during the subsequent numerical model development, as possible revisions may be identified. Thus, conceptual model formulation is an iterative and adaptive process that reflects the interdependence of models and measurements. Conceptual model development is important to question 1.d.

## 4.4 Computational Model Development

This step changes the conceptual model into mathematical terms and computer codes, which requires decisions about modeling code, hardware, software infrastructure, parameter estimation, pre- and post-processing, database management, and model history and revisions documentation. A modular approach is preferred because of its ability to easily add or remove parts without affecting the others.

## 4.5 Model Evaluation, Testing, and Revision

In considering the process of model evaluation, testing and revision, NRC (2007) adopts the perspective that a model is a "tool" designed to fulfill a task—providing scientific and technical support in the regulatory decision-making process—not a "truth-generating machine." A crucial element in model evaluation and application are uncertainty and sensitivity analyses. Multiple uncertainty and sensitivity approaches may be used, from a full Bayesian analysis or Monte Carlo analysis, to examining a small number of model scenarios in a deterministic manner. EPA has developed guidance for the development, evaluation and application of models (EPA, 2009), including best practices to help determine when a model, despite its uncertainties, can be appropriately used to inform a decision. Notable among these recommendations are for model developers and users to

> "(a) subject their model to credible, objective peer review; (b) assess the quality of the data they use; (c) corroborate their model by evaluating the degree to which it corresponds to the system being modeled; and (d) perform sensitivity and uncertainty analyses." (EPA, 2009, p. vii).

## 4.6 Model Use in Regulatory Context

In applying models to support an environmental regulatory issue, NRC (2007) stresses that the model developers and regulators need to evaluate how appropriate an existing model is for a specific setting and whether the assumptions and input data are relevant for the application. Moreover, it is important to have effective strategies for representing and communicating uncertainties. NRC (2007, p. 189) recommends that

> "when critical model parameters are estimated largely on the basis of matching model output to historical data, care must be taken to provide uncertainty estimates for the extrapolations, especially for models with many uncertain parameters."

# 5.0 ADDRESSING THE QUESTIONS ASKED OF THE PEER REVIEW TEAM

The peer review team commends the N-I team for its efforts in using limited data to model the fate of radionuclides in groundwater at Yucca Flat. Recognizing the key uncertainties and related recommendations discussed in Section 6.0 of this report, the peer review team has concluded that DOE is ready for a transition to model evaluation studies in the CADD/CAP stage.

## 5.1 Are modeling approaches, assumptions, and results consistent with regulatory use?

The first question and the related four sub-questions addressed by the peer review team are as follows:

1. Are the approaches, assumptions, and results consistent with the use of the models as decision tools for meeting FFACO regulatory requirements?

    a. Are the models of sufficient scale/resolution to adequately forecast contaminant transport in the YF/CM setting?

    b. Have the key processes been included in the models?

    c. Are the flow and transport modeling results and uncertainties technically sound and defensible?

    d. Are the conceptual models used in the different flow and transport models sufficiently consistent to provide representative integrated model results?

The peer review team answers these questions with a qualified yes—qualified in the sense that the uncertainties identified in Section 6.0 of this report presumably will be carefully addressed during the CADD/CAP stage. The modeling team's general approach is sound; their assumptions are logical; and the initial results of modeling are consistent with using the models as decision tools for meeting FFACO regulatory requirements.

As discussed in Section 6.0 of this report, there are gaps in the data that would normally be necessary for evaluating regulatory compliance at other sites with environmental contamination. Notably, some

useful available data have not been included in the model designs and calibration, and thus have not been considered in determination of the contaminant boundary. The peer review team expects that a reliable prediction of the contaminant boundary will be obtained during the CADD/CAP stage. The peer review team also expects that sufficient monitoring will be put into place during the CADD/CAP and CR stages that the most extensive radionuclide plumes in the groundwater will be detected, and adjustments to the monitoring plans will be made accordingly.

### 5.1.1 Sub-question a. Are the models of sufficient scale/resolution to adequately forecast contaminant transport in the YF/CM setting?

The peer review team considers the approach to modeling, including the scale and resolution, to be generally adequate. There are, however, concerns related to the extent of the model domain as discussed in Section 6.1, and some minor concerns regarding scale and resolution that are discussed in Sections 6.6.5 (concerning realistic geologic features) and 6.7.7 (concerning mesh refinement).

### 5.1.2 Sub-question b. Have the key processes been included in the models?

The peer review team commends the authors of N-I (2013) and its supporting documents for a tremendous amount of work accomplished to address the key processes of potential radionuclide contamination in groundwater and in detonation-created melt glass, altered rock, and surrounding rock near the detonations; flow of groundwater into the basin; and flow through permeable and relatively impermeable HSUs. The peer review team agrees that the key processes have been considered. As discussed in Section 6.0 of this report, several key uncertainties remain about these processes.

### 5.1.3 Sub-question c. Are the flow and transport modeling results and uncertainties technically sound and defensible?

Yes, the peer review team further commends the authors of N-I (2013) for identifying uncertainties in the key processes in a logical manner. Recommendations regarding evaluation of key uncertainties in the CADD/CAP stage are discussed in Section 6.0 of this report.

### 5.1.4 Sub-question d. Are the conceptual models used in the different flow and transport models sufficiently consistent to provide representative integrated model results?

Yes, the conceptual models for flow are generally consistent. However, the extent of the model domain and the decoupling of the aquifers in models used to evaluate the flow system are concerns. The peer review team expects that the conceptual models will be refined during the CADD/CAP stage, following recommendations outlined in Section 6.0 of this report.

## 5.2 Are the datasets and modeling results adequate for a transition to model evaluation studies?

The second question addressed by the peer review team is as follows:

2. Are the datasets and modeling results adequate for a transition to model evaluation studies in the CADD/CAP stage—the next stage in the UGTA strategy for the YF/CM CAU?

The peer review team answers this question with a qualified yes—qualified in the sense that the review team understands that considerably more data will be collected and more modeling will be done during the CADD/CAP stage. The N-I team has made a commendable effort in compiling available data and gleaning what they can from that sparse data. Because the site is, in the opinion of the peer review team, significantly undercharacterized, the next stage requires both more extensive field investigation and a broader uncertainty analysis to account for the many unknowns given the sparse data. The peer review team's recommendations regarding field investigations and uncertainty analysis are discussed in Section 6.0 of this report.

# 6.0 KEY UNCERTAINTIES

The NNSA/NFO clarified the charge to the peer review team in a letter dated October 9, 2014, from Bill R. Wilborn, NNSA/NFO UGTA Activity Lead, to Sam J. Marutzky, N-I UGTA Project Manager:

> "The model and supporting information should be sufficiently complete that the key uncertainties can be adequately identified such that they can be addressed by appropriate model evaluation studies. The model evaluation studies may include data collection and model refinements conducted during the CADD/CAP stage. One major input to identifying 'key uncertainties' is the detailed peer review provided by independent qualified peers."

The key uncertainties that the peer review team recognized are listed in this section, along with recommendations corresponding to each uncertainty. Potential concerns associated with each key uncertainty are outlined in the following sections. The uncertainties, concerns, and recommendations are summarized in Table 6-1.

## 6.1 Uncertainty in Model Domain/Boundary Conditions

### 6.1.1 Western Boundary

One concern with the current groundwater-flow model is that the direction of flow in some areas of the western part of the system is to the north, which is opposite to the direction presented in the conceptual model, opposite to the direction expected given the high gradient toward Yucca Flat from the Rainier Mesa area, and opposite to flow simulated by the regional model of the Death Valley Flow System. Uncertainty in boundary inflow rates and their spatial distribution, especially along the north, northwest, and eastern boundaries of the model, results in uncertainty in the transport velocities and, in the case of inflow from the northwest, unrealistic transport in the LCA first northward along the western side of the major faults and subsequent reversal of flow southward along the central and eastern areas of Yucca Flat. Such clockwise circulation in Yucca Flat causes most of the groundwater flow within the LCA to occur east of Yucca fault. The general clockwise circulation beneath Yucca Flat in the calibrated model appears to be in part an artifact of specifying zero inflow on the west/northwest boundary coupled with limited calibration (head) data in that area to indicate the need for inflow. Northerly flow along the western faults is not conservative; that is, if flow were to the

***Table 6-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 1 of 5)*

| Key Uncertainty | Concern(s) | Recommendation(s) |
|---|---|---|
| **Model Domain/ Boundary Conditions** | | |
| Section 6.1.1 | Western boundary | Expand the model domain to include Rainier Mesa, and use head and perched spring data from that area for calibration. |
| Section 6.1.2 | Southern boundary | Extend model domain to the south to capture contaminant boundaries that extend beyond the current model domain. |
| Section 6.1.3 | Northern boundary | Investigate inflow from the north with multi-well aquifer testing and water sampling. |
| Section 6.1.4 | AA/VA flow direction | Contour simulated water levels in the AA/VA; compare with available data; and include the resulting uncertainty in flux to the LCA in future modeling. |
| Section 6.1.5 | Hydraulic connection between aquifers | Evaluate uncertainty in flux to the LCA associated with the inconsistency of the boundary between the LCA and AA/VA models. Couple the AA/VA and LCA models, and use all the head data within the combined multi-aquifer system for calibration. |
| **Model Calibration** | | |
| Section 6.2.1 | Poorly posed calibration | Expand the model domain to couple the aquifer systems; extend the domain to the groundwater divide to the west; include more target data from the available dataset, as well as through additional data collection; and simplify the parameterization. |
| Section 6.2.2 | Lack of steady-state head data | Calibrate a coupled model of the aquifers; include more calibration targets; resurvey the well heads to ensure accuracy of the targets; and completely represent the data that were used to develop steady-state targets in the residual analysis. |
| Section 6.2.3 | Use of parameter bounds | Reduce the number of parameters through re-parameterization; remove bounds from the parameters; include more calibration targets; and adjust the model conceptualization and construction if the estimated parameter values are not reasonable. |
| Section 6.2.4 | Omission of available calibration data | Include as many calibration targets as possible (also use multiple targets at individual locations for the steady-state calibration to incorporate the transient nature of the data into the uncertainty of the steady-state calibration); include hydrogeologic features to facilitate a fit to those targets; and present residuals related to all of the measurements. Critically review all available calibration data. |
| Section 6.2.5 | Jacobian used to determine weights | Determine weights by evaluating the quality of the target data based on well construction and measurement procedures. |
| Section 6.2.6 | Field measurements of hydraulic conductivity not honored | After estimating parameters without bounds, compare the values to equivalent field values; if they are unreasonable, adjust the model conceptualization and/or construction. |

***Table 6-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 2 of 5)*

| Key Uncertainty | Concern(s) | Recommendation(s) |
|---|---|---|
| **Hydraulic Properties and Pathways** | | |
| Section 6.3.1.1 | Limited characterization of country rock | Conduct MWATs in the central and western parts of Yucca Flat. |
| Section 6.3.1.2 | Model permeabilities inconsistent with field measurements | Use available hydraulic properties data to delineate permeability zones in the model. |
| | | Honor the measured hydraulic conductivities. Reevaluate the choice of the “fast” scenario. |
| Section 6.3.1.3 | Preferential flow not considered in uncertainty evaluation | Thoroughly evaluate existing data for indications of karst, and install new wells to investigate for karst. If karst features cannot be ruled out, include alternative models that have continuous high hydraulic conductivity pathways from the northern to the southern end of Yucca Flat and passing through source zones. |
| Section 6.3.2 | Representation of faults | Extend the range of permeability considered for modeling faults well above the highest measured value, and include alternative models without impermeable fault cores. |
| | | Assign increased permeability to the material that is currently simulated as country rocks near major faults in the analysis of uncertainty. |
| | | Explore greater fault permeability in the AA/VA model, and characterize AA/VA fault behavior. |
| | | Evaluate the contaminant boundary using an alternative flow model in which all faults in the volcanic rocks serve as permeable pathways to the LCA. |
| | | Include an alternative model that has no or many fewer minor faults; this may require allowing flow and transport to occur between the AA/VA and LCA via the TCU in addition to the major faults. |
| Section 6.3.3 | Potential for vertical flow through the TCU, other than by faults | Evaluate the uncertainty in the contaminant boundary due to flow across the TCU that is not impermeable, but rather honors the available data on hydraulic properties of the TCU. |
| | | Develop new data and field testing to determine the lateral continuity of the TCU as an effective hydraulic barrier to vertical transport. |
| Section 6.3.4 | Effective porosity | Evaluate uncertainty in the contaminant boundary due to effective fracture porosity of the TCU. |
| Section 6.3.5 | Surface water flow into fractures in the alluvium | Model faults as local zones of preferential flow through the unsaturated and saturated alluvium. Gather field data to ascertain the degree to which fissures contribute to enhanced local recharge. |
| Section 6.3.6 | Anisotropy and preferential flow in the unsaturated zone | Determine the maximum depth of recent infiltration along possible flow pathways to detonation cavities at craters with high rates of recharge, |

***Table 6-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 3 of 5)*

| Key Uncertainty | Concern(s) | Recommendation(s) |
|---|---|---|
| **Source Term and Mass Flux to the LCA** | | |
| Section 6.4.1 | No uncertainty associated with RST | Include uncertainties in RST in modeling. |
| Section 6.4.2 | Uncertainties in partition factors not well defined | Develop support for partition factors used. |
| Section 6.4.3 | Water flow into cavities | Measure and monitor enhanced-recharge-driven transport in and below detonation craters. |
| Section 6.4.4 | Uncertainty in exchange volume not fully captured | Extend the uncertainty analysis to include exchange volumes of at least 5 $R_c$. |
| Section 6.4.5 | Chimney and cavity pathways to the LCA | Expand the uncertainty analysis to include a greater range of permeability enhancement assigned to the damage zone. Where possible, consider using post-shot holes to test field permeability of the damage zones. |
| **Transport** | | |
| Section 6.5.1 | Values for Pu retardation not well supported and may be too high | Decrease Pu $K_d$ values used for modeling. Collect more data to understand Pu retardation, and further evaluate existing data. |
| Section 6.5.2 | Melt-glass dissolution largely neglected | Include melt-glass dissolution in UZ models. Consider additional processes affecting cavity-debris behavior in the LCA, and include an instant-release case. |
| **Simulating Critical Observations** | | |
| Section 6.6.1 | Field-measured $^3H$ not simulated | Simulate sub-regions of the model with smaller mesh size and more particles to understand mismatches. |
| | | Incorporate processes that could lead to observed lateral transport of $^3H$ in the AA/VA. |
| | | Evaluate whether timing of sampling or nature of completion of non-detect wells may be such the $^3H$ occurrences were missed. |
| | | Gather field data to define the current extent of contamination, then adjust the model to better represent the field system. |
| Section 6.6.2 | Observed crater recharge not well matched in the model | Ensure that the crater-recharge model is conservative. |
| Section 6.6.3 | Geochemical and environmental isotope data not fully evaluated | Justify the choice of initial chlorine concentrations. Explain differences in interpretations of $^{14}C$ in the Yucca Flat and Ash Meadows LCA flow systems. Avoid interpreting ages from dissolved organic $^{14}C$ data. |

***Table 6-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 4 of 5)*

| Key Uncertainty | Concern(s) | Recommendation(s) |
|---|---|---|
| **Simulating Critical Observations** (continued) | | |
| Section 6.6.4 | Interpretation of temperature data | Explain temperature at the water table; use temperature data to inform calibration of the coupled flow model; and incorporate water fluxes indicated by temperature data into determination of the contaminant boundary. |
| Section 6.6.5 | Missing some realistic geologic features | Incorporate more realistic geologic features as computational capabilities, software, and data improve. |
| Section 6.6.6 | Other sources of data available | Review and use data from surrounding DOE and DoD facilities to further constrain water levels, boundary fluxes, and estimates of hydraulic properties. |
| | | Build confidence in the Yucca Flat model by using the modeling approach to simulate single-test detonations outside Yucca Flat where there has been groundwater monitoring. |
| **Uncertainty Evaluation** | | |
| Section 6.7.1 | 95th percentile not captured | Generate flow models that represent combinations of values from the upper end of their parameter distributions, and explore whether calibration is successful. |
| Section 6.7.2 | Expected alternative flow models not included | Include alternative flow models with fast flow fields from many detonation locations. |
| Section 6.7.3 | Limited number (100) of NSMC realizations | Employ the approach described in Section 6.7.1 to capture fast flow fields without excessive numbers of simulations. |
| Section 6.7.4 | Limited number of calibrated flow models used to evaluate transport uncertainty | Include more fast flow field models coupled with transport parameter values from the end of the distribution that enhances transport. |
| Section 6.7.5 | Limited alternative models to evaluate relevant detonations | Include more flow fields in the uncertainty evaluation with bias to capture the 95th percentile, and include all sources with enhanced transport. |
| Section 6.7.6 | Limited range of transport parameters | Include Pu isotopes with combinations of lower $K_d$ values and higher mass in the source term; expand the evaluated uncertainty range of matrix diffusion and include higher values of dispersivity. |
| Section 6.7.7 | Mesh refinement not necessarily conservative | Evaluate higher level meshes to determine definitively the mesh-refinement level for which there is no change in the contaminant boundary. |

***Table 6-1***
***Summary of Key Uncertainties with Related Concerns and Recommendations***
*(Page 5 of 5)*

| Key Uncertainty | Concern(s) | Recommendation(s) |
|---|---|---|
| **Unforeseen Uncertainties** | | |
| Section 6.8.1 | New concerns and approaches anticipated | Engage external experts in periodic peer review. |
| Section 6.8.2 | Climate change | Evaluate whether long-term climate change and associated extreme weather events would have a significant impact on transport of radionuclides. |
| **Location of Radionuclide Plumes** | | |
| Section 6.9.1 | Extent of contamination poorly defined at present | Determine the bounds of contaminant migration in both the AA/VA and LCA. |
| Section 6.9.2 | Inadequate observation-well network | Conduct a comprehensive formal review of existing data quality, and maintain a groundwater monitoring program designed to evaluate model uncertainties and delineate contaminant boundaries. |
| | | General locations for new wells, aquifer tests, and sampling during the CADD/CAP stage, including samples from existing wells, are recommended in Section 6.9.2. |

DoD = U.S. Department of Defense
RST = Radiological source term
UZ = Unsaturated zone

south in this area, the extent of the contaminant boundary could extend farther west and south than shown given the current simulations. Moreover, the calibrated hydraulic properties likely would be different; that is, the treatment of the western boundary likely is a source of uncertainty in model calibrations and predictions.

The peer review team cautions that boundary fluxes determined by model calibration should not be the basis for conceptual model development. A strong gradient from Rainier Mesa to Yucca Flat, as indicated by heads outside of the model domain, clearly indicates the need for inflow on the northwestern boundary.

> ***Recommendation:*** *The peer review team recommends inclusion of the Rainier Mesa area in the model and use of head data from that area as calibration targets (including the semi-perched springs that reflect saturated groundwater heads) to improve the representation of the flow field and build confidence in model predictions.*

### 6.1.2 Southern Boundary

The peer review team notes that a number of simulations show that the southern extent of the contaminant boundary (5 percent probability) lies beyond and south of the model domain. (See, for example, the base-case simulations in Figs. 6-60, 6-62b, and 6-64b; the alternative LCA source simulations in Fig. 6-67; the LCA sources with alternative NSMC LCA flow-field simulations in Figs. 6-81b, 6-82a, and 6-85b; and the combined transport model runs in Figs. 6-89 through 6-91. All figures referred to here are from N-I [2013].)

Because the model appears to be truncated on the south, the southern extent of the predicted contaminant boundary cannot be delineated for a number of simulations. The predicted extent of the contaminant boundary is relevant to assessing the area of institutional controls and designing a groundwater monitoring network.

> ***Recommendation:*** *The peer review team recommends that to better delineate the full extent of the contaminant boundary, future model simulations should extend the domain farther to the south to capture all areas where there is greater than a 5 percent probability of exceeding the MCL.*

### 6.1.3 Northern Boundary

The peer review team commends the N-I modeling team for recognizing the importance of uncertainty in flow from the north into Yucca Flat and for factoring this uncertainty into the model. On their second field trip to the NNSS, members of the peer review team examined exposures of faults and outcrops of fractured contact-metamorphosed LCA, granitic rocks, and volcanic rocks in the hills north of Yucca Flat. Although the peer review team recognizes that budgetary constraints may limit the number of wells and tests that can be undertaken during the CADD/CAP stage, significant flow from the north is possible and could be an important factor in radionuclide transport out of Yucca Flat.

> ***Recommendation:*** *Multi-well hydraulic testing and water sampling at the northern Yucca Flat boundary should be undertaken to investigate inflow from the north, including the fracture/fault hydraulic properties of rocks that occur along the northern extension of the Boundary/Yucca fault across the topographic divide to the north (Comstock stock, LCA, contact-metamorphosed LCA, and overlying Tertiary volcanic rocks).*

### 6.1.4 Water Table Boundary and AA/VA Flow Direction

The peer review team notes that the upper boundary of the shallow aquifer model was fixed at the elevation 750 m (N-I, 2013, p. 4-20) to coincide with the approximate average elevation of the water table. Across this boundary is applied a “constant, spatially variable flux (pre-testing) and … transient, spatially variable flux after the beginning of testing.” (N-I, 2013, p. 4-23). The simulated heads mapped in Fig. 4-20 of N-I (2013) are difficult to interpret, but the figure gives the impression that the simulated water table is flat over much of the domain, so that in the long term, after the testing effects dissipate, there seems to be little lateral flow toward the faults (e.g., in year 2978).

The peer review team has not been presented with information to clearly show the simulated direction of groundwater flow in the AA/VA system. The flow direction is relevant to evaluating uncertainty in the flux into the LCA via faults, because if near the major detonation areas the local flow direction in the AA/VA is more to the south and parallel to the faults there would be less flow and transport into the LCA than if flow were more east–west. Similarly, if flow is driven more to faults in the north end of Yucca Flat, then there would be less effect on the extent of the contaminant boundary than if flow entered the faults in the south part of Yucca Flat. The direction of groundwater flow in the shallow aquifer system is an unexplored area of uncertainty. It is probable that the flux into the LCA would

depend to some degree not only on the vertical gradient from mounding due to local infiltration, but on the lateral flow directions toward faults, in particular near detonations.

> ***Recommendation:*** *The peer review team recommends contouring simulated water levels in the AA/VA system and comparing the simulated contours to the horizontal gradients and flow directions shown in Fenelon et al. (2012) and in Fig. 4-2 of N-I (2013) to build confidence in the reasonableness of the predicted fluxes into the LCA. Given the poor quality of the available head data, especially due to its transient nature, the uncertainty associated with flux to the LCA resulting from uncertain spatially variable hydraulic heads and gradients in the AA/VA should be examined.*

### 6.1.5 Hydraulic Connection between Aquifers

Another observation of the results of the current groundwater-flow model is that the upper boundary condition for the LCA model and lower boundary condition for the AA/VA model are circular. The two models are uncoupled, and therefore the composite representation of the flow field is not well integrated. Regarding the AA/VA model, "Heads were determined by interpolating simulated heads at the top of the LCA model" (N-I, 2013, p. 4-23). Regarding the LCA model, "The top boundary receives recharge from the...saturated alluvial/volcanic aquifer system flow models" (N-I, 2013, p. 5-70). Thus, the simulated heads in the LCA depend on the recharge via leakage across the upper surface boundary from the AA/VA, and the leakage from the AA/VA in turn depends on the simulated heads in the LCA. Uncertainty in the flow into the LCA from the AA/VA is therefore at least in part attributable to uncertainty in model predicted heads in the LCA. Likewise, there is considerable uncertainty in the heads in the AA/VA as described above in Section 6.1.4 as well as in Section 4.2.1 of N-I (2013). AA/VA fault-zone intersections with the top of the LCA mark locations where the heads in the two aquifers should match; however, there are no measurements of head at any of these locations to compare against model predictions, and no confirmation is presented to ensure that such a head match occurs in the models.

> ***Recommendation:*** *The peer review team recommends that the uncertainty associated with the consistency of the upper boundary of the LCA model and the lower boundary of the AA/VA model be considered in future simulations of the contaminant boundary. One suggestion is to follow common convention for modeling multi-aquifer systems separated by an aquitard and model them together. This approach would ensure continuity of heads between aquifers where they are connected at the faults. The coupled model grid can be fairly coarse, at least much coarser than the decoupled models that were used for both flow and transport predictions of the contaminant boundary. Once the models are coupled, then all the head data within the combined multi-aquifer system*

*can be used for calibration. The flux leaking into the LCA from the coarse-grid coupled aquifer model would help constrain further calibrations with the fine-grid flow and transport model. Use of the most recent U.S. Geological Survey (USGS) regional modeling (Faunt, 2012) for establishing head boundaries in the local-scale flow model of Yucca Flat is recommended.*

## 6.2 Model Calibration

The most extensive presentation of the calibration process and subsequent uncertainty evaluation in N-I (2013) is for the LCA model, so the peer review team focused on concerns related to that process. The current calibration of the AA/VA model cannot be assessed because the results are not thoroughly presented. For example, only four hydrographs are shown while 60 locations were used. A map showing the simulated heads with the spatial residuals and a graph showing residuals as a function of time are not provided, while the graph of measured versus simulated heads for AA/VA model reveals many outliers.

### 6.2.1 Poorly Posed Calibration

Calibration of the LCA model is considered unreliable by the peer review team because it is poorly posed. A total of 145 parameters were specified for calibration including hydrologic parameters and boundary conditions. A total of 98 were allowed to adjust during calibration, but several were grouped such that 31 estimated parameters are presented. The number of calibration targets is insufficient to estimate this number of parameters. The calibration data consist of only 15 "steady-state" heads and some drawdowns from one pump test. Ultimately, N-I (2013, p.5-90) "concluded that only about seven parameters can be reliably estimated."

***Recommendation:*** *The peer review team recommends the problem be better posed by coupling the aquifers in one model; including more calibration targets (e.g., [1] AA/VA heads, [2] heads and springs east of the groundwater divide on Rainier Mesa, and [3] heads Fenelon identified as representative of the regional carbonate aquifer such as UE-8e, UE-10 ITS 3 (2160), UE-10bf, UE-10 ITS 5 before the measurement in 1972, U-7a, WW-C-1, and ER-3-1–this list provides examples and, as such, is not a compulsory nor comprehensive list); collecting additional calibration data via field activity; and simplifying the parameterization of the model.*

### 6.2.2 Lack of Steady-State Head Data

The "steady-state" heads are not concurrent and include averages from selected "steady" portions of hydrographs that are not obviously representative of a steady-state condition with lengths ranging

from 1 to 27 years over diverse time periods as early as 1961 through 1962 and as late as 2003. The head data are sparse, affected by detonations, and many come from sections with long well screens that straddle multiple aquifers. There were no wells, other than water-supply wells, in Yucca Flat before the first atmospheric detonation in 1951 and the first underground detonation in 1957, so it is difficult to establish the pre-development, or steady-state condition. The earliest water level in the database is from 1961. The lack of water-level data under natural, pre-detonation conditions leads to low confidence in the site conceptual model, and the uncertainty associated with this situation has not been incorporated into the modeling process.

A number of statements in N-I (2013) justify the current results by noting the excellent fit to the steady-state calibration data. This is a misrepresentation of the quality of the calibration. N-I (2013, p. 5-91) notes that without the MWAT data, "the problem is poorly constrained, as the steady-state heads can be reproduced by numerous combinations of parameters and boundary conditions, and consequently, the model calibration rapidly converges in close proximity to initial estimates of the parameters." In short, the parameter estimates are not informed by the steady-state data.

One reason the fit is not as good as presented in Fig. 5-43 of N-I (2013) (i.e., head differences are not within ±0.4 m) is likely because the "steady-state" data that provide the illustrated fit have been selected from non-concurrent non-steady sections of the hydrographs. The values selected for determining the steady-state average seem to be arbitrary, and the procedure for selection does not appear to be consistent from well to well. As recognized by N-I (2013), some water levels in wells show a gradual upward trend starting in the 1980s. This was deemed to be small enough to be a minor trend in a long-term steady condition. If the head values represent a long-term steady condition, then (after removal of outliers that represent recovery, measurement error, and response to a detonations) either all the values should be averaged, or alternatively all the data points (with previously noted deviations omitted) should be used, and the numerous residuals at each location would provide a realistic representation of the difference between measured and simulated heads. It is not appropriate to combine heads from different time periods to represent a steady-state flow field when conditions are changing over time (the temporal midpoints of the averaged values range from 1961 to 2003). In this case, the transient change in head is substantial relative to the difference in head over the area of interest (e.g., about 5-ft rise over about 15 years in ER-6-2 (2,444.6 ft in 1994 and 2,449.6 ft in 2009) with about 30-ft difference in head from north to south on the west side of the faults in Yucca Flat).

The transient head data are presented along with the sections selected to represent steady state in Appendix D of this report. The use of more and/or different (given the adjusted averaging) head targets may result in different estimated parameters.

> ***Recommendation:*** *The peer review team recommends calibrating a coupled model of the aquifers, including more calibration targets, resurveying the well heads to ensure both the accuracy of the targets and to determine whether the measuring point may have changed with time, as well as completely representing the data that were used to develop steady-state targets. To completely represent the data, use all the data points (with deviations due to recovery and measurement errors omitted) as targets, and present a residual at each location for every measurement that has been recorded over the years. This would provide a realistic representation of the difference between measured and simulated heads.*

### 6.2.3 Use of Parameter Bounds

Presumably to cope with the lack of data, bounds were used to constrain the values of parameters estimated in the calibration. A calibration should be conducted without bounds, because if the estimated parameter values are unreasonable, that is a clue that the model is not properly conceptualized, constructed, or posed, and/or the data are insufficient to estimate the specified parameters. Such issues should be addressed. Using bounds to constrain the estimates of parameter values yields false confidence in the calibration, concealing problems and leaving them unresolved.

The limiting of some parameters to the maximum bound is illustrated in a sampling of the cumulative distribution functions (CDFs) supplied by N-I (Andrews, 2014c and d; see Appendix E of this report). This is particularly notable for the hydraulic conductivity of the eastern zone of the LCA and the hydraulic conductivity of some faults.

> ***Recommendation:*** *The peer review team recommends reducing the number of parameters through re-parameterization, removing bounds from the parameters, including more calibration targets, and adjusting the model conceptualization and construction if the estimated parameter values are not reasonable. Parameters should not be constrained for the calibration. The resulting estimated parameter values should be compared with equivalent values measured in the field. Substantial differences between the parameter values estimated by the calibration and the values measured in the field are an indication that there is a problem with model conceptualization or construction, and such clues should be used to improve the model.*

### 6.2.4 Omission of Available Calibration Data

The near perfect fit between model-predicted and field-observed heads is cause for concern given so few data and a complex model. Possible causes are that the data define such a broad general pattern that many parameter combinations produce the same fit (this may be due to the limited number of data used for calibration); or the simulated system is so constrained that many diverse sets of parameters can fit the same data. This finding indicates that the model is non-unique, and parameter values are not successfully estimated, even though a good fit is achieved.

Heads in some wells are not used in the model even though Elliot and Fenelon (2013) classified them as representative of steady-state heads in the regional carbonate aquifer. They appear to meet the same criteria as the heads used for calibration in every way except they do not fit the low gradient assumed in the conceptual model (e.g., ER-3-1, WW-C-1, U-7a, UE-8e, UE-10bf, UE-10 ITS 3 [2160], UE-10 ITS 5 before the last measurement in 1972 as presented in ds533_NTS_hydrographs.xlsx).

Transients in the head data that are unrelated to the MWAT have not been used in the calibration. N-I (2013) concludes these trending hydrographs essentially represent a long-term steady condition. If that is the case, then all of the heads at each location (excluding recovery, errors, and detonation responses) should either be averaged for the steady-state head target, or preferably multiple targets would be included at each location with equal weights and the residuals for all the heads would be presented and included in the calculation of the sum of squared residuals. The head data are presented in Appendix D.

If head calibration targets do not fit the conceptual model of a flat potentiometric surface in the LCA, they should still be included as targets accompanied by an attempt to find explanations for them, and include the hydrogeologic features in the model that would simulate such observed heads (e.g., downward gradients, isolated carbonate blocks, low hydraulic conductivity zones along the top of the carbonate, focused recharge that causes mounds). If model features cannot reproduce those heads, the targets should still be included and the residuals shown. The report can note that the model design does not represent the conditions or processes that cause those values.

Given the scant head data for calibration, the use of a coupled AA/VA/LCA model would allow use of calibration data from the AA/VA and the TCU and render the calibration more robust. Elliot and

Fenelon (2013) indicated that wells UE-2aa and TW-7 have VA/AA heads showing a possible connection to the carbonate aquifer. Additionally the area to the south of TW-7 and continuing to the south–southwest across the Yucca fault is mentioned by Winograd and Thordarson (1975) as possibly having the welded or bedded tuff aquifer faulted against the top of the LCA (upthrown on the west).

> ***Recommendation:*** *The peer review team recommends using an expanded model domain and more calibration targets including those that do not fit the conceptual model of a flat potentiometric surface in the LCA. An attempt should be made to include features in the model that will generate heads similar to the targets. The residuals related to all of the measurements (excluding outliers that are likely errors and recovery conditions) should be presented. A critical review of all calibration data with respect to water levels, thermal effects, well completions, geophysical logs, and core and cuttings should be undertaken to clarify the conceptual model. Head data from all wells should be reevaluated to confirm the location of targets in the AA/VA/TCU/LCA, to determine whether each head measurement represents normal pressurization, and to assess whether the well completion is sufficient to ensure there is minimal communication between zones. If results of the reassessment are inconclusive, single-point piezometers should be installed in key areas as determined from the analysis.*

### *6.2.5 Using the Jacobian to Determine Weights for Targets*

Weights were determined by optimizing the condition number of the Jacobian. N-I (2013, p. 5-91) explains the reasoning for the weighting:

> "the steady-state solution does not constrain the hydrologic parameter estimation process, whereas the transient MWAT run does improve conditionality of the parameter estimation process. Therefore, if all the weights are assigned to the steady-state heads, then the problem is poorly constrained, as the steady-state heads can be reproduced by numerous combinations of parameters and boundary conditions, and consequently, the model rapidly converges in close proximity to initial estimates of the parameters. On the other hand, because the region of influence of the MWAT does not extend over the entire study area, imparting all weights to the MWAT would not allow all model parameters of interest to be estimated. Therefore, it is important to properly assign calibration weights to the steady-state head and transient drawdown targets so that the parameters are correctly identified."

Determining weights by optimizing the condition number is a mathematical artifact that is dependent on the model construction and does not reflect the reliability of the field measurements related to well construction and measurement procedures. Weights should be used to reflect the reliability of the measurements.

***Recommendation:*** *The peer review team recommends determining weights for each target by evaluating the quality of the target data based on well construction and measurement procedures.*

### 6.2.6 Field Measurements of Hydraulic Conductivity Not Honored in the Calibrated Models

Estimated parameter values are not consistent with equivalent field measurements as described in detail in Section 6.3.

***Recommendation:*** *The peer review team recommends that parameters be estimated without bounds, and the estimated parameter values be compared with equivalent values measured in the field. Substantial differences between the parameter values estimated by the calibration and the values measured in the field are an indication that there is a problem with model conceptualization or construction. These clues should be used to improve the model. If the parameters are unreasonable, adjust the model conceptualization and/or construction.*

## 6.3 Uncertainty in Hydraulic Properties and Pathways

### 6.3.1 Country Rock

For the purposes of this report, the peer review team defines “country rock” as rock and alluvium that is simulated as material between zones of identified faults that is undisturbed by fracturing or other deformation associated with nuclear detonations. As such, country rock does not include fault cores or disturbed zones of enhanced fracturing that parallel faults. As observed in core, however, country rock beneath Yucca Flat is locally fractured, and small faults occur between many of the major faults.

#### 6.3.1.1 Limited Characterization of Aquifer Properties

Hydraulic conductivity data have been collected at different scales. These scales have been referred to in N-I (2013) as pumping scale, slug-test scale, and laboratory scale. Researchers have developed methods to utilize the data from different scales in numerical models using upscaling methods. The modeling has not been forced to match the hydraulic conductivity measurements from any scale, and the combinations of measured values that would represent continuous high hydraulic conductivity zones have not been included in the uncertainty evaluation of the contaminant boundary.

Characterization of representative hydraulic properties at the model scale is limited. Many of the data are from small-scale core samples, slug tests, and single-well pump tests. In all of Yucca Flat, with

6 HSUs and 108 fault zones for which permeabilities are estimated in the numerical model, there is only one long-term aquifer pumping test with observation wells to quantify hydraulic conductivity of a single unit, the LCA. Pumping-scale single-well tests, although less accurate and therefore less representative of values needed for the simulations than MWATs (with observation wells), indicate hydraulic conductivity varies over four orders of magnitude in the LCA at Yucca Flat (N-I, 2013, Fig. 5-11); consequently, one multi-well aquifer pumping test is not sufficient to characterize transport in the LCA.

Detailed aquifer tests, such as the one at ER-6-1, are the essence of developing a site conceptual model and building confidence in that model. For example, the hydraulic response tests demonstrate that "(t)he Yucca Flat LCA is highly heterogeneous, both laterally and vertically..." and that "the LCA hydraulic conductivity is highly spatially variable and reflects the observed differences in fracturing and fault density." MWAT-type aquifer tests reveal useful information about the important geologic structures that affect flow.

> ***Recommendation:*** *The MWAT at ER-6-1 (1) provided the only calibration data that somewhat reduce the non-uniqueness of the Yucca Flat model calibration yet renders only seven of the many model parameters identifiable (all in the vicinity of the MWAT) and (2) did not test the central or western portions of Yucca Flat. Consequently, the peer review team recommends additional large-scale MWATs in the central and western portion of Yucca Flat to assess hydraulic properties of the country rock and faults, and to evaluate boundary conditions. Otherwise, there is little basis to justify setting such markedly lower permeabilities in the LCA west and central zones, compared with the permeability in the LCA east and ER-6-1 MWAT results.*

#### 6.3.1.2 Model Permeabilities Inconsistent with Field Measurements

The spatial distribution of pumping-scale permeability values (Figure 6-1) does not appear to support zoning the LCA into the three zones indicated in Fig. 5-29 of N-I (2013). Given the distribution of test results displayed in Figure 6-1, it could be argued that there is justification for zonation separating north from central from south, and that the east side may be less permeable than the west side. Thus, there is considerable uncertainty in not only the permeability within an LCA model zone, but uncertainty in whether the zones are reasonable and defensible partitions to simplify the hydrogeologic framework. For example, given the limited western extent of the model domain, the general clockwise groundwater flow pattern in the LCA beneath Yucca Flat, which is inexplicably northward in the LCA model on the west side of the major faults, is partially caused by the hydraulic

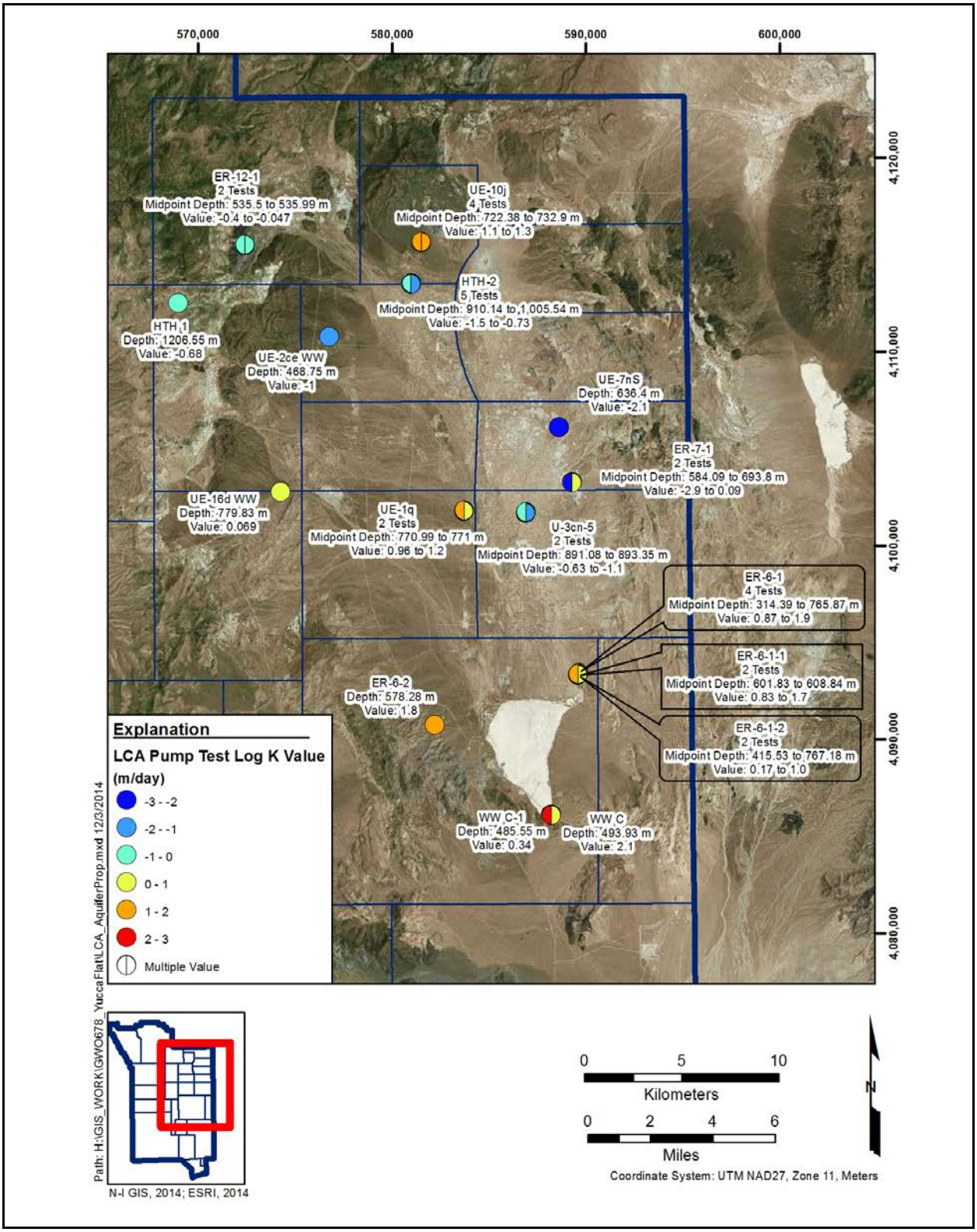



***Figure 6-1***
***Spatial Distribution of Pumping-Scale Hydraulic Conductivity Values for the LCA***
Source: Andrews, 2014b

conductivity distribution used in the model, which induces more flow to the more permeable east side of the basin before exiting to the south.

In the existing groundwater models, the process of flow in spatially variable heterogeneous media is not captured in either the AA/VA matrix or the LCA matrix. In the simulations, the hydraulic conductivity of the LCA was homogeneous within each of three geographic zones of the LCA (west, central and east); and the entire units of LCCU, LCA3, and UCCU were homogeneous. Uncertainty in the contaminant boundary due to LCA country rock heterogeneity was only approximated by allowing the conductivity in the zones of country rock to vary from one calibrated simulation to the other. Therefore, the conceptual model of a highly heterogeneous hydrogeologic system is not supported by the numerical model, except if one considers the faults together with the LCA country rock.

Spatial variability is discussed in N-I (2013) and is commonly considered in standard model-development protocol, but the effects of this well-known factor on flow and transport have not been addressed in the Yucca Flat models. A more refined representation of the spatial distribution in hydraulic conductivity, beyond the three LCA zones has not been included in evaluating the contaminant boundary, despite what appears to be a fair number of data for defining a more complex spatial distribution. In the AA/VA, there are 44 reported pumping-scale tests, 22 slug tests, and 68 lab cores. In the LCA, there are reportedly 36 pumping-scale tests, 9 slug-scale tests, and 4 core tests. The spatial distribution of the pumping-scale data is shown in Figure 6-1. Based on these field data, the basis for this three-zone (west, central, and east) partitioning does not appear to be justified.

Permeability values obtained by calibrating the model do not honor the available field data collected at the pumping-test scale. In the LCA west, model calibration of the base case estimated $1 \times 10^{-14}$ square meters ($m^2$) (N-I, 2013, Table 5-11), but field data range from about $10^{-13}$ to $6 \times 10^{-11}$ $m^2$ (Figure 6-1). In the LCA west zone, the field data show LCA country rock permeability is more than 1,000-fold greater than the model. In the LCA central zone, model calibration of the base case estimated $1.8 \times 10^{-14}$ $m^2$, and field data ranged from about $3 \times 10^{-14}$ to $1 \times 10^{-10}$ $m^2$. The field-permeability-test data range up to nearly 10,000-fold greater than the calibrated model for the LCA central zone. In the LCA east zone, model-calibrated permeability for the base case is $1.25 \times 10^{-12}$ $m^2$, whereas field data range from $1.2 \times 10^{-15}$ to $5 \times 10^{-11}$ $m^2$, up to about 40-fold greater than the permeability in the calibrated model.

Permeability values selected to represent the LCA country rock in NSMC simulations are also inconsistent with the field data shown in the cumulative probability distributions for country rock permeability, which were recently presented to the peer review team (Andrews, 2014c). The country rock permeability distribution for the LCA west and LCA central zones suggests that the population of values sampled is roughly 10 times less permeable than the population represented by the distribution obtained from the LCA pumping-scale values shown in Figs. 5-11 and 6-2a,b of N-I (2013). Conversely, the cumulative probability distribution derived from the NSMC simulations for the LCA east is roughly 10 times more permeable than the dataset shown in Figs. 5-11 and 6-2 of N-I (2013). Overall, from the NSMC runs used in the flow model sensitivity analysis, the calibrated LCA permeability values ranged up to $3 \times 10^{-11}$ $m^2$ (Andrews, 2014a), which is about to the 85th percentile on the cumulative probability distribution of field measurements (N-I, 2013, Fig. 5-11); consequently, the NSMC sensitivity analysis does not appear to capture the full range of uncertainty in permeability measurements at the pumping-test scale.

There is also an apparent inconsistency in the values of hydraulic conductivity derived from independent analyses of the MWAT and from the model calibrations. For example, Table 6-4 of N-I (2013) shows that at ER-6-1 upper, K = 100 meters per day (m/day) and at ER-6-1 lower, K = 85 m/day. In contrast, earlier analyses for these same intervals indicated K = 71 to 76 m/day (SNJV, 2005a, Table 3-1), about 10 to 25 percent lower than values in Table 6-4. This difference was not explained and suggests some uncertainty exists in parameters due to the method used to interpret the water-level time-series data. More importantly, both interpretations of the constant rate test data have values that are much greater than the maximum value of country-rock permeability sampled in the NSMC analysis; as provided, the CDF for 11_lcae (Appendix E), which shows a maximum hydraulic conductivity of about 10 m/day, and the “fast” NSMC case, is about 3 m/day.

Uncertainty in the hydraulic conductivity field of the east zone may affect model calibrated hydraulic properties and therefore affect flow and transport in other areas of the LCA. For example, the generally clockwise groundwater flow pattern in the LCA, starting in the southwest part of Yucca Flat, and the unreasonable prediction of northerly flow, is likely in part related to the relatively much greater permeability of the LCA east. Thus, modeled impacts from detonations in the west and central zones of the LCA show little transport because of the low permeability and correspondingly low groundwater velocity in the country rock. Consequently, the extent of the contaminant boundary may be underestimated. The low values of calibrated hydraulic conductivity in the central and western

zones of country rock may be attributable to a conceptual model that prescribes that there are numerous thick, permeable fault zones which, during model calibration, effectively mask the importance of the country rock. Furthermore, because the Yucca fault seems to have prevented drawdown from propagating to the west from ER-6-1, there are no observations of drawdown in the LCA central and west zones to verify the values obtained by model calibration.

The extent of the contaminant boundary from detonations in the LCA east area may be underestimated because the value of permeability from calibration assigned to the LCA country rock for the NSMC "fast" case ($3.06 \times 10^{-12}$ m$^2$) was less than the maximum permeability in the NSMC simulations ($3 \times 10^{-11}$ m$^2$) by a factor of 10. The LCA east permeability for the "fast" transport case also was less than the permeability of the MWAT interpretations by a factor of roughly 30 to 40.

Moreover, because the upper range of permeability values quantified by all the pumping-scale field tests in the LCA is greater than the upper limit assumed in the LCA model, the model is likely to underestimate the maximum extent of contaminant migration, especially if the high-permeability pathways such as those identified in the ER-6-1 test are continuous. Most of the large detonations with the greatest potential impact to groundwater are located in the east zone of the LCA country rock. Therefore, it is highly relevant to recognize the full range of hydraulic conductivity and its spatial variability in this area in order to not underestimate the southern extent of the contaminant boundary.

In addition to the concern that the model permeabilities are less than the values measured in field tests, it is important to note that given the limited testing in Yucca Flat, it is unlikely that the highest permeabilities have been captured by the field tests. Consequently the contaminant boundary is likely underestimated.

Vertically within the LCA, there is also significant spatial variability in hydraulic conductivity. For example, within ER-6-1 #2, roughly 70 percent of the flow was derived from about 25 percent of the 1,300 ft of the LCA evaluated by borehole spinner logging. The hydraulic conductivity of individual water producing horizons ranged from 0 to as much as 4,235 feet per day (ft/day) (SNJV, 2005a, Table 3-1), while $1 \times 10^{-11}$ m$^2$ (about 10 m/day; 33 ft/day) was the upper limit allowed for the permeability of the LCA in the numerical model calibration (N-I, 2013, Table 5-8). Many calibrations butted against this prescribed upper limit for the LCA east model zone, suggesting that the range should have been set to a higher value of permeability.

As will be discussed later, the model calibration process utilizes the MWAT time drawdown data. The result from calibration is that high permeability is assigned not to the LCA east, but to the faults, especially "untied" fault 147 (K = over 100 m/day), which is shown to be intercepted by and terminating near ER-6-1 #2 in country rock. It is notable that others have interpreted the MWAT pumping-test data without invoking a conceptual model that included the many local faults near ER-6-1 #2, such as fault 147; instead, they considered the LCA permeability (and transmissivity) as spatially variable (Halford, 2012). Thus, there seems to be some disagreement or uncertainty over the interpretation of the MWAT data and whether it is representative of the country rock, fault 147, or something in between.

> ***Recommendation:*** *The peer review team recommends honoring the available hydraulic properties data for the country rock in assessing uncertainty in the extent of the contaminant boundary. Unless the field-measured hydraulic conductivity data are weighted more heavily in parameterizing the model, the available information suggests that the southern extent of the contaminant boundary will be underestimated. The choice of NSMC run 46 as the "fast" scenario in evaluating the extent of the contaminant boundary seems to be misleading. The peer review team recommends reevaluation of the choice of a "fast" scenario and additional simulations to account for other uncertainties described elsewhere in this report.*

#### 6.3.1.3 Preferential Flow

Local-scale permeable pathways within the country rock of the LCA are not captured by the existing groundwater models. In the northern part of Yucca Flat, temperature-log profiles indicate significant horizontal flow within the carbonate aquifer in wells UE-2ce, WW-2, and UE-10j (Gillespie, 2005). In the southern part of Yucca Flat, spinner logs in wells ER-6-1 and ER-6-1 #2 show significant vertical variation in hydraulic conductivity, with values ranging from near zero to more than 4,200 ft/day in one discrete 30-ft-thick zone. Although N-I (2013) states that there are no measurements of permeability of major faults, the report concluded that the high-permeability zones in ER-6-1 area show the effects of the fault damage zone.

However, it is not clear whether this zone is attributable to fracturing or perhaps karst features. Karstic or cave-like features can be observed in the LCA outcrop near the Mercury entrance, and karstic zones are mentioned in the available reports (SNJV, 2005a, p 3-5; SNJV, 2006b, p. 6-51; Weary and Doctor, 2014). At two very closely spaced wells (WW C and WW C-1, which are approximately the same depth), the hydraulic conductivity differs by more than 100-fold, a contrast

that could be attributable to karstic conditions. Weary and Doctor (2014) indicated that the LCA is a unit of "dry climate karst," for which deep-seated solutional karst or paleokarst features may occur.

Karst features have been detected in deep wells in the LCA near the NNSS. According to records on file at the Nevada Bureau of Mines and Geology (NBMG) (2014a and b), two exploratory oil wells were drilled in 1990 and 1991, 1.8 mi south of Lathrop Wells (14.5 mi north–northwest of Devils Hole); the wells are "Felderhoff Federal No. 25-1" (API 27-023-005454), and "Felderhoff Federal No. 5-1" (API 27-023-05453). These wells are along the western flow path for the discharge area for Yucca Flat. On October 4, 1991, at 3,876 ft in Paleozoic limestone and dolomite, Felderhoff Federal No. 25-1 encountered "abundant caving." Felderhoff Federal No. 5-1 was plugged and abandoned at 1,468 ft due to lost circulation caused by many fractures and caverns. A USGS report on these wells (Carr et al., 1995) stated: "drill hole 5-1 encountered two large cavities 24 inches wide or more in dense carbonate rock of uncertain, but probable Paleozoic age. These openings may be tectonic and controlled by a regional system of northeast striking faults." The peer review team cites these wells as evidence that LCA formations not exposed above the water table during the Pleistocene are capable of containing solution cavities and/or enlarged openings along fault zones.

Transport along high-permeability pathways is difficult to model and to monitor; nevertheless, they can be the most important avenues for transport, because such zones may be more permeable than the fault zones. To illustrate, the hydraulic conductivity of 4,200 ft/day (about $1.3 \times 10^{-9}$ $m^2$) near ER-6-1 is significantly greater than the maximum permeability for the Yucca fault in the calibrated flow model, $4 \times 10^{-10}$ $m^2$. If this high-permeability measurement is attributable to dissolution, instead of fault damage, and if the pathway is continuous, then the extent of the contaminant boundary will be underestimated unless this source of geologic uncertainty is eliminated or reduced.

Using average effective hydraulic properties to represent large zones of the LCA is not likely to capture the most permeable pathways within the fractured country rock matrix.

> ***Recommendation:*** *The peer review team recommends a thorough examination of all the field data relevant to the question of whether karst features do exist and are continuous below the water table. This would include reviews of drill logs (e.g., lost circulation, rod drops), geologists notes, borehole flowmeter data, geophysical logs (televideo logs, caliper, others), outcrop descriptions, and stratigraphic correlations of anomalous features. New monitor wells should be analyzed specifically with karst features in mind. Determine whether the karst features do or do not exist, and if they cannot be ruled out, include alternative flow and transport simulations that do include karst features.*

### 6.3.2 Representation of Faults

Another key element in developing the model is identifying migration pathways. In the basic conceptual model, there are approximately 178 normal faults and several thrust faults in the bedrock units. Each normal fault is represented with one low-permeability core node and at least two higher-permeability damaged zone nodes on each side of the core node with a nodal spacing of 125 m. Faults are portrayed as permeable pathways, and including so many of them in the model is intended to account for the highly heterogeneous nature of the LCA.

However, there is not a single measurement of the hydraulic conductivity of the main fault zones; as noted by N-I (2013, p. 5-85): "there are no field tests that represent permeability values in the major faults." Model calibration results show fault permeability varies over a wide range, about 10,000 fold. Where there are data that may reflect enhanced permeability along faults, the permeabilities are not directly assigned to nodes in the model. Instead, the model parameter-estimation procedure selects values of permeability from a specified range, given there is an acceptable calibration to hydraulic head data. At the MWAT at ER-6-1, a relatively high-permeability interval was quantified using spinner logs. This interval has a hydraulic conductivity of 4,200 ft/day (a permeability of about $1 \times 10^{-9}$ m$^2$; 1,280 m/day). If this interval reflects fault damage, then this value is 2.5 times greater than the maximum value of permeability ($4 \times 10^{-10}$ m$^2$; N-I, 2013, Table 5-11) obtained from the model calibration for any fault. It is not clear why, if ER-6-1 is believed to represent fault damage, that this value was not considered for assignment to all or some of the faults in an alternative conceptual model.

> ***Recommendation:*** *It is unlikely that the only multi-well test in Yucca Flat identified the highest value of fault damage-zone permeability. The peer review team therefore recommends that the range considered for modeling extend well above the highest measured value. Given that none of the major faults have been investigated in the field, include alternative models with permeable faults and no impermeable core to determine their effect on the flow field and transport.*

Great emphasis was placed on a geological framework that stressed the importance of the major faults—in particular, the Yucca, Topgallant, and Carpetbag fault systems. However, in the calibrated dataset (N-I, 2013, Table 5-11) and in the NSMC run 46 "fast" flow field, which are used to illustrate the extent of the contaminant boundary, none of these major faults has a permeability as high as those of some of the "minor" faults in the eastern part of Yucca Flat, which exceed $1 \times 10^{-10}$ m$^2$. In fact, for

these runs, the three major faults are about as permeable as the surrounding country rock, on the order of $1 \times 10^{-12}$ to $1 \times 10^{-14}$ $m^2$.

The major faults do not seem to play an important role in the transport simulations, as it is the minor faults that have the highest permeability, and most of these faults are relatively short, compared with the major faults. In simulations with the calibrated data (N-I, 2013, Table 5-11), there are 4 faults, all east of Yucca fault, with permeability greater than $1 \times 10^{-10}$ $m^2$; and in the "fast" simulation NSMC run 46, there are 12 faults, all east of Yucca fault, with permeability greater than $1 \times 10^{-10}$ $m^2$. Inexplicably, the high-permeability zones are not in the long major fault zones as one might have expected from the geological framework presented. Furthermore, the country rock between and near the Yucca and Topgallant fault systems, which likely was subjected to more tectonic stress than anywhere in Yucca Flat, is represented as with no greater permeability (e.g., due to fracturing) than country rock far removed from these major fault systems.

Fenelon et al. (2012, p. 29) stated:

> "The inverted V-shape pattern of the carbonate-aquifer contours, which generally parallels the carbonate aquifer boundary, is accentuated by the heterogeneity and anisotropy of the carbonate aquifer. The low-hydraulic-gradient, central corridor of Yucca Flat is parallel to the series of normal faults that transect the basin in a north–south direction (pl. 4). This low-gradient potentiometric trough, which extends southward to Ash Meadows (fig. 1), has been recognized by previous investigators and has been interpreted to be a highly transmissive corridor that is less than 3 mi wide (Winograd and Thordarson, 1975; Winograd and Pearson, 1976). This several-mile-wide trough in Yucca Flat is thought to be a zone of high transmissivity relative to the carbonate rock to the west and east. Additionally, the aquifer is highly anisotropic, with enhanced flow parallel to the trough as a result of the high degree of open faults and fractures along the axis of the trough."

Fenelon et al. (2012, p. 22) also recognized the possibility of enhanced permeability in the eastern part of Yucca Flat:

> "A large number of subsidiary normal faults occur east of Yucca fault in eastern Yucca Flat (section D–D', pl. 1). It is possible that the aggregate width of fractured rock associated with these faults sufficiently enhances the permeability of the carbonate aquifer to create a broad zone of carbonate rock with elevated permeability. The existence of such a zone would help explain the extremely low north-to-south gradient of the potentiometric surface in east–central Yucca Flat."

> ***Recommendation:*** *The peer review team recommends assigning increased permeability to the material that is currently simulated as the country rock near the major faults in the analysis of uncertainty.*

The recently provided cumulative probability functions for hydraulic conductivity of the major faults (Andrews, 2014c; see Appendix E of this report) shows striking contrasts in the distributions. The CDFs of the two adjacent Yucca fault lines 145_yf1 and 148_yf2 are completely different from one another, with the central tendency of the permeability of Yucca fault 148 to be about 100 times smaller than Yucca fault 145. The two fault lines for the Topgallant fault, 178_topgalla and 190_topgalla, while much more similar to one another, tend to be much less permeable than the Yucca faults, especially 145. There does not seem to be geological basis for such significant differences in the populations of fault permeability. In addition, none of the CDFs for the major faults appear to include the highest conductivity value measured, 1,280 m/day, the only measurement in Yucca Flat reported to be in the fault damage zone. Again, it is unlikely that the limited field investigations have identified the highest values beneath Yucca Flat; thus, the ranges considered in model evaluation should extend above the highest measured values.

It is potentially relevant to the prediction of the contaminant boundary that the permeability of the two sub-parallel Yucca fault lines is so different. Most of the detonations lie east of Yucca fault where there are a number of discontinuous highly permeable faults. To be consistent with the geological framework, which establishes that the major faults are the main transport pathways, flow to and through these faults should be facilitated in the model. However, Yucca fault 148, which is the easternmost of the two sub-parallel Yucca fault segments, generally has much lower permeability than Yucca fault segment 145. That is, it appears that for the large majority of the simulations, the eastern Yucca fault 148 inhibits flow and transport to the much more permeable pathway in Yucca fault 145. If Yucca fault 148 were assigned a CDF similar to that of Yucca fault 145, more of the simulated scenarios would exhibit a greater extent of southerly migration and the contaminant boundary would potentially be larger.

Additionally, the CDFs (see Appendix E) for the major faults from the calibrated simulations are inconsistent with the conceptual representation of fault zones in Fig. 6-2b of N-I (2013). In general, with exception of Carpetbag fault segment 176_yf_50b, the CDFs have little to only minor resemblance to the CDF expected for faults, based on pumping-scale data that were partitioned into “fault zones” and “country rock” (N-I, 2013, Fig. 6-2b). Most of the fault CDFs derived from the

simulations have distributions that are more consistent with data considered representative of "country rock." There should be some explanation for why many of the faults appear to have lower than anticipated permeabilities.

The MWAT at ER-6-1 is reported to reflect the permeability of a fault damage zone. The pumped well ER-6-1 #2 is located at the southern end of fault 147 (147_yf_103n1). The CDF for fault 147 shows a relatively high-permeability distribution. Many of the calibrated simulations used the maximum value in the range allowed for this fault, $4 \times 10^{-10}$ m$^2$. The maximum field measured permeability was $1 \times 10^{-9}$ m$^2$ from the spinner logs. Thus, there seems to be justification to allow for a greater permeability range specified for the faults on Table 5-8 of N-I (2013), including fault 147.

Except for fault 147, based on the CDFs shown in Appendix E, on average in the vicinity of the MWAT, the faults are not much more permeable than the LCA east country rock, and in fact the only continuous fault connecting the vicinity of ER-7-1 to ER-6-1 #2 (169_yf_119n1) is on average less permeable than the LCA east country rock. As with the major faults, the CDFs of the faults near the MWAT suggest that each fault has a unique permeability distribution. While this could be the case, a reasonable alternative is that the minor faults are all equally permeable and have a permeability that comports with the high-permeability zone from the spinner log test in ER-6-1 #2. Similarly, a reasonable alternative to consider is a conceptual model in which the major faults are even more permeable than the minor faults, owing to the greater displacements, if all other rock mechanical properties are the same.

The conceptual model presented to the peer review team is that faults in the AA/VA system are preferential pathways for flow and transport into the LCA. According to Table 4-4 of N-I (2013), maximum fault permeability used in the cases simulated is only $1 \times 10^{-12}$ m$^2$. This fault permeability is the same as that of the AA matrix (N-I, 2013, Table 4-4); and for four of the seven cases, the faults are less permeable than the AA units. In some cases simulated, the faults that cross the TCU are also less permeable than some of the HSUs that comprise the TCU. Thus, faults in the AA/VA system do not appear to consistently function as conduits, either horizontally or vertically. Faults in the AA/VA also seem to have the same permeability whether they cut across the AA or TCU, and fault permeability in the AA/VA system is the same for all faults within a case simulated, in contrast to the way fault permeability variability is characterized in the LCA using CDFs.

***Recommendation:*** *The peer review team recommends that the effect of greater fault permeability in the AA/VA model should be explored in CADD/CAP, and if model tests show that fault permeability in the AA/VA system is relevant to the LCA contaminant boundary prediction, field data should be collected to characterize AA/VA fault behavior.*

Although the conceptual model is one in which faults are the key pathway to the LCA, the simulations show that many of the faults are not modeled as highly permeable. For example, in Table 5-11 of N-I (2013), 38 of the faults have the same low value of permeability, $4.38 \times 10^{-14}$ $m^2$, which is close to the low end of the specified range and close to the calibrated permeability for the LCA country rock in the central and west zones. Many of these low permeable faults are in the LCA east zone. Faults that have lower permeability than the country rock will be barriers to flow into the LCA instead of permeable pathways. The simulations and the portrayal of impacts to the LCA from the numerous faults in the basin are inconsistent with the conceptual model derived from the detailed structural geologic analysis of the fault systems.

***Recommendation:*** *The peer review team recommends that the uncertainty in the contaminant boundary due to all the faults serving as permeable pathways to the LCA be evaluated, and alternative models include faults without impermeable cores.*

There is considerable uncertainty in the permeability assigned to the faults, especially the long, major faults.

***Recommendation:*** *The peer review team recommends including an alternative conceptual model that has no or many fewer minor faults in the LCA; this may require allowing flow and transport to occur between the AA/VA and LCA via the TCU (fractured) as described further below, in addition to the major faults. For example, flow in the LCA in Yucca Flat was recently modeled without faults by Halford (2012).*

### 6.3.3 Tuff Confining Unit

The importance of heterogeneity on the process of flow across the TCU is not considered in the uncertainty analysis, except at faults. Although there is only one pumping-scale measurement in the TCU at Yucca Flat, there are a considerable number of data collected throughout the NNSS investigation area (e.g., SNJV, 2006b, Fig. 6-17). The NNSS data appear to follow nearly a lognormal distribution, which is typical, and span nearly six orders of magnitude. Most likely, there are fractures that explain the high-permeability range in the TCU dataset, which actually overlaps the upper end of permeability for the LCA at Yucca Flat (compare with SNJV 2006b, Fig. 6-19). The mean

permeability from the NNSS-wide dataset for the TCU is about $1 \times 10^{-13}$ $m^2$ (about 0.3 ft/day), which is nearly 10 times larger than the value (about $1 \times 10^{-14}$ $m^2$) obtained from the model calibration in the LCA central and west areas (N-I, 2013, Table 5-11). Thus, in these two areas of the LCA model, available hydraulic conductivity data suggest that the TCU could be as permeable, or more so, than the LCA country rock. The process of vertical flow through the TCU to the LCA, other than by faults, has not been adequately accounted for in either the conceptual models or the numerical models of Yucca Flat.

Recognizing that there may be more permeable zones within the TCU is important in developing alternative conceptual models. For example, an alternative conceptual model that was not considered is a more permeable tuff matrix in the confining unit, at least in places, in lieu of, or as a complement to, the numerous faults, some of which have locally high-permeability zones through the TCU. Based on available permeability data for the TCU (N-I, 2013, Fig. 4-12), it is possible that a water flux ranging from perhaps 5 to 50 kg/s, or more, rather than 0 kg/s as assumed, occurs as leakage through the matrix rock of the TCU in the central part of Yucca Flat underlying the AA/VA, based on Darcy's Law calculations of the type used by Winograd and Thordarson (1975).

Several other observations suggest that the vertical permeability of the TCU may be locally higher than modeled. For example, it appears that most or all of the recharge through Rainier Mesa (several centimeters per year [cm/yr]) passed through this unit before construction of the tunnel complexes that short circuited drainage out to the edge of Rainier Mesa. Alternative models are proposed for diversion of the recharge westward rather than downward, but the fact remains that it is plausible that the TCU can support downward fluxes of several centimeters per year, rather than the several tenths of millimeters per year that are used in the AA/VA model. Secondly, the majority of perched springs in the Yucca Flat area emerge near the contact of the TCU with the underlying clastic aquitard (Eleana Formation), suggesting that the Eleana Formation forms the relatively low-permeability perching layer, rather than the zeolitic tuff being the limit to vertical transport. Beneath Yucca Flat, the Eleana formation is largely absent, suggesting that leakage through the TCU would directly reach the LCA system. Third, geochemical mixing models of wells in the LCA suggest predominantly local sources of recharge in places, such as near UE-2ce, in an unfaulted area. Fourth, MWAT data has been interpreted as showing the test encountered constant head boundary conditions, one explanation for which is leakage across a fractured TCU.

There also was a detailed study of fractures in four core holes in Area 7 (NSTec, 2008), which indicated that fractures exist in the TCU, and there is uncertainty in the degree of fracturing. While the results of that study

> "indicate that the TCU in the central portion of Yucca Flat is poorly fractured,...the core holes analyzed in this study are located significant distances (greater than 609.6 m [2,000 ft]) from major faults. Also, because only natural fractures were examined, fractures that may have formed as a result of underground nuclear testing were not included in the analyses. The potential for increases in permeability due to enhanced fracturing of the TCU beneath Yucca Flat by faulting and underground nuclear detonations is poorly understood (Laczniak et al., 1996)."

Uncertainty in the location of the contaminant boundary due to fracturing in the LCA should be considered as it affects permeability, effective porosity, and the hydrogeologic boundary with the LCA.

***Recommendation:*** *The peer review team recommends that uncertainty in the contaminant boundary include an alternative conceptual model for analysis of the importance of flow across a TCU that is not impermeable but rather honors the available data on hydraulic properties of the TCU.*

***Recommendation:*** *Given the importance of the TCU to isolate much of the radionuclide inventory, the peer review team recommends developing new data and hydraulic field testing to determine the lateral continuity of the TCU as an effective hydraulic barrier to vertical transport.*

### 6.3.4 Effective Porosity

While conceptual models used for the LCA fault zones, their structure, width, and permeability are consistent with general hydrologic principles, the choice of parameters and geometry is speculative, as little or no field data are available to guide these choices. Effective porosity is a critical factor in determining transport domains; however, field-measured effective porosity data are largely absent in the AA/VA and TCU. In addition, where effective porosity data are available for materials characterized as porous media, they do not represent the effective porosity for transport, as from tracer tests; rather, the data represent drainable pore space from moisture retention curves. The data are insufficient to determine whether the values used for connectivity, hydraulic conductivity, and effective porosity are conservative.

Appropriate characterization of effective porosity in the AA/VA and TCU is highly relevant to evaluating impacts to the LCA. For example, transport in the TCU is assumed as flow in porous media, without any fracturing. To reflect this conceptualization of an unfractured TCU, the effective porosity of the TCU is roughly 100 times larger than in the fractured LCA (N-I, 2013, Table 4-6). The travel time downward across the TCU via low porosity fractures may increase the radionuclide mass flux into the LCA in comparison to the travel time laterally in the AA/VA then downward in a fault.

> ***Recommendation:*** *Evaluate the uncertainty in the extent of the contaminant boundary due to effective (fracture) porosity of the TCU.*

### 6.3.5 Potential for Flow of Surface Water into Fractures in the Alluvium

In Appendix E, the peer review team summarizes information on the potential for flow of surface water into fractures in the alluvium, including observations of open fractures at the surface. Some faults in Yucca Flat definitely reach the surface and may be drains for flow of surface water into the ground. Many or most of the other faults that cut the Tertiary volcanic rocks also come close enough to the surface to be potential conduits for flow of surface water to the water table. Several faults have been reactivated by nuclear detonations, generally with displacements in the same sense as their pre-testing, tectonic displacements. Ponding of water—in craters, at Yucca Lake, and at other local depressions—is likely to enhance percolation of surface water into faults in the alluvium.

> ***Recommendation:*** *Modeling should include the reasonable and conservative approach that would permit faults to be local zones of preferential flow through the unsaturated and saturated alluvium into the underlying stratigraphic units.*

> ***Recommendation:*** *Field measurements are recommended to ascertain the degree to which fissures contribute to enhanced local recharge and local groundwater flow directions, including the earth fissures near Yucca Lake and the fissures associated with faults that extend to the surface in the alluvium.*

### 6.3.6 Anisotropy and Preferential Flow in the Unsaturated Zone

In the UZ model, some processes pertaining to water flow were not considered. A process that enhances lateral flow due to moisture-dependent anisotropy was not included in the simulations. This process causes increasing anisotropy with decreasing moisture content and would likely be most relevant in stratified materials. Ignoring this process leads to more rapid downward migration. Consequently, wetting fronts and transport downward to the TCU/LCA calculated in the model are

likely to be conservative (i.e., lack of anisotropy will lead to more rapid vertical transport than would otherwise occur). Additionally, hysteresis was not considered in any of the simulations. Hysteresis, which is relevant to intermittent wetting and drying events, also tends to slow the downward movement of the wetting front. Ignoring hysteresis leads to models that overestimate the downward rate of contaminant migration. In both of these cases, the existing UZ model would likely overestimate vertical transport, and the model choice is therefore judged by the peer review team to be conservative in nature.

On the other hand, preferential flow in the unsaturated zone has not been included or considered in UZ model sensitivity analysis. Preferential flow could be important in predicting rates of water infiltration from the bottoms of craters, especially before the crater bottoms may seal. Vertical preferential pathways created by the collapse chimneys would destroy existing stratification, which would have otherwise enhanced lateral flow migration from the crater through the unsaturated zone. To date, no data are available from directly above cavities to determine whether rapid infiltration has reached any of the above-water table detonations.

> ***Recommendation:*** *During the CADD/CAPP process, data collection efforts should be undertaken at those craters determined via field testing or modeling to have high rates of enhanced recharge to determine the maximum depth of recent infiltration and possible flow through preferential pathways to detonation cavities.*

## 6.4 Source Term and Mass Flux to the LCA

The concentration of radionuclides in water in the cavity is important to modeling of the contaminant boundary. This concentration is calculated from the masses of radionuclides available for dissolution divided by the volume of water available for that dissolution. The radionuclides available are the total inventory (the RST) times the proportion of the RST that partitions into the aqueous phase. The water volume is the pore space in the exchange volume if the cavity is saturated or the volume of water that flows through the cavity. There are uncertainties in all these factors, some of which are explicitly addressed and some of which are not.

### 6.4.1 No Uncertainty Associated with the RST

The inventory of radionuclides produced by a nuclear detonation depends on a number of factors. According to the International Atomic Energy Agency (IAEA) (1998, p. 92), radionuclides present after a nuclear detonation have several sources:

- Residual fuel materials
- Reaction products of fuel materials
- Fission products
- Activation products of non-fuel device components
- Activation products of construction materials and detonation host rocks

To these, the following should be added:

- Radionuclides that may have been added to a device as tracers (e. g., $^{14}C$ added to HANDCAR, according to Carle et al., 2008)

Thus, the radionuclides from each detonation will depend on the device design and performance and on the test design.

According to Rose et al. (2011), the inventories of each underground test at the NNSS are fairly well known from measurements on samples of detonation residua collected from post-shot drilling or excavations. These have been reported by Miller et al. (2002). However, this information is classified.

For the purposes of the UGTA Activity, an unclassified inventory has been developed consisting of the total inventories of all detonations in each CAU. The inventory for the YF/CM CAU is subdivided into totals of detonations with working points above and below the water table. ("Water table" in this context refers to an elevation 100 m above the measured water table.) The inventories for individual detonations in the Frenchman Flat (NNES, 2010b) and Pahute Mesa (Rose et al. 2011) CAUs are taken as the decay-adjusted total inventory per CAU divided by the number of detonations in the CAU. For Yucca Flat, the inventory per detonation is the decay-adjusted total inventory per CAU weighted by the proportion of the detonation yield to the total yield of all detonations in the CAU.

The peer review team is required to consider only maximum yields and average inventories while addressing the RST. However, it is also charged to consider whether all key processes are included. Thus, the peer review team would be remiss not to note that uncertainties in the RST are not included

in the calculations. In particular, the method of calculating the inventories of individual detonations assumes that all devices in a given CAU were of equal design and performance, which certainly was not the case. However, no uncertainties representing the differences between individual detonations and the average are applied to the inventories used.

> ***Recommendation:*** *The peer review team suggests that uncertainties in the RST values be included in the modeling. It would be possible to evaluate unclassified RST uncertainties by comparing the unclassified inventory of each detonation calculated as above with the corresponding classified inventories from Miller et al. (2002). The distribution of differences would evaluate the uncertainties in the unclassified RST values based on the average CAU inventories without revealing any information about individual classified RST values.*

Note that the UGTA Activity already uses classified inventories and other classified data. For example, as discussed below, factors for the partitioning of U and Pu into test debris and water for the CHANCELLOR test were calculated from classified analyses of debris samples and the classified inventory (Rose et al., 2011, Section 5.0).

### 6.4.2 Uncertainties in Partition Factors Are Not Well Defined Particularly for Cavities in Carbonate Rock

The radionuclide information important to this work is the inventory available for transport rather than the total inventory (RST). Gaseous and dissolved radionuclides are most readily available; followed by radionuclides sorbed on the rubble, which can be released to solution fairly rapidly; and, finally, radionuclides in the glass, which dissolves slowly. Partition factors represent the proportions of the RST that are found in the glass, rubble, water, or water plus glass.

The most direct approach to evaluate partition factors would be to sample water and detonation debris from representative cavities and calculate partition factors for radionuclides directly from these data and RST values. This has been done only once at the NNSS for the CHANCELLOR detonation, a 143-kiloton (kt) device detonated on Pahute Mesa in the Echo Peak rhyolite at a working point depth of 624 m on September 1, 1983. A reentry hole was drilled in August 2004. From this and two side-track holes, samples of glass and rubble were collected. Approximately the bottom one third of the cavity was water-filled. A sample was taken from this water in September 2004 after extensive pumping. Rose et al. (2011) describe the sampling and the analytical procedures, and give the unclassified analytical results and partition factors calculated from them. Analytical data for U and Pu

are classified, but partition factors calculated from them and from the classified Miller et al. (2002) inventory are given.

Before the Rose et al. report, the only partitioning data available were those developed by the IAEA (1998) as part of a radiological assessment of the impact of French weapons tests carried out in 1995 and 1996 at the Mururoa and Fangataufa atolls in French Polynesia. These tests were carried out in basalt saturated with seawater, so their relevance to conditions at the NNSS is questionable. However, they were the only partitioning data available for the early UGTA work, and many of the NNSS values are still based on them.

Rose et al. (2011) calculated partition factors using RST values in three different ways, which are described in detail in Section 4.1 of their report. The first approach used the total unclassified inventories for Area 19 (Pahute Mesa CAU) divided by the number of detonations in the CAU. The amount of glass produced was based on the rule of thumb that 1,000 metric tons of glass is produced per kiloton yield (Rose et al., 2011, Section 1.4), and the glass-bound inventory was calculated from the measured glass concentrations. For all but highly soluble radionuclides, the remainder of the inventory is assumed to be associated with the rubble. The second approach also uses the unclassified inventory with masses of melt glass, rubble, and water estimated from a careful material-properties evaluation and a particular interpretation of which samples represented glass concentrations and which represented rubble concentrations. The third approach does not use the unclassified inventory but instead uses fission-product yields and the yield of the device to estimate masses of fission products in the melt glass.

The results are given in Table 6-2, which summarizes results given in Tables 4.2 through 4.5, and 7.1 of Rose et al. (2011). The “Unclassified inventory,” “Fission yield,” and “Glass, rubble, and water amounts” columns are values calculated by each of these approaches. The partition factors recommended by the IAEA are given in the columns labeled “IAEA (1988).” Except for $^{137}$Cs, values calculated using the unclassified inventory differ widely from those given by the IAEA. They seem unreasonable in that only 55 percent or less of the refractory elements Eu and Am would partition into the glass and that two Eu isotopes have different partition coefficients despite the fact that they should have virtually identical chemical behavior. Rose et al. (2011) attribute this difference to errors in the unclassified inventory. This supports the contention in the previous section that it is important to assess the uncertainty in the unclassified inventory values.

## *Table 6-2*
## *Partition Factors Calculated by Rose et al. (2011) by Several Methods for a Detonation in Rhyolite, and as Given by the IAEA (1998) for a Seawater-Saturated Basalt, Compared with Ranges of Values Used in the Source Term Calculations*

| Nuclide | Unclassified Inventory [a] | Fission Yield [b] | Glass, Rubble, and Water Amounts [c] | Adjusted Glass, Rubble, and Water Amounts [d] | | | IAEA (1998) [e] | | | Ranges Used for HST [f] |
|---|---|---|---|---|---|---|---|---|---|---|
| | Glass (%) | | | Glass (%) | Rubble (%) | Water (%) | Glass (%) | Rubble (%) | Water (%) | Glass (%) |
| $^{60}$Co | -- | -- | 62 | 91 | 9 | 0.01 | 90 | 10 | 0 | -- |
| $^{99}$Tc | 45 | 47–63 | -- | 45–65 | 35–55 | 0.3 | 80 | 20 | 0 | 40–80 |
| $^{125}$Sb | -- | 7–384 | 63 | 60 | 39 | 1 | 70 | 30 | 0 | -- |
| $^{129}$I | 1.5 | 1–4 | -- | 1–28 | 24–45 | 43–66 | 50 | 40 | 10 | 10–50 |
| $^{137}$Cs | 36 | 32–47 | 58 | 40 | 60 | 0.07 | 25–40 | 60–75 | 0 | 25–40 |
| $^{152}$Eu | 37 | -- | 61 | 94 | 6 | 0.01 | 95 | 5 | 0 | 95–100 |
| $^{154}$Eu | 55 | -- | 63 | 95 | 5 | 0.01 | 95 | 5 | 0 | 95–100 |
| $^{155}$Eu | -- | 17–119 | 62 | 94 | 6 | 0.01 | 95 | 5 | 0 | 95–100 |
| $^{241}$Am | 39 | -- | 67 | 95 | 5 | -- | 98 | 2 | 0 | 95–100 |
| U | -- | -- | -- | 73 [g] | 27 [g] | <0.01 [g] | 90 | 10 | 0 | 70–90 |
| Pu | -- | -- | -- | 96 [g] | 4 [g] | <0.01 [g] | 98 | 2 | 0 | 95–100 |

[a] Based on Tables 4.2 and 7.1 of Rose et al. (2011).
[b] Based on Tables 4.5 and 7.1 of Rose et al. (2011).
[c] Based on Tables 4.3 and 7.1 of Rose et al. (2011).
[d] Based on Tables 4.4 and 7.1 of Rose et al. (2011).
[e] Based on Table 7.1 of Rose et al. (2011).
[f] Based on Appendix C (p. C-23) of N-I (2013).
[g] Based on Miller et al. (2002) inventory.

-- = Not reported

Ranges of values based on inventories calculated from fission product yields are given in the "Fission yield" column. The value for Cs is consistent with those from the other approaches, but values for the other elements reach above 100 percent, which is not possible.

Two sets of results are given for calculations based on material-balance estimates of the amount of glass, rubble, and water actually present. The first set, given in the "Glass, rubble, and water amounts" column, is based on one interpretation of which particular core samples represent glass and which represent rubble. While partition coefficients for Sb and Cs are consistent with the IAEA values, those for Co, Eu, and Am are unreasonably low for such refractory elements. Partition coefficients in the "Adjusted glass, rubble, and water amounts" columns are based on a different interpretation of the core samples and are entirely consistent with the IAEA values. However, there seems to be no *a priori* reason for preferring one interpretation of the core samples over the other.

Values for U and Pu given in the last two rows of the table were calculated using classified inventory data. These are consistent with the IAEA data and with the chemical properties of the elements.

The ranges of partition coefficients used for the HST calculations are shown in the last column. They appear to be an amalgamation of values given by the IAEA for basalt and by the adjusted model of Rose et al. (2011) for rhyolite. Because the primary reason for preferring the "Adjusted glass, rubble, and water amounts" in Table 6-2 seems to be that its results are similar to those given by the IAEA, the ranges of glass partition coefficients in the last column could well be extended to include the generally lower values of the "Glass, rubble, and water amounts" column. Lower glass partition coefficients would lead to higher HST concentrations indicating the values used for modelling may not be conservative. This leads to the following:

> ***Recommendation:*** *Develop arguments supporting the relevance of IAEA partitioning data to tests in silicate rock at the NNSS by examining what differences would be expected between partitioning in cavities in seawater-saturated basalt and partitioning in cavities in unsaturated or fresh-water saturated rhyolite. That is, should one expect consistency between the IAEA partition factors and those from the CHANCELLOR test?*

Another uncertainty is the partitioning to be expected in limestone. It appears the values used in the modelling are simply assumed to be the same as those adopted for silicate rock. However, it seems unlikely that carbonate values would be the same as those for silicate rocks. For example, with the low silica content of carbonates, the amount and composition of glass formed, if any, will be different.

Also, the presence of alkaline earth oxides and hydroxides in carbonate cavity debris will tend to make water reentering the cavity alkaline. This will enhance the solubility of many elements including silica, increase the rate of glass dissolution, and influence sorption behavior. Without further consideration of partitioning in carbonates, it is not evident that adopting values for silicates is appropriate. Such consideration could be supported by theoretical evaluation of in-cavity chemistry, laboratory examination of debris from cavities in carbonate, or, preferably, from collection of both water and debris from a carbonate cavity with a view to interpreting their chemistry as Rose et al. (2011) interpreted field samples from the CHANCELLOR test.

> ***Recommendation:*** *Provide support for the partition factors used in interpreting carbonate tests. This could include theoretical considerations, laboratory examination of cavity debris, and/or—most convincing—collection and interpretation of field data from a carbonate test like those that were available to Rose et al. (2011) for the CHANCELLOR test.*

### 6.4.3 Water Flow into Cavities

Of most importance for modeling the fluid and radionuclide transport through the cavities and into the LCA is the surface flux into the unsaturated zone, both naturally and via enhanced recharge through craters. In several cases, measurements of crater infiltration have been made; however, modeling results suggest that enhanced crater recharge is unimportant, when combined with low permeability of the TCU to cause significant migration from the cavities into the LCA.

Data collected to date indicate that enhanced recharge through craters is occurring, and model results over the 1,000-year time frame do show contact of recent recharge with some of the cavities. The modeling results appear to underpredict measured recharge. That may be the result of higher than “normal” precipitation during the sampling period than considered in the recharge modeling. However, the importance of enhanced recharge is negated by modeling results that indicate little flux through the TCU.

The TCU is represented in the modeling effort as a significant barrier to transport from the majority (greater than 60 percent) of all nuclear detonations in Yucca Flat. While some laboratory-scale data support the concept that this unit is an effective barrier to flow into the LCA, its field-scale properties have not been the focus of characterization efforts in recent times, when it has become clear that the barrier characteristics of the TCU are likely controlling the model results.

The TCU is reported to have a wide range but generally low permeabilities. Consequently, as modeled, the TCU isolates any unsaturated test from the LCA over the 1,000-year model time frame. Under conditions of natural recharge, the permeability of the TCU is unimportant for the radionuclide transport from the unsaturated zone, because velocities under natural recharge are documented to be low (less than 1 cm/yr or 1 millimeter per year [mm/yr]). However, under the case of enhanced recharge from the overlying subsidence craters, significantly greater local recharge is occurring, and modeling predicts that at least some of these craters support sufficient recharge for radionuclides to reach the TCU well within the 1,000-year modeling period. Therefore, the vertical permeability and lateral continuity of the TCU is a critical factor in determining the transport of more than 60 percent of the total inventory.

It is clear that enhanced recharge will intersect some of the detonation cavities in the 1,000-year regulatory period (and may have already reached shallow cavities today) and will provide a mechanism to transport soluble radionuclides downward. The assumed low permeability and distance to the LCA results in model calculations that do not show this to be important. Given the uncertainties in the hydraulic properties beneath detonation cavities in the TCU, and the potential for rapid transport if assumptions are incorrect, the peer review team recognizes uncertainties in these calculations that should be addressed in upcoming evaluations.

> ***Recommendation:*** *Given that liquid transport from the cavities is the dominant mechanism for downward movement, the peer review team recommends a concerted effort to measure and monitor enhanced-recharge-driven transport in and below detonation cavities, with emphasis on detonations within the TCU.*

### 6.4.4 Uncertainty in the Exchange Volume Not Fully Captured

"The protective characteristics of the TCU may have been compromised," according to N-I (2013, p. 4-11). This is not surprising, inasmuch as even relatively small detonations, such as AARDVARK (40 kt) and HAYMAKER (67 kt), had measurable effects on Yucca fault movement (N-I, 2013, p. G-18), and detonations were often felt in Las Vegas, approximately 80 mi away. The report has assumed that this damage zone surrounding the cavity extends up to 3 $R_c$ (N-I, 2013, Appendix C). The basis for 3 $R_c$ as the extent of fracturing is the reports of Boardman and Skrove (1966) and U.S Congress, Office of Technology Assessment (1989). However, in Appendix G, Fig. G-1 from more recent work by Laczniak et al. (1996) indicates that the zone of fracturing extends out to 5 $R_c$ (Figure 6-2).

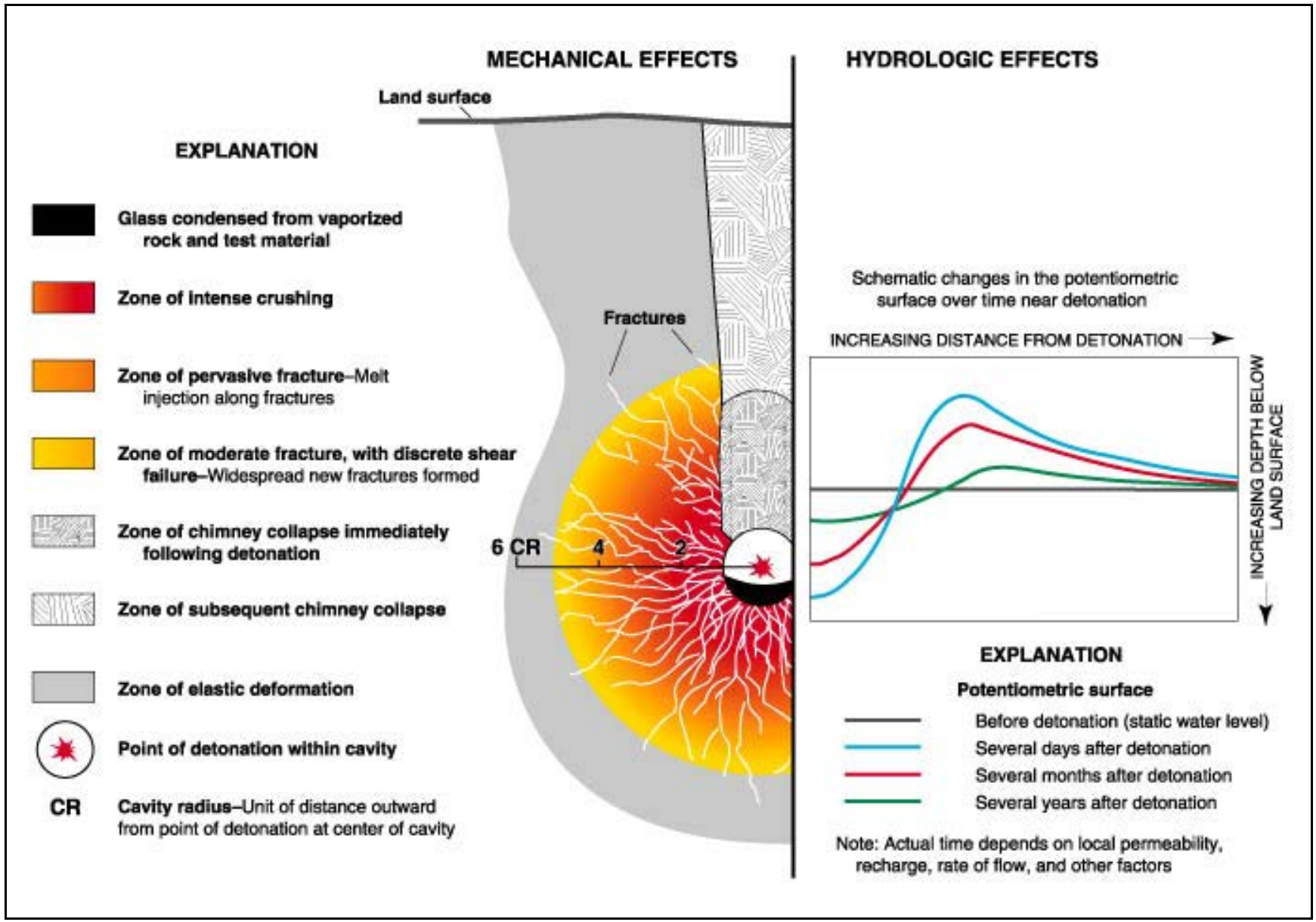



***Figure 6-2***
***Illustration of Mechanical and Hydrologic Effects from an Underground Nuclear Detonation***
Source: Laczniak et al., 1996; N-I, 2013, Fig. G-1

N-I (2013) is silent on the reason for this discrepancy, which may represent a considerable potential source uncertainty in predicted impacts to the LCA. For example, the thickness of TCU is about 300 to 400 m, and the average cavity radius, 1 $R_c$, is about 50 m. A detonation in the center of the TCU would create a breach scenario at only about 3 to 4 $R_c$. But, at 5 $R_c$, the majority of the detonations in the TCU would potentially have compromised the integrity of the TCU. With a larger $R_c$ for the exchange volume for detonations with cavities near the top of, or which intersect, the LCA there would be more mass placed directly in the LCA. For breached detonations, more water would potentially flow into the exchange volume from the overlying AA/VA and leach contaminants into the LCA.

For detonations that do not breach to the LCA with this larger $R_c$, the role of even short fractures within the TCU could be significant as they would provide rapid pathways into the LCA. Because the model assumes only matrix flow in the TCU, faster radionuclide migration through pre-test or post-test fractures in the TCU toward the LCA is not considered in the simulations and may therefore underestimate contaminant potential. For detonations in the TCU that do not have exchange volumes that intersect the LCA, at 5 $R_c$ those exchange volumes would be closer to and possibly intersect faults that do connect to the LCA (Figure 6-3). In addition, with a larger $R_c$ to consider, more of the exchange volumes would overlap, so that low permeability crushed zones and melt glass zones may fracture as well. The additive effects of detonations on hydraulic properties do not appear to be taken into account. It is possible that the more common scenario, and one to consider for the base case, is a conceptual model in which there are considerably more fractures throughout the entire thickness of the TCU subsequent to testing. In places, rising water levels in some of the LCA observation wells may be attributable, at least in part, to increased leakage through the TCU.

> ***Recommendation:*** *The peer review team recommends that the uncertainty analysis of the contaminant boundary include the effects of extending the exchange volume to at least 5 $R_c$.*

### 6.4.5 Possible Chimney and Cavity Pathway to the LCA

As discussed in Section 6.4.4 regarding uncertainty in the size of the exchange volume and damage zone, the base-case scenario for transport modeling may be one in which the TCU is compromised. In this case, there is a potential permeable pathway created from the land surface crater, through the chimney, across the AA/VA and the TCU and into the LCA. The flux of water into the LCA would be controlled primarily by the head difference between the AA/VA and LCA, which also depends on

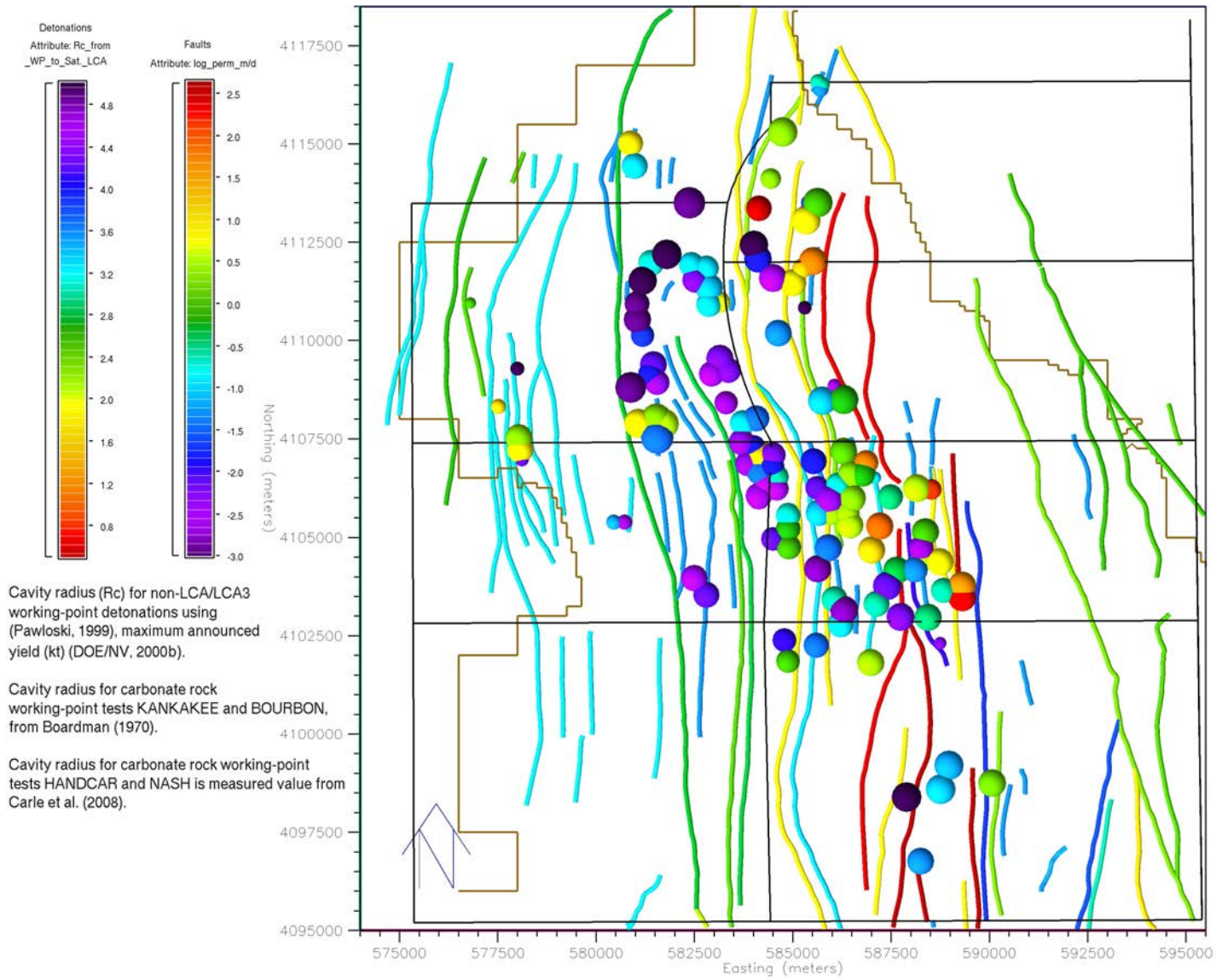



***Figure 6-3***
***Detonations with Working Points within 5 $R_c$ of the Saturated LCA***

Note: The 5 $R_c$ spheres are color coded by the distance to the saturated LCA. The view is from top down, so some spheres may be partially obscured by higher elevation spheres that overlap the underlying spheres. Also included in the figure are the modeled faults color coded by the base-case hydraulic conductivity, in m/day (per Andrews, 2014e).

recharge rates and permeability of the water-bearing formations as well as the permeability of the damage zone.

The permeability of the damaged rock surrounding the detonation may be the limiting factor controlling water flow into the LCA for a breach scenario. For example, in one conceptual model, the permeability surrounding the cavity is reduced by 10 to 50 percent from the surrounding country rock. This conceptual model was proposed by Tompson (2008). Whether this zone of reduced permeability exists at all appears to be subject to some uncertainty. It is assumed that the permeability of the TCU in the crushed zone would actually be reduced by as much as a factor of 10 compared with the country rock. However, there are no field data presented on permeability of the crushed zone or any other zone surrounding the cavity to support this assumption.

As a result of the low permeability assumed by Tompson (2008), which led to little transport, an alternative conceptual model was applied that led to a larger compressed damage zone with enhanced permeability in some simulations, and this in turn led to significantly greater transport.

The extents of the compressed zone and potential zone of enhanced permeability due to hydrofracturing depend on the amount of overpressuring caused by the detonation (see N-I, 2013, p. G-7). The maximum overpressuring used in the model was 1,229 m of head. However, Tompson (2008) indicates that heads of 8,000 m could have occurred. Thus, there is considerable uncertainty in the extent of hydrofracturing and enhanced permeability, which has not been taken into account thus far.

In the breakthrough predictions shown in Fig. 4-41 of N-I (2013), the importance of $R_c$ is clear. LBB_Case 1 gives the most breakthrough; this is the case where a breach node occurs wherever the overpressure is more than 70 percent of the lithostatic load. In Case LBB_3, a breach occurs only if the cavity is within 3 $R_c$, and there are fewer breach nodes compared with LBB_Case 1, so there is less mass into the LCA. Had the simulations used 5 $R_c$ instead as a criterion here, the impacts to the LCA likely would have been greater than LBB_Case 3. It appears to be significant that in the four breach scenarios shown in Fig. 4-41 each used conceptual model #1 and has the case designation of N3, which is a reduction of permeability, not an enhancement. It is difficult to discern from information presented what effect enhanced permeability has on transport. However, it appears that the permeability of the country rock may be enhanced only by as much as a factor of about 2 within the rock-damage zone. There are no field data presented to support this assumption.

***Recommendation:*** *The peer review team recommends that the uncertainty analysis of the contaminant boundary include breaches from detonations not only within 5 $R_c$ but also include a greater range in the permeability enhancement assigned to the damage zone. Where possible, consider evaluating whether post-shot holes can be used to test the field permeability of the damage zones in situ.*

## 6.5 Transport

It is recognized that uncertainties in the source-term conceptual model, the initial distribution of the radionuclide inventory, and the transport-parameter distributions are more significant than flow-system uncertainty. Uncertainties in the source term and radionuclide inventory distributions are addressed in the previous section. The conceptual model considers transport to be driven by advection and dispersion moderated by matrix diffusion and sorption occurring both in the matrix and on fracture surfaces. Solute transport velocity is related to the modeled groundwater flux through the effective porosity. Uncertainty in this parameter is addressed above in Section 6.3.4. The process addressed here is retardation by sorption, particularly that of Pu.

### 6.5.1 Values Used for Pu Retardation Are Not Well Supported and May Be Too High

Because of their long half-lives, Pu isotopes dominate the total inventory after about 200 years. The concentrations in both silicic and carbonate cavities less the fraction partitioned into the glass are illustrated in Figure 2-9. This figure shows Pu concentrations of greater than $10^3$ MCL and greater than $10^4$ MCL in silicic and carbonate rock cavities, respectively. If the glass fractions were included in these cavity concentrations, the relative Pu concentration would be considerably greater because, in modeling the cavity, at least 95 percent of the total inventory of this element is partitioned into the glass (Table 6-2). If sorption on the rubble is considered, the cavity concentrations of Pu would be lower, although still greater than 10 MCL in silicic rock cavities (Figure 2-10). For conservatism in the modeling, however, sorption in the cavity is neglected in the source term (per conversation with Bob Andrews in October 2014).

Elements that are not retarded during transport reach the CAU boundary within a few hundred years. This is illustrated for $^{129}I$ in Figure 6-4, which shows concentrations greater than $10^{-14}$ moles per liter (mol/L) at the southern boundary by 300 years. This corresponds to $10^{-4}$ MCL, far below cavity concentrations of about 10 MCL because of dilution in the LCA. Because Pu concentrations in the

cavities are so high ($10^3$ to $10^4$ MCL), it could well be that if Pu were not retarded, its concentration would approach or even exceed the MCL at the southern boundary.

Retardation parameters used for modeling are based on laboratory measurements of retardation in model systems, such as artificial fractures in core samples, or are calculated from laboratory-measured, batch distribution coefficients ($K_d$ values) or sorption parameters (SNJV, 2007; Powell et al., 2011). Pu is difficult to work with experimentally for several reasons. First, its sorption behavior is sensitive to its redox state with Pu(IV) more strongly sorbed than Pu(V) ($PuO_2^+$). Reactions between Pu redox states occur only slowly, and both Pu(IV) and Pu(V) states can be present in the range of redox conditions typical of open-air laboratory experiments and likely to be present in Yucca Flat groundwaters (Hu et al., 2008b; Powell et al., 2011). Second, Pu colloids form easily and add uncertainty to the interpretation of laboratory experiments.

Table 6-3 shows ranges of $K_d$ values and retardation factors for carbonate rock as given by N-I (2013), SNJV (2007), and Zavarin (at the April 8, 2014, peer review team meeting) on which the modeled retardation was based, as well as additional data from Hu et al. (2008a). Laboratory data on experiments in fractures are reported as retardation factors while for batch measurements on the matrix, $K_d$ values are given. For comparison, retardation factors corresponding to the matrix $K_d$ values have been calculated using the conventional expression:

$$R = 1 + K_d * \text{bulk density/porosity}, \qquad (6\text{-}1)$$

using nominal bulk density and porosity values of 2.7 grams per milliliter and 0.02, respectively.

The ranges of values used for modeling are also shown in Table 6-3. Modeled values are selected from triangular distributions with upper and lower bounds shown in the table and mode equal to the average value. Note that the range used for modeling has higher values at both its upper and lower ends than the values given in SNJV (2007), and that the values reported by Hu et al. (2008a) are below the lower end of the range modeled.

The high $K_d$ values for the matrix lead to strong retardation. Those given by SNJV (2007) and used as the basis for the values used for modeling represent measurements on samples from the Culebra dolomite from the Waste Isolation Pilot Plant. The Culebra is a carbonate rock but otherwise has little

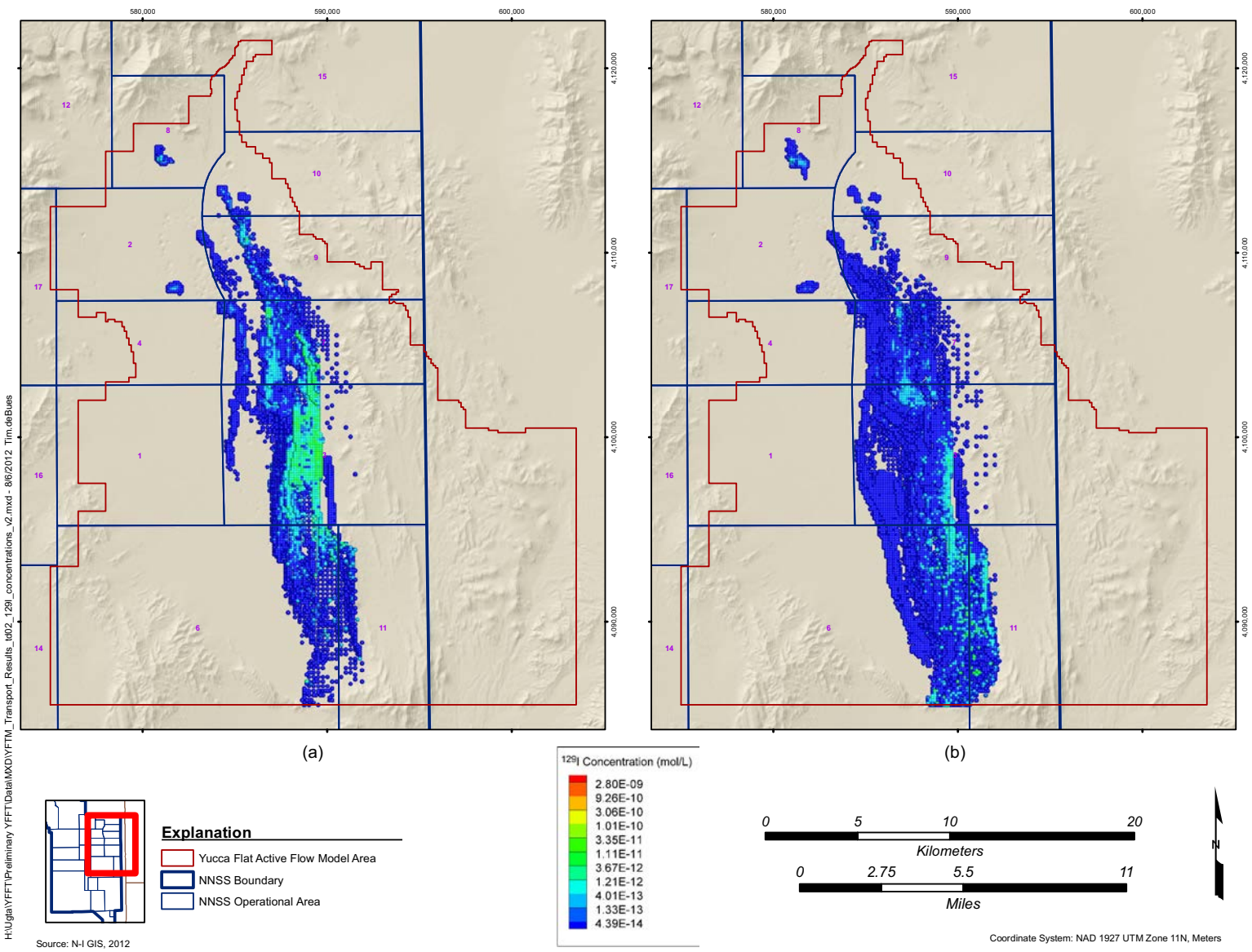



***Figure 6-4***
***Base-Case Representative $^{129}I$ Concentrations for LCA Sources: (a) 300 Years, and (b) 1,000 Years***
Note: Base-case LCA flow model and median realization
Source: N-I, 2013, Fig. 6-60

**Table 6-3**
**Summary of Corresponding Retardation Factors and $K_d$ Values for Pu in Carbonates Including Ranges Used for Modeling [a]**

| Source | | $K_d$ - mL/g | | R at 2% porosity | |
|---|---|---|---|---|---|
| SNJV, 2007 (Table 11-5) | Matrix | 100 | 10,000 | $1.4 \times 10^{+04}$ | $1.4 \times 10^{+06}$ |
| SNJV, 2007 (Table 12-4) | Fracture | N/A | N/A | $0.0 \times 10^{+00}$ * | $5.0 \times 10^{+01}$ |
| Hu et al., 2008a | Matrix: Controlled atmosphere | 116 | 162 | $1.6 \times 10^{+04}$ | $2.2 \times 10^{+04}$ |
| N-I, 2013 (Table 6-2) | Fracture retardation modeled | N/A | N/A | $2.4 \times 10^{+00}$ | $5.0 \times 10^{+01}$ |
| N-I, 2013 (Table 6-3) | Matrix retardation modeled | 900 | 20,000 | $1.2 \times 10^{+05}$ | $2.7 \times 10^{+06}$ |

[a] Experimental data are underlined; other values are calculated as described in the text.

Note: A retardation factor of zero is not possible, but because this is the value given in Table 12-4 of SNJV (2007), it is retained here. Zavarin et al. (2007) is reported to be the source of the Pu data in Table 12-4. These authors state that their values are based on model fits to experiments in artificial fractures, but that the model used only poorly represents the experimental data. Pu retardation factors of less than one have been reported, presumably due to colloids, but the lowest value actually given by Zavarin et al. (2007) is 2.5. This is essentially the low end of the range of values used in N-I (2013) as this table shows.

mL/g = Milliliters per gram
N/A = Not applicable

in common with the LCA. For example, water in the Culebra is more reducing and much more saline than in the LCA; both factors influence $K_d$ values. Values reported by Hu et al. (2008a) were measured on core of the LCA in water with controlled redox conditions and salinities thought to represent those *in situ*. Fracture retardation reported in SNJV (2007) is based on measurements in simulated fractures in LCA samples. These indicate little or no retardation.

With the high range of $K_d$ values used for the modeling, it is no surprise that Pu, despite its high cavity concentrations, does not appear to be an element of concern.

These considerations lead to two recommendations:

> ***Recommendation:*** *The Pu $K_d$ values used for modeling should be decreased to reflect the lower end of the measured range, and values lower than those measured should be used to evaluate the uncertainty associated with the lowest measurement. This would be a more conservative approach than emphasizing the high end of the range as is now done. Sensitivity analyses would also be useful to determine at what a range of retardation values Pu transport would be a concern.*
>
> ***Recommendation:*** *With respect to additional data, site-specific data should be collected to develop a better mechanistic understanding of Pu retardation processes and improve the representation of the in situ chemical conditions in which the retardation takes place in Yucca Flat. In addition, evaluation of existing data should continue to determine*

*whether it is possible that retardation values can reach levels that the modeling indicates may cause concerns.*

### 6.5.2 Melt-Glass Dissolution Is Largely Neglected

Melt-glass dissolution is neglected in the unsaturated zone and LCA models. The dissolution rate of melt glass in volcanic terrain is taken as 1 percent/1,000 year. This value is attributed to an unavailable report, and no uncertainty is associated with it. Melt-glass dissolution is neglected in the unsaturated zone on the grounds that flow through this zone is too low to support transport.

The sensitivity of the AA/VA model to melt-glass dissolution rate is examined by allowing instantaneous release of all melt-glass radionuclides. Even this degree of uncertainty is insignificant relative to the uncertainty in the initial inventory assigned to each detonation.

Refractory radionuclides in tests in the LCA are expected to be segregated not in siliceous melt-glass (except BOURBON), but rather in carbonate cavity debris, principally calcite and dolomite. Release from this debris is neglected on the grounds that the water in the LCA is saturated with respect to calcite and dolomite, so the cavity debris will not dissolve. Other likely processes seem not to be considered. These include reactions related to the creation of lime (CaO) from calcite ($CaCO_3$) in the limestone by intense heat created by detonations. Hydration of CaO will initially produce calcium hydroxide ($Ca[OH]_2$) and highly alkaline water; dissolution of siliceous melt-glass, if present, will be greatly enhanced in alkaline fluids; $Ca(OH)_2$ is considerably more soluble than calcite; carbonation of $Ca(OH)_2$ is relatively slow.

***Recommendation:*** *Include melt-glass dissolution in UZ models that allow for enhanced flow.*

***Recommendation:*** *Consider additional processes affecting cavity-debris behavior in the LCA model. Include an instant-release case among the sensitivity analyses, similar to that in the AA/VA model.*

## 6.6 Simulating Critical Observations

An objective of the hydrogeologic models for the NNSS is to predict where and when radionuclides from detonations will appear in the groundwater. The peer review team expects that the model for Yucca Flat should be able to predict the occurrence of detonation-related radionuclides that have been observed in wells far from the detonations. Predictions of radionuclide concentrations above those

measured illustrate conservatism in the model. Measurable radionuclide concentrations above those modeled indicate shortcomings in the model and should be explained.

### 6.6.1 Field Measured $^3H$ Concentrations Are Not Simulated by the N-I (2013) Model

Tritium concentrations simulated by the AA/VA model were compared to isotopic measurements from 10 wells located sufficiently far from working points (greater than 300 m) for the simulations to be meaningful (N-I, 2013, Table 4-46, pp. 4-130 to 4-131). None of the simulated $^3H$ concentrations was above zero at any time. Whereas the lack of $^3H$ at wells in the simulations was consistent with 5 of the 10 measurements, the simulations were inconsistent with low $^3H$ concentrations observed in wells ER-2-1, UE-6d, UE-6e, TW-B, and WW-A (Table 6-2). These wells are at a distance of 0.64 to greater than 2 km from detonations. The conceptual and numerical models of the AA/VA do not account for $^3H$ concentrations at such large lateral distances from the detonations in the AA/VA. The N-I (2013, p. 4-129 to 4-131) report suggests one explanation:

> "Given that the specified initial tritium concentration[s] in cavities was approximately [$1x10^9$] pCi/L, it is not surprising that the model is not able to adequately represent concentrations six orders of magnitude lower. Perhaps by using much larger numbers of particles, the model would be capable of doing so."

This hypothesis is not unreasonable but should be tested by running a sub-region of the model encompassing an unexpectedly high measured concentration using many more particles.

A second hypothesis, not explored in N-I (2013), is that there is a mismatch between the mesh spacing and the scale of the heterogeneities of transport properties. In this case the modeled concentrations will be the average over the block volume, while a measured concentration may represent a considerably smaller volume with a concentration different from the average. This hypothesis could be explored by examining differences in concentrations calculated in runs with different block sizes. It could also be tested in the field by examining whether concentrations change as the volume sampled increases during a long period of pumping.

The peer review team does not agree with the concluding statement in N-I (2013), Section 4.0 (p. 4-138), that "...numerical modeling can reasonably estimate $^3H$ concentrations in far-field locations (greater than 300 m from a detonation location)," because the presence of $^3H$ in several far-field wells has not been predicted by the model. Although some low $^3H$ values could be attributed

to contamination during sampling (a hypothesis that was not confirmed with additional sampling in several wells, but appears to have been confirmed with careful sampling in June 2014 from ER-6-2, as indicated in Table 6-4), the time-series data for WW-A and the relatively high concentration in UE-6d suggest detonation sources. In addition, the apparent presence of $^{99}$Tc in ER-2-1, albeit close to the detection limit, is consistent with a detonation source for radionuclides in that far-field well. UE-6d is located on a major fault that appears to be close to a number of detonations to the north, which may contribute to the contamination at this location.

***Table 6-4***
***Summary of Selected $^{3}$H Measurements That Do Not Appear to Have Been Captured by the N-I (2013) Modeling [a]***
*(Page 1 of 2)*

| Well | Nearest Detonation | | | | | $^{3}$H | $^{99}$Tc | Sample | |
|---|---|---|---|---|---|---|---|---|---|
| | Distance (km) | Name | Date | HSU Working Point | Yield (kt) | (pCi/L) | | Date | HSU |
| ER-2-1 | 2 | INGOT | 03/09/1989 | TMWTA | 20–150 | 228 | 12 & 8 (duplicate) | 09/03/2003 (pumped) | TMWTA, TMLVA, LTCU |
| | | | | | | <MDL | | 09/05/2003 (bailed) | |
| WW-A | 0.64 | HAYMAKER | 06/27/1962 | AA | 67 | ~MDL | NA | 1972–1987 | AA |
| | | | | | | 37 | | 1987 | |
| | | | | | | 170 | | 1990 | |
| | | | | | | 573 | ~MDL | 2001 | |
| | | | | | | 342 | | 2010 | |
| UE-6d | >2 | DUORO | 06/20/1984 | TMUVTA | 20–150 | 710 | NA | NA | AA |
| UE-6e | >1 | VILLITA | 11/10/1984 | AA | <20 | 25 | NA | NA | VA |
| TW-B | >2 | VILLITA | 11/10/1984 | AA | <20 | <MDL | NA | 1965 | TSA |
| | | | | | | 260 | NA | 1976 | |
| | | | | | | 158 | NA | 1987 | |
| | | | | | | 109 | NA | 1990 | |
| | | | | | | NA | <5 | 1993 | |
| | | | | | | 44 | NA | 1998 | |

**Table 6-4**
**Summary of Selected $^{3}H$ Measurements That Do Not Appear to Have Been Captured by the N-I (2013) Modeling [a]**
*(Page 2 of 2)*

| Well | Nearest Detonation | | | | | $^{3}H$ | $^{99}Tc$ | Sample | |
|---|---|---|---|---|---|---|---|---|---|
| | Distance (km) | Name | Date | HSU Working Point | Yield (kt) | (pCi/L) | | Date | HSU |
| ER-6-2 | >2 | RUSSET | 03/05/1968 | AA | <20 | <MDL | NA | 07/20/2004 (bailed) | LCA3 |
| | | | | | | 92 | <MDL | 08/04/2004 (pumped) | |
| | | | | | | <MDL | NA | 06/19/2014 (pumped) | |

[a] Data are taken from Tables 4-46, B-1, and D-1 [b] of N-I (2013); Appendix A of Reiner (2007); and Marutzky (2014). For reference, the MCLs of $^{3}H$ and $^{99}Tc$ are 20,000 and 900 pCi/L, respectively.
[b] The peer review team notes that Table D-1 of N-I (2013) does not include data on wells UE-6d or UE-6e.

NA = Not available

Comparisons of simulations with field observations in the LCA also are mixed. Some field concentrations in the LCA (Table D-1 of the N-I [2013] report) are near the MCL for $^{3}H$, while the model forecasts concentrations that far exceed the MCL. Other observations in the LCA are below the MDL, while the model forecasts concentrations well above the MCL. Additional LCA field observations indicate significant contamination that is not consistent with the representation of essentially no contamination at those locations in models that use low infiltration rates. Finally, some observations of minimal contamination are consistent with the simulation of essentially no contamination when using an infiltration rate of 0.1 mm/yr.

In addition to the five wells for which simulations did not predict observations in the AA/VA, at least one far-field well in the LCA (ER-6-2, Table 6-4) had a low, but measurable, $^{3}H$ concentration at a distance sufficiently far from detonations (greater than 2 km) to be of concern. As observed by a portion of the peer review team during its second field trip to Yucca Flat on June 18, 2014, additional water samples were taken from well ER-6-2, in part to determine whether the $^{3}H$ measured in August of 2004 was a measurement error. A possible explanation for detecting $^{3}H$ in this well (offered during the peer review team's meeting in Las Vegas on June 16, 2014) is rapid infiltration of meteoric water that, during storms, enters a nearby gravel (borrow) pit that is centered approximately 300 m northeast of the well. While local rapid recharge is possible, the depth to the water table in this well has been measured 83 times since 1994 showing little change in depth (between 543 and 545 m;

1,781 to 1,787 ft [Elliot and Fenelon, 2013]) indicating that local recharge is unlikely. Furthermore, the modeled direction of groundwater flow is inconsistent with local recharge from the borrow pit. Therefore, while local recharge cannot be ruled out, no data or rigorous and consistent analysis have been developed in the intervening decade to explain the elevated $^{3}H$ found in this well when it was first (and only) sampled. The RUSSET and PRESIDO detonations in that area were not included in the modeling (p. 3-4 of the N-I [2013] report), so the field observation has not been compared with meaningful simulated concentrations. Results below the MDL (approximately 3 pCi/L for $^{3}H$) on duplicate samples collected on June 19, 2014, from pumped discharge after ER-6-2 had been purged such that water-quality parameters measured in the field were stable, suggesting that the August 2004 measurement resulted from post-sampling contamination.

Arguments for the discrepancies between field and simulated concentrations are presented in both directions in N-I (2013). For cases where field values are less than simulated values, arguments include (1) observation wells may not intersect flowing features that are hydraulically connected to the source of contamination; and (2) the assumed extent of initial contamination may not reflect the actual extent of contamination. For cases where field values are greater than simulated values, arguments include (1) some model locations may lack inclusion of drill-back fluid losses or chimney drainage; or (2) models may have underestimated enhanced-crater recharge or local infiltration.

It was reported to the peer review team during the April 11, 2014, meeting that in the 1960s $^{3}H$ was released into well WW-C at the south end of the Yucca Flat basin. This same well is included among the wells that are periodically monitored for radionuclides. This well is the southernmost well capable of detecting groundwater impacts. Details on the nature of this release are unknown. $^{3}H$ was detected in this well, along with the adjacent well WW-C-1. The residual effects of this release may be difficult to distinguish from migration from detonations, making samples from this location potentially unreliable.

***Recommendation:*** *The peer review team recommends the following actions to address $^{3}H$ observations:*

- *Simulate a sub-region of the model encompassing an unexpectedly high measured concentration using many more particles to determine whether the reason for the mismatch is the low number of particles used to represent $^{3}H$ transport.*
- *Simulate a sub-region of the model encompassing an unexpectedly high measured concentration using smaller block sizes.*

- *Determine what processes could lead to the observed apparent lateral transport of $^{3}H$ in the AA/VA and incorporate them into the model.*
- *Evaluate whether the timing of the sampling or the nature of the completion of the non-detect wells may be such that $^{3}H$ occurrences were missed.*
- *Given that there are so few contaminant data in the LCA, results of comparisons are mixed, and contaminant movement in the LCA is expected to follow discrete pathways, the next step is to gather field data that will define the current extent of contamination to better evaluate the simulations and adjust the model to better represent the field system.*

### 6.6.2 Crater-Infiltration Data Are Not Well Matched in the Model

Of most importance for modeling the fluid and radionuclide transport through the unsaturated zone is the rate of surface flux into the unsaturated zone by enhanced recharge through craters. In several cases, measurements of crater infiltration have been made; however, the enhanced infiltration model does not appear to capture these observations well.

The UZ model surface flux is driven by a detailed and well-designed surface runoff modeling effort to estimate the contributing area to runoff and to model its transport to the crater, where it both infiltrates and evaporates. This rainfall-runoff model is also unprecedented in its detail and complexity. However, it is relatively unconstrained by measurements. In addition, runoff in arid regions is challenging to model with traditional rainfall-runoff models developed for more humid regions with vegetation. Nonetheless, the model was calibrated against the few measurements available for runoff volumes.

This runoff model was coupled with a one-dimensional UZ model to produce a 1,000-year average infiltration rate from each subsidence crater, using a reconstruction of the mean precipitation. Fig. E-23 of N-I (2013) summarizes the distribution of recharge for all 462 craters on Yucca Flat and shows a strongly tailed distribution. The mean infiltration rate is 0.26 meters per year (m/yr).

The infiltration data shown in Fig. E-23 and Table E-5 of N-I (2013) suggest that the few available physical measurements are anomalously high. While some of these study craters may have been chosen based on observations of ponding, their physical characteristics do not appear significantly different from other craters, and therefore the underestimation of modeled infiltration at these field test sites is of concern. For example, test LAGUNA (U3fd) in Table E-5 of N-I (2013) has a modeled recharge flux of 0.072 m/yr, while the physically observed and reported flux was 0.5 m/yr; thus, the

modeled flux is almost an order of magnitude lower than observed. At crater U3bh (HYRAX), infiltration was observed to reach a depth of 55 m in 33 years, implying an average wetting front velocity of 1.66 m/yr. Assuming a 10 percent increase in water content during infiltration suggests an annual flux of 0.166 m/yr. The model results, however, suggest a mean annual infiltration rate of 0.079 m/yr, approximately 50 percent of the reported rate.

Finally, crater U10i (BYE) showed wet conditions and high matric potentials to the bottom of the hole at 33 m. Given the about 30 years since this crater was formed, a simple velocity calculation suggests a minimum wetting front velocity of about 1 m/yr, with infiltration rate (assuming again a 10 percent increase in moisture content) of 0.1 m/yr. The actual recharge could be much higher as the drilling did not reach the bottom of the wetting front. In this case, the model overpredicts the observed recharge significantly, and is modeled at 1.79 m/yr, which is much higher than most craters.

> ***Recommendation:*** *Determine why the modeled crater-recharge estimates do not match well the limited observations, and ensure that the crater-recharge model is conservative in its estimates of enhanced recharge.*

### 6.6.3 Geochemical and Environmental Isotopes Not Fully Evaluated

In Appendix G, the peer review team discusses interpretation of geochemistry and environmental isotope data. Geochemistry is used to support or corroborate two aspects of the flow and transport modeling: (1) sources and flow paths of groundwater in the Yucca Flat system, and (2) flow rates inferred from estimates of the time since the water in a given sample was recharged or last in contact with the atmosphere or soil air. The peer review team evaluated the interpretation of isotope data, including assumptions of initial isotope concentrations, effects of geochemical reactions on isotopic composition, effects of mixing, and retardation.

The peer review team recognizes that the flow paths derived from chemical mass balance modeling (SNJV, 2006a) were not used to constrain the flow and transport model and so does not make specific recommendations based on the shortcomings in the chemical balance modeling pointed out in Appendix G.

With respect to the hydrologic application of environmental $^{36}Cl$ and $^{14}C$ isotopes, Appendix G points out several shortcomings about which the peer review team does make recommendations. First, the

Cl content of recharge that is required to interpret $^{36}Cl$ data was taken as the average of seeps in Rainier Mesa tunnels. This selection should be supported for the following reasons:

- Recharge that formed what is now shallow groundwater in Yucca Flat occurred ≥10 thousand years (ka) and may not be the same as the present.
- Rainier Mesa is not considered a recharge area to Yucca Flat.
- Moran and Rose (2003) have demonstrated considerable regional variation in Cl and $^{36}Cl$.

Second, there appear to be differences between $^{14}C$ retardation in the Ash Meadows flow system and in the way it is treated in the Yucca Flat work. In particular:

- $^{14}C$ velocities in the Ash Meadows flow system appear to be about one-tenth of those based on oxygen-18 ($^{18}O$). This difference must be attributed to $^{14}C$ sorption, because matrix diffusion for both isotopes should be about the same.
- The Ash Meadows and Yucca Flat LCA flow systems should be roughly equivalent; yet it is not clear to what extent.
- $^{14}C$ sorption is considered when interpreting the Yucca Flat data.

***Recommendation:*** *The choice of initial Cl concentrations used to adjust the measured $^{36}Cl/Cl$ ratios should be examined carefully, and strong justification should be provided for the value finally chosen.*

***Recommendation:*** *The behavior and interpretation of $^{14}C$ in the Yucca Flat and Ash Meadows flow systems should be compared and contrasted. If results of such a study indicate retardation in Ash Meadows but not in Yucca Flat, an explanation should be sought for such a profound difference in the behavior of two otherwise similar flow systems. Finally, it should be made clear whether the rates of groundwater flow supporting the modeled transport of detonation-derived radionuclides are more similar to those based on retarded or on unretarded $^{14}C$ flow rates.*

The peer review team questions the correctness and relevance of groundwater ages based on dissolved organic carbon (DOC).

***Recommendation:*** *The existence of $DO^{14}C$ data needs to be mentioned, but no age interpretations should be reported unless it can be demonstrated that the data are sound and that the interpretive methods are appropriate.*

### 6.6.4 Interpretation of Temperature Data

The peer review team struggled with interpretations of temperature data illustrated Fig. 5-16 in N-I (2013), until it realized that the contoured data were not, as the figure caption indicated, temperatures at the water table, but measured and modeled temperatures at an elevation that approximates the elevation of the water table in the LCA on the eastern side of Yucca Flat. The peer review team requested that a new figure be prepared (Figure 6-5 of this report) and discussed its implications.

The peer review team suspects that the relatively high temperatures in wells ER-3-1, ER-7-1, and UE-7ns may be the result of deeper LCA water rising along faults, and/or deep regional groundwater in the LCA enhanced by structural geology to flow to shallower depths.

The cool temperature anomaly in the center of Yucca Flat is somewhat consistent with younger groundwater ages in the LCA shown in Fig. 5-14 of N-I (2013). The numerous faults in this area are suggested to provide a conduit downward for shallow groundwater to leak across the confining units and may explain $^{14}C$ contents in the LCA. However, in the center of the basin, the water table appears to be within or above the TCU, near the base of the alluvium (e.g., see slide 12 of the S. Drellack and L. Prothro presentation at the April 8, 2014, peer review team meeting); consequently, the anomalous temperature at the water table here is not likely due to infiltration along faults, because in the conceptual model, faults in unconsolidated sediments are not believed to be preferential pathways.

An alternative conceptual model may be viable and should be considered, that is, that the shallow detonations have displaced cooler and younger, antecedent soil moisture and perched groundwater to the water table. This drainage process, which led to groundwater table mounding, was suggested by Carle et al. (2008; p. 4-4) at the NASH site. If there are wells with the low-temperature anomalies in the confined LCA, then, in the absence of local faulting, detonations may have induced breaches in the TCU. Such breaches were contemplated in sensitivity runs (N-I, 2013, p. 4-105) and found to be quite important, although it does not appear that the breach scenarios were carried forward in the transport simulations to define the contaminant boundary, except for 12 locations where the top of the LCA was within 2 $R_c$ of the working point. If the groundwater temperature data at the water table and in the LCA can be explained by breaches in the TCU, sans faulting, then an alternative conceptual model with more breach locations is appropriate to consider for transport simulation of the contaminant boundary.

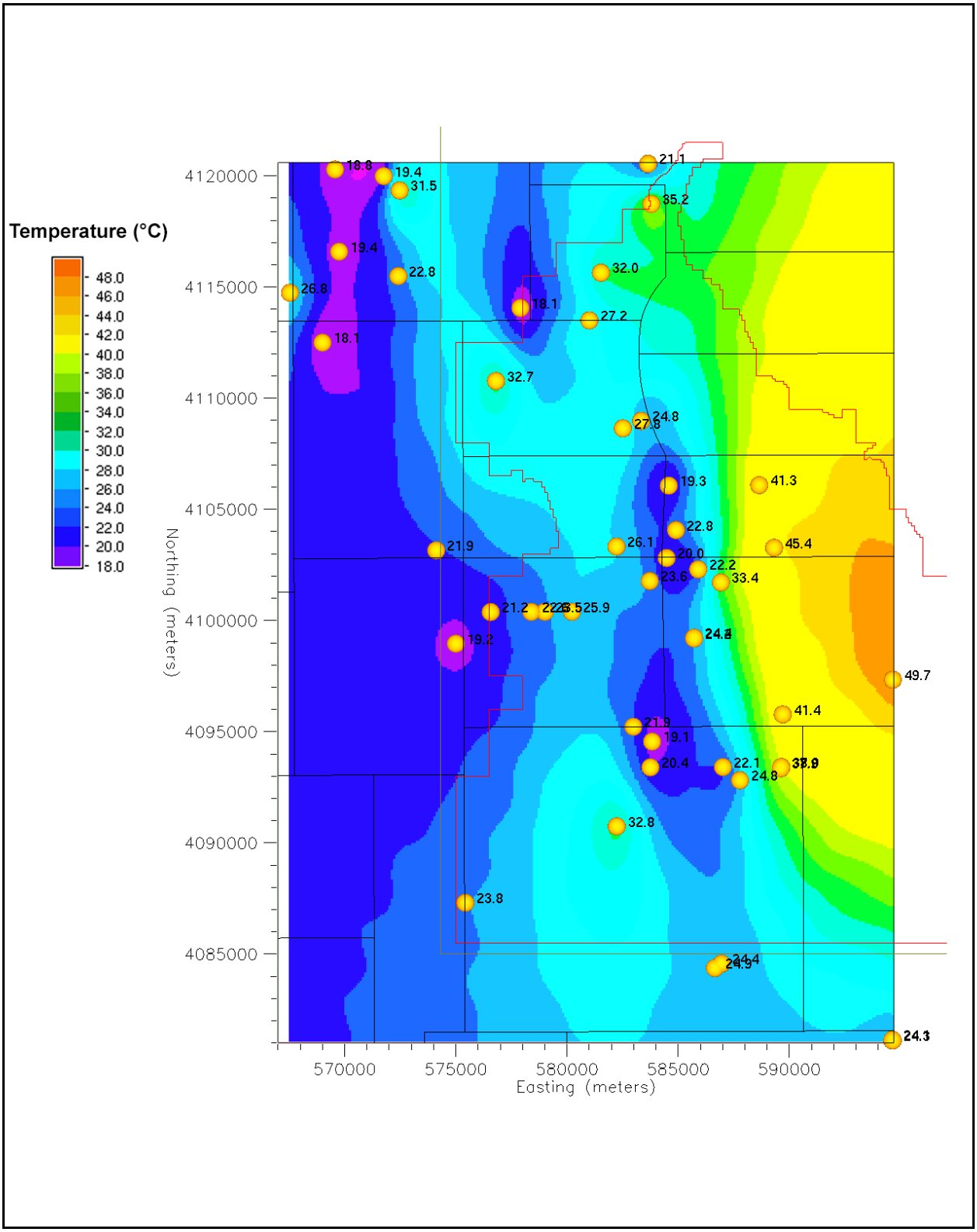



***Figure 6-5***
***Temperatures at the Water Table in the Yucca Flat Area, Contoured with 2× Anisotropy in the North–South Direction***
Source: Data from Reiner (2007) and NNES (2010b).

Another possible explanation for the observed temperatures at the water table in the AA/VA and in the LCA may come from considering the water-level time series response. A number of LCA wells have shown a rising water-level elevation trend. While some of this may be due to regional recharge, it is possible that some is attributable to drainage from the AA/VA where detonations have caused breaching across the TCU, allowing hydraulic connection with the LCA.

> ***Recommendation:*** *Investigate and explain temperatures at the water table; use the temperature data to inform the calibration of the coupled flow model that integrates flow in the AA/VA and LCA (recommended in Section 6.2.1); and incorporate water fluxes that may be indicated by the temperature data into the determination of the contaminant boundary.*

### 6.6.5 Realistic Geologic Features

The hydrogeologic model could incorporate more realistic geological features, because the hydrostratigraphic model developed by BN (2006) for the YF/CM area has simplifications that are geologically unrealistic. For example, although the model incorporates a complex set of faults as potential fast flow paths, the faults could be modeled to represent features that are closer to field observations. Some of the features listed here may have significant impact on the contaminant boundary, whereas others likely have little impact.

- The faults are modeled as generally dipping approximately 75 degrees (the average of outcrop and borehole data collected over years of investigation), whereas Carr (1974) described the average dip of faults in and near Yucca Flat as dipping 60 degrees and argued that some faults curve to shallower dips at depth, thereby accounting for the tilting of the Tertiary volcanic rocks. The N-I modeling team noted that most of the curving, lower-angle portions of faults are at significant depth below the tests and dominant flow regimes, such that they would have no impact on modeling radionuclide transport. Nonetheless, variable dips may have an impact on intersections with the 3 $R_c$ or 5 $R_c$ volumes around detonations. A more realistic hydrogeologic model would have the actual dips of individual faults and incorporate uncertainties in the dips, where data from drill-hole intercepts are sparse.

- According to the N-I modeling team, 39 antithetic faults in Yucca Flat (west-dipping, in contrast to the east-dipping faults with large displacements) are included in the groundwater flow model. Intersections of west- and east-dipping faults are likely to be zones of enhanced flow. Estimating the locations of these intersections would require incorporating the true dips of the faults, rather than modeling all faults with an average dip.

- The faults in Yucca Flat were modeled as planar features having low-permeability cores (with clay-rich gouge, pulverized rock, or matrix-supported breccia) that are bounded on both sides by damage zones (with clast-supported breccias and fractured rock). An unrealistic

aspect of the EarthVision model is assigning widths of 62.5, 125, or 250 m to the fault cores. All fault cores that the peer review team has seen or referenced in the geological literature are much narrower than 62.5 m. Prothro et al. (2009) documented that the fault cores in the Yucca Flat area are relatively narrow zones. All are less than 3 m wide, and most are much narrower.

- As noted by Fenelon et al. (2012),

  > "... young faults and seismically active and potentially active faults, such as the north-striking normal faults in Yucca Flat, may enhance permeability at depth (Potter and others, 2002). These fault-enhanced pathways could allow for shallow-to-deep or deep-to-shallow flow along fault conduits."

- Furthermore, in the experience of the peer review team, it would be unlikely for a low-permeability fault core to exist everywhere along the fault plane, because faults tend to have bends and disparities, where the grinding that produces fine particles and gouge is either absent or less intense. That is, a more sophisticated model may include not only thinner fault cores but zones along the fault plane where a low-permeability core is missing.

- Whereas Phelps and McKee (1999) interpreted gravity data from Yucca Flat to indicate several east-striking normal faults, few, if any, such faults are in the BN (2006) model. Such faults, if they exist, could be significant pathways for flow. The N-I modeling team noted, however, that the east-striking faults are short, pre-Tertiary structures that tend to be healed and less conductive (Prothro et al., 2009) than Basin and Range normal faults, which are included in the hydrologic flow model.

- The LCA is modeled using a constant hydraulic conductivity with depth, but it is actually a series of layered strata, for which there is undoubtedly variability in hydraulic properties among the layers. Some layers may be locally cavernous. As seen in the outcrops of these rocks in the hills around Yucca Flat and from interpretations of subsurface data [Fig. 3-1 of BN (2006) and Figure 2-2 of this report], the Paleozoic rocks are folded and have variable strikes and dips. A more sophisticated alternative model would account for the attitude of the LCA strata, assign hydraulic properties that are consistent with field observations of those units where they crop out in Nye and Clark Counties, and allow for possible channelization of groundwater flow along high-permeability layers.

- The EarthVision model shows little or no displacement of the contact between the LCA and the underlying LCCU along the Yucca fault or other Basin and Range normal faults, but there is undoubtedly as much displacement there as there is at the base of the Tertiary stratigraphic section. Nonetheless, the peer review team recognizes that transport of radionuclides in the LCA is likely to be so far above this contact that ignoring this displacement should have no impact in modeling groundwater flow.

***Recommendation:*** *Realistic geologic features (normal faults cutting the Paleozoic strata; variable dips on normal faults; fault intersections and active faults as higher permeability zones; alternative interpretations of faults based on geophysical data; narrow fault cores; gaps in the fault cores; lack of fault cores for some faults; and*

*attitude of LCA strata, including high-permeability layers) should be incorporated in the model as computational capabilities, software, and data improve.*

### 6.6.6 Other Sources of Data Are Available but Unused

The development of the conceptual model relies heavily on relatively limited hydraulic data from Yucca Flat. Other wells exist in the general vicinity of Yucca Flat that have not been included in the conceptual model development, specifically with respect to investigating the boundaries to the west, north, and east. Other facilities on land managed by DOE and DoD surrounding Yucca Flat should be queried for pertinent water-level and permeability information. While some of these data may not be publicly available, there should be sufficient justification for this project to release some forms of these data that would not jeopardize security.

***Recommendation:*** *Data from the surrounding DOE and DoD facilities need to be reviewed and used to further constrain water levels, boundary fluxes, and estimates of hydraulic properties of the LCA.*

The model for Yucca Flat is so complicated, and the number of detonations is so large, that it is difficult to isolate the effects of separate detonations on groundwater samples from wells drilled nearby.

***Recommendation:*** *Among other approaches discussed in previous sections of this report, the peer review team recommends building confidence in the Yucca Flat model by using the Yucca Flat modeling approach to simulate single-test detonations outside Yucca Flat in similar geological units where there has been groundwater monitoring (e.g., the 40-kt RULISON test in 1969 in Colorado, the 200- to 1,000-kt FAULTLESS test in 1968 in central Nevada, or the 12-kt SHOAL test in 1963 in northern Nevada).*

## 6.7 Uncertainty Evaluation

Capturing the 95 percent contaminant boundary originating from Yucca Flat is challenging given the lack of data and numerous uncertainties related to the complex system. The process requires evaluation of uncertainty in the conceptual models of source terms, hydrogeology, and contaminant transport, as well as the parameters that populate those models. The alternative conceptual models need to span a broad spectrum of possibilities that current data cannot rule out. Given the substantial computational demands of simulating a large and complex system, it is important that the alternative models do not represent small variations on one theme, but include major variations of the unknown nature of the system. In addition, given that the number of models to be evaluated is limited due to the

computational demands, it is important that the alternative models are biased toward more rapid contaminant migration. Standard procedures such as NSMC for evaluating parameter uncertainty require large numbers of parameter combinations to capture the 95 percent boundary; thus, a tractable alternative is needed.

### 6.7.1 Current Evaluation Does Not Capture the 95th Percentile

A theoretical conceptualization of the unknown probability distribution and the 95 percent probability (red arrow) for the furthest extent of the contaminant boundary is illustrated in Figure 6-6. The peer review team's perception of the approximate position of the current base case is noted by a blue arrow, and their perception of the range of evaluated cases is illustrated in orange. This perception arises from the fact that the N-I team strove to create a conservative base case, and many of the alternatives evaluated indicated a smaller contaminant boundary than the base case. The peer review team concludes that cases at the upper end of the distribution have not been simulated and should be included in the analysis. Theoretical samples of cases at the upper, unsampled end of the uncertainty distribution are included in green on Figure 6-6.

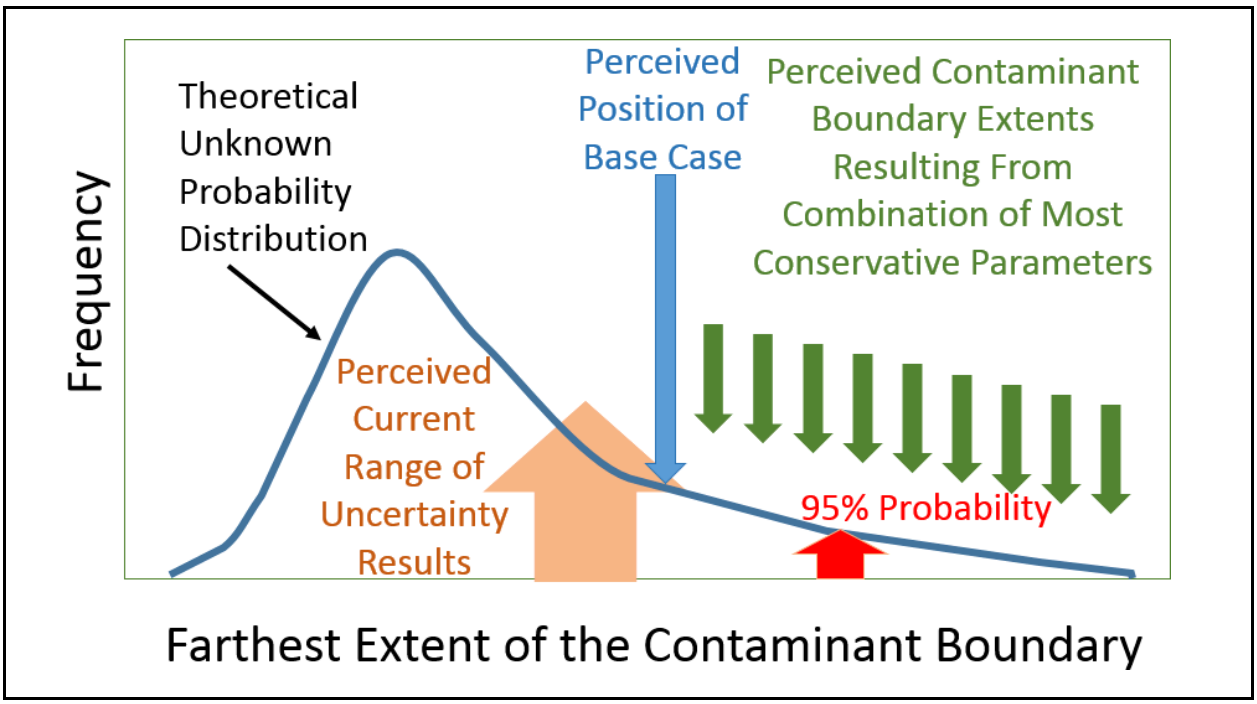



**Figure 6-6**
**Capturing the Upper Portion of the Uncertainty Distribution**

The perception that the 95 percent boundary has not been captured arises for a number of reasons. First, for example, reasonable alternative flow models that would result in more extensive contaminant transport are not included in the assessment. A second example is that it is not clear that the source term for $^{90}$Sr represents the 95th percentile, and N-I (2013) notes that

> "even the small fraction of $^{90}$Sr that is initially in the saturated LCA (about 0.1 percent of the total inventory for the 12 detonations that intersect the LCA with an exchange volume of 2 $R_c$) can have a significant impact on the extent of contaminant migration … because the initial concentration in the exchange volume is more than 100,000 times the MCL and there is assumed to be no sorption of $^{90}$Sr on the carbonate minerals in the LCA."

A third example is that Pu isotopes do not contribute to the 95 percent contaminant boundary due to the high $K_d$ value assigned for Pu isotopes in the LCA matrix. To capture the 95 percent contaminant boundary the evaluation needs to include the combined effect of values from the tails of input-parameter distributions that lead to more extensive transport (e.g., lower $K_d$ values and higher initial mass in the source term coupled with flow fields with continuous high-K pathways).

> ***Recommendation:*** *The peer review team recommends an approach where models that represent combinations of values from the upper end of their parameter distributions (those that would enhance transport) are generated manually and explored. Such exploration would start with the alternative flow model scenarios (including those listed in Section 6.7.2) using the most extreme parameters. For example, very high values for continuous, high hydraulic conductivity zones from the northern to the southern boundary and passing through sources would be held constant while other values are adjusted to determine whether an acceptable calibration can be obtained. If it cannot, the process would be repeated with a substantially lower value of continuous high hydraulic conductivity, and if that calibration is successful, then the difference (in log space) between the values of hydraulic conductivity would be halved until the maximum acceptable continuous high hydraulic conductivity value for the pathway is identified. A sampling scheme that captures combinations of parameter values from the portion of the transport parameter distributions that would enhance transport should be coupled with the faster flow fields.*

### 6.7.2 Expected Alternative Flow Models Were Not Included

As discussed in detail in previous sections of this report (primarily Sections 6.1, 6.3, and 6.4), a number of alternative conceptual models that are consistent with known data were not included in the flow model portion of the uncertainty analysis, including the following:

- A fully integrated model of the saturated hydrogeologic system of Yucca Flat extending northwest to Rainier Mesa, south to include the full extent of the contaminant boundary, and upward to include the TCU and AA/VA.
- A model that includes boundary flux from the northwest to represent recharge from the Rainier Mesa area.
- The fundamental conceptual model presented for Yucca Flat involving the major faults as the primary conduits for flow.
- A model with increased hydraulic conductivity of the material that is currently simulated as country rock in the vicinity of major faults.
- A model representing a highly heterogeneous LCA matrix including small but continuous high hydraulic conductivity pathways (which may represent connected faults or karstic features) between contaminant sources and the southern end of Yucca Flat.
- A model with minor faults all equally permeable with a high permeability comparable to that measured by the spinner log test in ER-6-1 #2, coupled with major faults that are more permeable than the minor faults, owing to more fracturing related to greater displacements.
- A model that has no or many fewer minor faults (this may require allowing flow and transport to occur between the AA/VA and LCA via fractured zones in the TCU).
- A model including higher permeability zones in the TCU matrix (to complement, or in lieu of faults) coupled with enhanced recharge through craters.
- A model including enhanced-recharge-driven transport in and below detonation craters.
- A model with a greater range of enhanced permeability assigned to the detonation damage zone.

***Recommendation:*** *The peer review team recommends the models listed in this section be evaluated as described in Section 6.7.1 and the "fast" flow fields from many strong source locations be used in combination with source and transport parameters that result in the most distant locations of MCL exceedance.*

### 6.7.3 Limited Number (100) of NSMC Realizations of the Flow Model Produced Parameter Value Combinations That Do Not Capture the 95th Percentile of Parameter Combinations That Lead to Rapid Transport

NSMC was used to address parameter uncertainty. Only 100 NSMC models were generated, and 83 were accepted (based on reaching an acceptable fit within a given period of time). Typically, many thousands of NSMC realizations are required to search parameter space for feasible parameter sets that collectively allow appraisal of parameter uncertainty (Keating et al., 2010). As a result of the limited model realizations, the analysis of flow and transport in the LCA used hydraulic conductivity values for the LCA that are not conservatively high (see Section 6.3 for more detail) and do not include the upper range of permeability values quantified by field tests in the LCA country rock or fault zones. In short, the range of hydraulic conductivity for zones within the LCA is not sufficient to capture the effects of the most permeable pathways; consequently, the extent of the contaminant boundary is likely underestimated.

> ***Recommendation:*** *Use the manual modification of a bias sampling approach as described in Section 6.7.1 to capture fast flow fields without excessive numbers of simulations. Confirm that the calibrated hydraulic conductivities are consistent with maximum field measurements. This requires increasing the range of considered permeabilities to include values beyond that measured in the spinner logs in wells ER-6-1 and ER-6-1 #2.*

### 6.7.4 Limited Calibrated Flow Models Used to Evaluate Transport Uncertainty

Ultimately, only three of the NSMC flow models (the base case, and a slow and moderate velocity model) were used to evaluate transport uncertainty. This does not capture the 95th percentile of the flow system behavior in the determination of the contaminant boundary. The fastest model (N-I, 2013, Fig. 6-81b) did not include combinations of measured values that would represent continuous high hydraulic conductivity zones (Andrews, 2014d). Even the major faults were not represented as continuous, high hydraulic conductivity values. After assessing transport in the models considered for the composite boundary, the fastest NSMC model was initially omitted from the presentation of the contaminant boundary (N-I, 2013, Fig. ES-3) because it was “deemed less likely” (N-I, 2013, p. 6-182). If the fastest model included the continuous high hydraulic conductivity zones as implied by various field measurements (e.g., the ER-6-1 aquifer test), it would be faster than the fastest flow field that was omitted from consideration. The fastest flow field selected did not represent

the upper end of the flow velocities and yet was omitted based on subjective judgment that it was "deemed less likely" rather than on the basis of quantitative data.

Two alternative framework models, which were deemed to potentially impact groundwater flow, were evaluated: the UCCU and the CP thrust fault alternative models. Applying the calibrated base-case hydrogeologic parameters in the two alternative HFM models resulted in hydraulic heads that were nearly identical to the values for the base-case model at the observation wells. The particle-tracking simulations indicated no discernible differences in particle trajectories between the base and alternative models. This suggests that these alternative models were not significantly different from the base case. As mentioned previously, the computationally intensive problem requires that substantially different alternative conceptual models be considered.

> ***Recommendation:*** *More flow fields (relative to the previous stage, which included only three) should be considered for the transport uncertainty evaluation, and biased sampling of transport parameters (in the direction that enhances transport) should be used to limit the number of transport simulations required to capture the 95th percentile. Additional flow fields should be generated by considering alternative conceptual models as described in Section 6.7.2 and associated parameters that lead to fast transport from source locations to the south end of Yucca Flat.*

### 6.7.5 Limited Alternative Models Used to Evaluate Relevant Detonations

The alternative source-term scenario (N-I, 2013, Fig. 6-67b) was also initially omitted from the composite contaminant boundary (N-I, 2013, Fig. ES-3) due to the subjective judgment that it was "deemed less likely." Many sources have been excluded from the analysis based on preliminary analyses to the point that it appears the upper tail of the contaminant boundary location has not been captured. It is not clear that a source that was determined to have a small contribution for the cases where it was considered will also have a small contribution for other scenarios. Some potentially important flow scenarios that were not considered in the initial analysis to determine the detonations that contribute to the contaminant boundary include, but are not limited to, (1) scenarios with combinations of high hydraulic conductivity for key hydrologic units; (2) scenarios with preferred flow pathways from detonation source areas to the southern end of Yucca Flat; (3) scenarios that include the effect of leakage through the matrix of the TCU to complement, or in lieu of, the fault pathways; and (4) scenarios with alternative boundary conditions in the northwest that simulate inflow from the Rainier Mesa recharge area (where there is a high gradient toward Yucca Flat, which

would likely produce southerly groundwater flow directions on the west side of the basin in the LCA—consistent with the Yucca Flat conceptual model and the Death Valley Regional Flow Model).

> ***Recommendation:*** *Alternative source terms need to be considered with associated flow conditions that move radionuclides rapidly to the LCA (e.g., breaches, high infiltration) and rapidly through the LCA (continuous high-permeability zones connected to source locations) in order to capture the upper end of the cases that will provide the 5 percent exceedance of MCLs.*

### 6.7.6 Limited Range of Transport Parameters Values Used to Evaluate Transport Uncertainty

N-I (2013) notes that the most important parameters influencing transport through the AA/VA layers to the LCA are source strength, matrix porosity, fracture porosity, and matrix diffusion of welded-tuff aquifer units, which include fault zones, and chimneys and cavities. The report also notes that without matrix diffusion, a much larger portion of radionuclides would have entered the LCA model. Matrix diffusion is included by increasing the effective porosity. The data for matrix diffusion are limited, and only a small portion of the site has been evaluated; thus, the potential for less matrix diffusion is likely.

The ranges of transport properties used for modeling the LCA are based on a limited field sampling in small areas and on laboratory studies of LCA core or material from other, presumably analogous formations. The ranges of properties are not expanded sufficiently to reflect possible values in unmeasured areas of the LCA or observations in other similar materials.

The N-I team decided that the appropriate dispersivity is 20 m longitudinal, 2 m transverse, and 0.2 m vertical; and a range of dispersivities was not explored. Dispersivities were interpreted from observations in the LCA of Yucca Flat with short travel distances (up to 130 m). The highest value of dispersivity reported is 30 m, but dispersivity was not considered in the uncertainty analysis, so the simulations do not include a scenario with a dispersivity of 30 m. As discussed in the supporting transport parameter document (SNJV, 2007), Gelhar's data show higher values for longer travel distances in fractured and carbonate materials, but those are not considered because they are deemed to be less reliable than values determined for short distances. For example, a limestone in Georgia had a longitudinal dispersivity of 61 m and transverse of 18 m for a 1,500-m travel distance (Davis et al., 1985). The 1,000-year period of concern in Yucca Flat may involve thousands of meters

travel distances. Field data suggest dispersivity could be one to two orders of magnitude greater than the assumed 20 m (SNJV, 2007, Figs. 9-3 and 9-4).

The source contribution from the model with the highest considered infiltration rate (10 mm/yr) was not included in the source-term uncertainty from the AA/VA model during the uncertainty evaluation of transport in the LCA. N-I (2013) argues that the high rate was used not because that magnitude of infiltration was thought to occur, but rather to generate an upper bound on the source term, yet this source term was not included in the uncertainty assessment for transport in the LCA.

> ***Recommendation:*** *Pu isotopes need to be included in the transport model with combinations of lower $K_d$ values and higher mass in the source term than presently specified in the uncertainty analysis. Improve the estimates of matrix diffusion or expand the evaluated uncertainty range such that the simulations will have little doubt of capturing the upper 5 percent tail of the contaminant boundary. Include higher values of dispersivity in the uncertainty evaluation. The range of dispersivity included in the uncertainty analysis needs to be commensurate with the degree of heterogeneity in the hydraulic conductivity field incorporated in future models.*

### 6.7.7 Mesh Refinement Not Necessarily Conservative

N-I (2013) evaluated use of the more detailed nodal spacing (level 3), which represents narrower faults compared to the level 2 spacing (62.5 m vs. 125 m). Particles from some locations arrived slightly faster than for the fastest NSMC case, and others arrived slower than the medium and fast NSMC cases. The report concluded that there is not a significant difference in the particle paths and travel times simulated with the more detailed mesh, and that the bounding level 2 models (i.e., the fast and slow NSMC cases) will generally encompass the extent of contaminant transport emanating from the detonation locations. Given that some level 3 cases produced faster times than the fastest level 2 case, then bounding level 2 models will not encompass the extent of contaminant transport. The difference in mesh size between level 2 and 3 is small, and this limited evaluation does not build confidence that the faults have been sufficiently resolved in the model. Consequently, a greater concern is whether particles will arrive much faster and the contaminant boundary will extend much farther if a level 4 or 5 mesh is used. This has not been evaluated.

> ***Recommendation:*** *Evaluate higher level meshes to determine definitively the mesh-refinement level for which there is no change in the contaminant boundary.*

## 6.8 Unforeseen Uncertainties and the Need for Extended Peer Review

### 6.8.1 New Concerns and Approaches Will Likely Arise

The peer review team recognizes and appreciates the enormity of the effort expended to develop the conceptual and numerical model of flow and transport in Yucca Flat. The system is complex and data are limited, which has led to a strong reliance of conservative estimates of hydraulic properties and flow paths. The modeling team and those involved with the Yucca Flat evaluation have certainly more experience than most in the area of nuclear testing hydrology, and this knowledge has been effectively used to augment the relatively sparse hydrologic and source-term experimental data from Yucca Flat. The peer review team recognized several key uncertainties and associated concerns that are discussed in other sections of this section. The peer review team further recognized uncertainties related to the decision-making process for aspects of the monitoring, sampling, and model development. For example, the rationale for resampling of monitor wells and their sampling frequency was not clear to the peer review team. Given the complexity of the Yucca Flat hydrogeologic system, including the effects of detonations and monitoring, the peer review team anticipates that other uncertainties and concerns will arise as new data are collected during the CADD/CAP and closure stages, and new approaches to those concerns will become available.

While there has been an effort in developing appropriate hydrologic and source term data for contaminant transport modeling of Yucca Flat in the 1990s and early 2000s, the conceptual model used still largely resembles that developed in the early 1970s by Winograd and Thordarson (1975), who used an even sparser dataset for their conceptual model. New data have been developed that serve to refine this general conceptual model, yet several key components of transport pathways described in previous sections remain largely untested. The peer review team's concerns revolve around (1) the limited hydrologic characterization data available for model development and (2) the potential for development and testing alternative conceptual models that go far beyond the commonly held view or conceptual model. With the development of new data in the 1990s and 2000s, the conceptual model of flow through Yucca Flat and in the highlands surrounding the valley has remained relatively unchanged. Some aspects of the conceptual model have been verified through data gathering, and the modeling team is to be commended for this; however, there remain significant components of the flow system that are uncharacterized and untested. Some of these new data could potentially support alternative flow models, such as, but not limited to, transport from Rainier Mesa and various flow paths through to Frenchman Flat. New analysis of head data in the TCU suggests

long-term drainage of this unit; however, locally higher fluxes potentially associated with testing and breaching of the TCU have not been tested in the field. The conceptual models of fault zone architecture and fault permeability used in the current modeling effort are based on limited hydraulic testing in Yucca Flat. Limited refinement of conceptual flow models is not uncommon, but with new datasets, it is critical that models be evaluated and new conceptual models be considered. New flow models, which sometimes can even be perceived as being "radical ideas," challenge the "status quo," and often are not easily accepted. Often, it takes a "fresh set of eyes" to challenge long-held theories of flow and to propose alternative flow models. This is made even more difficult on sites where security and access are limited, such as the NNSS.

> ***Recommendation:*** *The peer review team recommends that DOE initiate a wider "vetting" of the models and monitoring, and continued review of assumptions and rationale for choices made in data gathering, inclusion, and exclusion.*

The peer review team was surprised to find that model developers were forced to draw data from distributions that were limited or non-existent, or that monitoring data were not routinely collected. The peer review team fully recognized the difficulty in obtaining data from this site and the efforts of the model developers; however, given the importance of the site and nature of the contamination, the peer review team expected a more consistent and thorough characterization effort to have been conducted to date.

> ***Recommendation:*** *Therefore, the peer review team recommends that DOE should consider annual or biennial independent and external review of the hydrologic modeling, testing, and characterization efforts at Yucca Flat. This would foster development of new conceptual models; would lead to efficiencies in developing characterization plans, as it would provide an independent and unbiased assessment of the efficacy of new characterization efforts; and would help focus DOE efforts on critical characterization gaps. An outside evaluation could take, as this peer review team has been able to do, a "30,000-foot" view of the conceptual flow model and characterization efforts in a continuous manner to help guide efforts to close the most important knowledge gaps and build model confidence.*

Such a periodic external review would also help build the confidence of NDEP regulators that the model and related data-collection efforts are using best available technologies and scientific understanding. Continued peer review and evaluation can also provide significant input into monitor-well design, placement, and subsequent evaluation. Review will also help direct monitoring efforts and provide independent support to assumptions and model pathways chosen. Review

provides a continuity of planning and corporate knowledge to this project, which will undoubtedly continue well past the careers of many who have worked on the effort.

### 6.8.2 Climate Change

As an example of a perhaps unforeseen uncertainty, climate is likely to change over the 1,000-year time frame of concern. Whether the NNSS will become more or less humid is uncertain. Modeling of climate change will improve in coming years, providing more reasonable predictions of precipitation.

In addition, major storms could cause ponding in craters and low spots within Yucca Flat. Porter et al. (2010) modeled the "ARkStorm" scenario in nearby California as a major storm event resulting from an atmospheric river (pineapple express) with tropical moisture coming off the Pacific Ocean over several days. Dettinger et al. (2012) noted that daily precipitation in excess of 380 mm/day (15 inches per day) has occurred from such storms in California in the past. They are likely to occur once every 500 to 1,000 years. Some of the precipitation from such storms reaches Nevada.

> ***Recommendation:*** *As climate models are refined in the future, modeling should evaluate whether long-term climate change and associated extreme weather events would have a significant impact on the transport of radionuclides from Yucca Flat.*

## 6.9 Location of Radionuclide Plumes—Recommendations for Monitor Wells and Testing/Sampling Programs during the CADD/CAP Stage

A key uncertainty to be addressed in the CADD/CAP stage is the extent of radionuclide plumes from the 744 detonations in Yucca Flat. Significant plumes may be currently undetected, and, as mentioned in previous sections of this report, the possibility that radionuclides could be transported along fast pathways out of Yucca Flat is perhaps the major concern for public safety. The public's confidence regarding long-term monitoring during the closure stage will be bolstered if significant plumes are detected, and if a better understanding of potential fast pathways can be obtained during the CADD/CAP stage.

### 6.9.1 The Extent of Contamination Is Poorly Defined at Present

There are insufficient data of sufficient quality to determine the nature and extent of contamination in Yucca Flat. Determining the nature and extent of contamination is fundamental to contaminant transport analysis and remediation investigations, including natural attenuation of radionuclides.

No plume has been drawn to show where, after more than 50 years, there is impacted groundwater and where there is not, for any water-bearing unit or permeable pathway such as the major faults. If the spatial distribution of potential contaminants cannot be determined with reasonable confidence from field data today, and this distribution faithfully reproduced by the simulations, the public is not likely to have much confidence that models can predict where contaminants will be in 1,000 years.

Where there are samples from wells, the number of wells is too few and not appropriately located to delineate a plume with any reasonable certainty. A large majority of the sampled wells have well screens that are too long to provide useful information on contaminant detection. Further, the sampling of the existing wells has been too infrequent and at markedly different times to reasonably combine for plume delineation. In some instances, the most downgradient wells appear to have had impacts, suggesting that the current extent of contamination is poorly defined. In other instances, detections during initial rounds of sampling were dismissed as contamination caused by poor sampling techniques. More discussion on monitoring short-comings is presented below.

> ***Recommendation:*** *The peer review team recommends determining the bounds of contaminant migration in both the AA/VA and LCA aquifer systems. The emphasis should be on delineating the downgradient edge of the plume, targeting preferential geologic pathways (including faults) and placing monitor wells in the path predicted by the model for the year 2020, for example.*

### 6.9.2 The Existing Observation Well Network Is Inadequate

The simulation results are presented as evidence that “with high probability, ... the Yucca Flat CAU contaminant boundary will remain in the confines of the NNSS.” Evidence to support this claim includes data that indicated that no significant widespread contamination was found and that the model over predicted the observed concentrations in observation wells. There is significant uncertainty in the extent of contamination, owing in part to inadequacies in the design, location, and sampling frequency of many of these wells. The uncertainty in the extent of contamination leads to uncertainty in model evaluation assessments and to uncertainty in the predicted extent of the contaminant boundary.

Wells are the key means by which hydraulic head data and water-quality samples are collected. Most wells in Yucca Flat were drilled not for groundwater monitoring but for purposes of collecting information about the effects of the detonations. One reason for the difficulty in interpreting

water-level and chemical data is due to the character of the well construction, which varies from well to well. Yucca Flat and NNSS CAUs are unique compared with other federal facilities under environmental regulation, and as a result, Yucca Flat has not been subject to a comprehensive groundwater monitoring program to ensure that the data are representative of the flow system and suitable for decision making in a regulatory framework. For example, of the 60 wells used for calibration of the AA/VA (N-I, 2013, Table 4-8), only 2 have well screen lengths less than 20 ft, and most are more than several hundred feet long, up to 3,392 ft. Wells with long well screens that extend above the water table may intercept perched water, well screens that straddle multiple aquifers represent some average condition, and long well screens within a thick formation may be affected by vertical flow within the well bore. These conditions affect both hydraulic head and water-quality sampling. Standard practice on groundwater monitor wells would be to place a nominal 20-ft long well screen across the water table, or across specific permeable zones below the water table. In fact, in the groundwater monitor well guidance from NDEP, screens should be sufficiently short to prevent contaminants or water from separate strata from commingling (NDEP, 2012).

Except for the wells drilled or completed in accordance with the YF/CM CAIP (DOE/NV, 2000a)—including ER-2-1, ER-6-1, ER-6-1 #1, ER-6-1 #2, ER-7-1, and ER-8-1—wells in Yucca Flat were not designed for collecting water-level or water-quality data to be used in regulatory decision making. The number of far-field wells is too few to define the nature and extent of contamination. Most wells that are monitored at least periodically are on the perimeter of the detonation area. Fault zones are believed to be the pathways for contaminant migration, but none of the monitor wells are in the major fault zones.

At the scale of a single detonation, spatially distributed monitoring is also inadequate to build confidence that transport processes are well understood and model predictions are reliable. Each detonation creates a potential source area up to a radius of approximately 260 m (based on cavity radii ranging from 1 to 87 m). To assess the nature and extent of contamination released from a source or group of sources, if one wanted to know whether there were releases from a specific detonation for purposes of model validation, standard practice would place multiple wells near the source and downgradient of it, to define the zone of contamination. At no place has a plume of contamination been delineated using multiple monitor wells either for a single detonation, a group of detonations, or for all the detonations taken together in any HSU.

Available data suggest that radionuclides of concern at significant concentrations do not appear to be widespread; nevertheless contamination has been detected in groundwater observation wells near detonations. For some of those nearby monitor wells with no, low, or sporadic detections, it is uncertain whether the well was downgradient of the source, whether contamination may have bypassed the well in a preferential pathway or "conductive feature," whether the well was properly developed and in good hydraulic communication with the formation, or whether groundwater flow directions changed over time, for example. Owing to the sparse sampling, there is considerable uncertainty in impacts to groundwater and whether the available data are sufficient for model evaluation.

There are only four observation wells near LCA detonations: BILBY, BOURBON, NASH, and TORRIDO/MICKEY as presented in Appendix D of N-I (2013). Some radionuclides were detected in all of the four observation wells, mostly at levels below MCLs. In BILBY, the observation well was within about 2.5 $R_c$, so it is not surprising so many radionuclides were detected in U-3 cn#5 about 120 m southwest of the working point. However, this well is not outside the exchange volume, so it is difficult to assess to what extent groundwater in the LCA is impacted beyond this well. Moreover, the velocity vectors from the simulations indicate that groundwater flows east from BILBY, not to the southwest. At the BOURBON test, with a working point in the LCA 41 m above the water table, a satellite well, UE-7nS, was drilled 137 m southeast of the emplacement hole (Carle et al., 2008; p. 3-43), within about 2 $R_c$ of the working point. Several radionuclides were detected below MCLs. Because groundwater flows to the southwest at this location, the satellite well is not downgradient of the source. Furthermore, the satellite well produced little water when pumped; therefore, it is not surprising that concentrations are so low. Again, there is no monitoring just outside the exchange volume at BOURBON. At the NASH test, reportedly the most thoroughly characterized hydrologically, one satellite well, UE-2ce, was drilled 183 m south of the NASH working point; however, based on the easterly flow direction shown in Fig. 4.2 of the Carle report, this satellite well is not downgradient of the detonation. That pumping over three years (1977 through 1980) at this well location produced a 1,000-fold increase in $^3$H concentrations (Carle et al., 2008, Fig. 3-5) is consistent with the observation that the axis of the contaminant plume does not trend south. Interestingly, NASH (39 kt) is in the LCA3, which is described as less permeable than the LCA, so significant contaminant transport would be expected for detonations similar to NASH that intersect the more permeable LCA. And at the TORRIDO (20 to 200 kt) and MICKEY (20 to 200 kt) detonations, working points were above the water table centered near the OSBCU, which seems to be

highly anisotropic. The downgradient well ER-7-1 in the LCA is open across the water table. The absence of significant impacts here could be related to lateral migration within the TCU or low yield of the detonations.

With respect to the AA/VA system, Table 4-46 (N-I, 2013) shows 11 far-field wells and associated distances from specific detonations. The absence of $^{3}H$ at six of the locations cannot be used to infer that no migration from the detonation has occurred, as suggested in the report (N-I, 2013, p. 4-129): "The lack of detectable $^{3}H$ in so many wells...is notable." The absence of detections, or low concentrations, may be more related to the location of the sampled well with respect to prevailing groundwater flow, or to preferential flow in fractures that may bypass the well, than to retardation of the chemicals during transport. The directions of groundwater flow within the AA/VA, as shown by Fenelon et al. (2012), are extraordinarily complex. Without sufficient observation wells to establish the hydraulic gradient and without sufficient near-field water chemistry data near a single detonation, there is low confidence in the nature and extent of contamination at any scale.

Groundwater geochemical monitoring data collected over time, especially synoptically, are important in developing a site conceptual model for predicting fate and transport of contaminant migration. Unfortunately, time-series data are limited, sporadic, and not current. Of the 24 observation wells sampled for radionuclides but notably not called "monitor wells" in N-I (2013) (e.g., Table D-1), only 5 were sampled in the past 5 years, and 10 were last sampled 10 or more years ago. About 135 points—including springs, water wells, observation wells, tunnels, and other sources—were sampled for isotopes and/or solutes important for defining the pattern of regional water chemistry and the geochemical evolution of water (SNJV, 2006a). Like the radionuclide samples, no geochemical samples have been collected for the past decade, and about 25 percent of the points have not been sampled for at least two decades. Chemicals of concern have not been analyzed with consistent frequency, and the methods of sample collection have not been presented to the peer review team for consideration. In some cases, the depths of sample collection are not known. Quoting N-I (2013) (Appendix D, p. D-4), "There have been significant differences in sampling and analytical protocols over the years; hence, caution should be used when comparing data from different wells." Some of the differences are due to different sampling methods, which ranged from bailing to pumping samples from the wells.

> ***Recommendation:*** *The peer review team recommends a comprehensive formal review of existing data quality, including chemical sampling and laboratory testing methods.*

*Going forward, a groundwater monitoring program should be maintained to collect samples for purposes such as evaluating model uncertainties and delineating contaminant boundaries. Existing observation wells included in the monitoring program should be flagged with appropriate data-quality designations. New monitor wells are recommended in the near field and far field downgradient of key detonations, especially west of Yucca fault; in one or more permeable fault zones; and at the southern end of Yucca Flat where contamination is anticipated based on modeling.*

*Initial CADD/CAP monitor wells should be sited with the goal of finding contaminant plumes and simultaneously collecting valuable hydraulic property data from the fault zones and country rock of the AA/VA, TCU, and LCA. The peer review team recommends at a minimum additional monitor wells for two purposes:*

1. *To further evaluate the nexus between large detonations and the LCA via major faults, such as in the vicinity of STRAIT and the Topgallant fault, or near the impacted AA/VA holes U-4uPS 2A/U-7ba PS 1AS and Yucca fault, and*

2. *To find the extent of contamination along expected pathways bordering the detonations on the south, between ER-6-1 and ER-6-2.*

   - *One well near the Topgallant fault and*

   - *One well near the junction of Yucca fault and other minor faults such as those extending south from BILBY.*

   - *If either of the above two monitor wells show impacts, add two additional monitor wells to the south of Yucca Lake (e.g., near the outlet to CP Basin and Frenchman Flat).*

*Regarding construction of the wells, the peer review team recommends using angled drilling and doglegs when possible to cross the faults at multiple positions and investigate multiple issues with one hole.*

*In addition, the peer review team recommends resampling some of the drill-back holes and, as needed, sampling from new drill holes to understand whether radionuclides are migrating out of cavities. Drill holes near detonations with working points in and near the LCA may be most useful.*

*Furthermore, the peer review team recommends aquifer testing and sampling, and new drilling if necessary, to determine inflow to Yucca Flat from the north.*

Fenelon et al. (2012) recognized the importance of the Yucca fault as a possible pathway for radionuclides to enter the LCA. On p. 21 of their report, they stated:

> "Yucca fault is the probable structure hydraulically connecting the local alluvial–volcanic aquifers with the underlying regional carbonate aquifer. The

> connection may be through fault-induced secondary permeability or by fault-induced juxtaposition of carbonate and alluvial–volcanic rock (Bechtel Nevada, 2006). Where the alluvial–volcanic and carbonate aquifers are hydraulically connected by the fault, water is inferred to drain from the alluvial–volcanic aquifer into the carbonate aquifer, which has a lower hydraulic head (Winograd and Thordarson, 1975). The lowest hydraulic heads in the northern and southern alluvial–volcanic aquifers are 2,424 ft in well *UE-2aa* (*2207 ft*) and 2,391 ft in well *TW-7*, respectively. These heads are similar to heads in the regional carbonate aquifer at these two locations (pl. 4), suggesting some hydraulic connection between the local aquifer and the regional carbonate aquifer along the eastern side of Yucca Flat. If this connection exists, radionuclides in the alluvial–volcanic aquifers in Yucca Flat could migrate into the regional carbonate aquifer. Several wells open to the carbonate aquifer down-gradient from one of these hydraulic lows in the local alluvial–volcanic aquifers would be needed to determine if radionuclides are migrating to the regional carbonate aquifer."

Although the peer review team recognizes that the number of monitor wells drilled in and downgradient from Yucca Flat may be limited by budget constraints and the fact that significant plumes of radionuclides have been detected elsewhere on the NNSS, the peer review team agrees with Fenelon et al. (2012) that several wells may be needed to detect likely plumes.

All monitor wells should be pumped with sufficient rates and volumes to capture possible contamination. Groundwater chemistry should be analyzed with the intent of using state-of-the-science, complete, charge-balanced analyses in geochemical modeling and to understand such issues as colloidal transport. Cores and geophysical logs should be taken to characterize the structures and hydrologic properties.

> ***Recommendation:*** *In addition to new monitor wells, existing wells may be used to better understand processes and decrease uncertainty in hydraulic and geochemical properties. The testing and sampling programs listed in Table 6-5 should be undertaken in the CADD/CAP stage of the project to build confidence in the conservative nature of the predicted contaminant boundary. This list is neither exhaustive nor prioritized, and NNSA/NFO or NDEP may identify other key processes and pathways that require additional characterization during the next stage of work. The models should be used to identify additional data that would lead to the greatest reduction of uncertainty in the extent of the contaminant boundaries.*

## Table 6-5
## Recommended Non-exhaustive List of Testing and Sampling Programs to Better Characterize Key Pathways That Control the Contaminant Boundary

- Multi-well hydraulic testing on the central and western portions of the LCA to investigate both the fracture/fault hydraulic properties of the LCA and the vertical hydraulic continuity of the TCU. Water samples should be collected from known intervals and with time during testing in order to define the vertical as well as the horizontal distribution of water types and to define chemical changes (e.g., changing radionuclide concentrations) with the increasing aquifer volume sampled as pumping continues. Where appropriate, intervals should be packed off during sampling to prevent sample mixing due to vertical gradients.
- Multi-well hydraulic testing and water sampling at the northern boundary of the Yucca Flat to investigate inflow from the north, including the fracture/fault hydraulic properties of rocks that occur along the northern extension of the Boundary/Yucca fault across the topographic divide to the north (Comstock stock, LCA, contact-metamorphosed LCA, and overlying Tertiary volcanic rocks).
- Sampling and testing designed to maximize the ability to interpret data from hydraulic testing
  - Temperature profiling through the TCU to estimate vertical leakage
  - Lithologic logging (preferably of drill core) and geophysical logging of the TCU and LCA, with an emphasis on characterization of flow in fractures and faults in both units, and, in the case of the LCA, subsurface mapping of individual stratigraphic units that may contain karst or fracturing that would provide fast pathways
  - Packer testing to investigate hydraulic and chemical character of discrete preferred flow zones as well as the TCU
  - Spinner logs (as undertaken in ER-6-1) to investigate preferred flow zones
  - Head measurements at discrete depth intervals across the TCU and in the LCA to quantify the gradient
- Chemical data collected from discrete depth intervals and during pumping to define changes as boreholes are cleaned out and with increasing volume pumped:
  - Key radionuclides ($^{3}H$, $^{14}C$, $^{90}Sr$, $^{99}Tc$, $^{36}Cl$)
  - Major constituents (including field determinations) for charge balance (pH, major ions) as well as constituents required to assess equilibrium with formation minerals and aqueous speciation of radionuclides affecting their solubilities and sorption behavior

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# Appendix A

# Biographic Information on Peer Review Team Members

# A.1.0 BIOGRAPHIC INFORMATION ON PEER REVIEW TEAM MEMBERS

**John Klenke** – John Klenke is a geoscientist at the Nye County Nuclear Waste Repository Project Office (NWRPO). He is also the principal investigator for the NWRPO Regional Water Level Measurement Program and is a field manager for the Natural Gradient Tracer Test. Mr. Klenke was the senior geologist responsible for designing and implementing borehole geophysics and neutron logging for Yucca Mountain site characterization. He also was an exploration/consulting geologist at Cryo-Genie Mine in San Diego, CA. Mr. Klenke has a B.S. in Geology (with a Mathematics minor) from the University of Nevada, Las Vegas, and he has written approximately 10 publications and presentations.

**F. Joseph Pearson** – F. Joseph Pearson is a consultant in geochemistry, radiochemistry, geochemical modeling, and isotope hydrology to several high-level radioactive waste programs (including POSIVA, Finland; NWMO, Canada; NAGRA, Switzerland; BRGM and ANDRA, France; JNC, Japan; OECD/NEA; and ONWI, WIPP, EPRI, and Yucca Mountain, U.S.A.). He was Project Chief for Research in Isotope Hydrology for the USGS from 1966 to 1979, where he ran the USGS tritium and radiocarbon laboratory. Dr. Pearson is a State of Virginia Professional Geologist and a Fellow of the Geological Society of America. He has an A.B. in Geology from Harvard University, and an M.S. and a Ph.D in Geology from the University of Texas. Dr. Pearson has written more than 150 publications and internal reports, including co-authoring *Major Carbon 14 Anomaly in a Regional Carbonate Aquifer: Possible Evidence for Megascale Channeling, South Central Great Basin* (Winograd and Pearson, 1975), and he was the editor of *Applied Isotope Hydrology – A Case Study in Northern Switzerland* (1991).

**Eileen Poeter** – Eileen Poeter is a groundwater flow and transport modeler who is president of Poeter Engineering. She was director of the International Groundwater Modeling Center from 1997 to 2011 and organized the MODFLOW and More modeling conferences in 1998, 2001, 2003, 2006, 2008, and 2011. She was also a Distinguished Darcy Lecturer for the National Ground Water Association in 2006, with the topic “All Models Are Wrong: How Do We Know Which Are Useful?” Dr. Poeter is a Colorado Professional Engineer and an Emeritus Professor at the Colorado School of Mines, with

more than 50 graduate students. She has a B.S. in Geology from Lehigh University, and a M.S. in Engineering and a Ph.D. in Engineering Science from Washington State University. Dr. Poeter has had more than 50 groundwater consulting contracts, including AECOM/BLM review of groundwater models in Clark, Lincoln, and White Pine Counties, Nevada. She was a software developer for UCODE and MMA, which are distributed by USGS; and she has written more than 60 publications.

**Jonathan G. Price** – Jonathan G. Price is a geologist who is President of the Geological Society of Nevada and Vice President/President-Elect of the Geological Society of America. Dr. Price is Nevada State Geologist Emeritus and was the Director of the Nevada Bureau of Mines and Geology and Professor at the University of Nevada, Reno from 1988 to 2012. He was also President of the Society of Economic Geologists (2003); President of the Association of American State Geologists (2000–2001); President of the American Institute of Professional Geologists (1997); President and Chair of the Board of Directors of the Western States Seismic Policy Council (1998–2002); and Staff Director of the Board on Earth Sciences and Resources of the Commission on Geosciences, Environment, and Resources for the National Research Council, National Academy of Sciences (1993–1995). Dr. Price received the Ben H. Parker Memorial Medal from the American Institute of Professional Geologists in 2013; the Gold Medal from the Mining and Metallurgical Society of America in 2013; the Public Service Award in honor of Eugene and Carolyn Shoemaker from the Geological Society of America in 2010; and the Ian Campbell Medal for Superlative Service to the Geosciences, American Geological Institute in 2009. He has a B.A. in Geology and German from Lehigh University, and an M.A. and Ph.D. in Geology from the University of California, Berkeley; and he has written more than 200 publications.

**Daniel B. Stephens** – Daniel B. Stephens is principal hydrologist and Chairman of the Board of Daniel B. Stephens & Associates, Inc. (DBSA), an employee-owned hydrology, engineering, and geosciences consulting firm formed in 1984 that currently employs 110 professionals. He has worked on more than 200 consulting projects, providing expert testimony. Dr. Stephens was chairman of a team that developed vadose zone hydrology research strategies at DOE facilities; and he has performed technical reviews at numerous DOE facilities and projects, including Yucca Mountain, Hanford, Fernald, INEEL, LANL, LBNL, and WIPP. He also was on the Board of Directors and served as Vice President of the National Ground Water Association. He has a B.S. in Geological Sciences from Pennsylvania State University, an M.S. in Hydrology from Stanford University, and a Ph.D. in Hydrology from the University of Arizona. Dr. Stephens is the author of *Vadose Zone*

*Hydrology* (1995), and he has written more than 160 publications and presentations, including book chapters.

**Scott W. Tyler** – Scott W. Tyler is an unsaturated zone hydrologist who is Foundation Professor for the Department of Geological Sciences and Engineering at the University of Nevada, Reno. He is Chairman of the Board for the Consortium for the Advancement of Hydrologic Sciences (CUAHSI), and he received the John Hem Award for Excellence in Science and Engineering from the National Ground Water Association in 2013. Dr. Tyler was a panel member for the National Academy of Sciences: Challenges and Opportunities in the Hydrological Sciences from 2009–2011, and he was Chairman of the Hydrogeology Division of the Geological Society of America in 2007. He is also a Fellow of the Soil Science Society of America, Agronomy Society of America, and the Geological Society of America; and he was a Distinguished Darcy Lecturer for the National Ground Water Association in 1999 with the topic "Ground Water Recharge in Arid Regions: Questions About Today and the Past." He has a B.S. in Mechanical Engineering from the University of Connecticut; an M.S. in Hydrology from New Mexico Institute of Mining and Technology; and a Ph.D. in Hydrology/Hydrogeology from the University of Nevada, Reno. Dr. Tyler was Editor of *Water Resources Research* from 2005–2009; and he was Associate Editor for *Vadose Zone Journal*, *Advances in Water Resources*, *Geological Society of America Bulletin*, *Water Resources Research*, *Groundwater*, and *Hydrogeology Journal*. He has written more than 100 peer-reviewed publications, including book chapters.

# Appendix B

## Agenda and Attendees
## Peer Review Kickoff Meeting
## Las Vegas, Nevada
## April 7–11, 2014

(7 Pages)

# The U.S. Department of Energy

Welcomes You to...

Yucca Flat/Climax Mine CAU Peer Review Kickoff Meeting

April 7–11, 2014 - Las Vegas, Nevada

## Agenda for Monday, April 7

| Time | Topic | Presenter |
|---|---|---|
| 7:30 - 8:00 | COFFEE AND BAGELS (30 min) | |
| 8:00 - 8:15 | Peer Review Facilitator – Welcome | Sam Marutzky, Navarro-Intera, UGTA Project Manager |
| 8:15 - 8:25 | Nevada National Security Site Environmental Management – Mission | Scott Wade, NNSA/NFO Assistant Manager for Environmental Management |
| 8:25 - 8:40 | Nevada National Security Site Environmental Management – Mission | Rob Boehlecke, NNSA/NFO Environmental Management Operations Manager |
| 8:40 - 8:50 | Overview of Environmental Management, Environmental Restoration, and the UGTA Strategy – NDEP Perspective | Chris Andres, NDEP Bureau of Federal Facilities |
| 8:50 - 9:40 | Underground Test Area (UGTA) Organization and FFACO Strategy | Bill Wilborn, NNSA/NFO UGTA Activity Lead |
| BREAK (10 min) | | |
| 9:50 - 11:30 | Introduction and Overview of Technical Presentations and Conceptual Model | Ed Kwicklis, Los Alamos National Laboratory, CAU Lead |
| 11:30 - 12:00 | Corrective Action Investigation Stage FFACO and QA Requirements | Irene Farnham, Navarro-Intera, Science Advisor |
| LUNCH (60 min) | | |
| 1:00 - 2:15 | Underground Nuclear Testing: The Source of the Groundwater Contamination | Gayle Pawloski, Lawrence Livermore National Laboratory, Science Advisor |
| BREAK (10 min) | | |
| 2:25 - 4:00 | Geology of Yucca Flat and the Hydrostratigraphic Framework Model | Sig Drellack and Lance Prothro, National Security Technologies |
| BREAK (10 min) | | |
| 4:10 - 5:00 | Regional and Local Groundwater Flow Systems | Joe Fenelon, U.S. Geological Survey |
| 5:00 - 5:30 | Discussion | |
| END OF DAY 1 | | |

# The U.S. Department of Energy

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Yucca Flat/Climax Mine CAU Peer Review Kickoff Meeting

April 7–11, 2014 - Las Vegas, Nevada

## Agenda for Tuesday, April 8

| Time | Topic | Presenter |
|---|---|---|
| 8:00 - 8:05 | Welcome to Day 2 | Sam Marutzky, Navarro-Intera |
| 8:05 - 8:55 | Death Valley Regional Groundwater Flow System: Numerical Modeling | Wayne Belcher, U.S. Geological Survey |
| 8:55 - 9:45 | Yucca Flat Groundwater Geochemistry | Ed Kwicklis, Los Alamos National Laboratory |
| BREAK (15 min) | | |
| 10:00 - 10:40 | Yucca Flat Infiltration Summary | Ed Kwicklis, Los Alamos National Laboratory |
| 10:40 - 11:20 | Yucca Flat Hydrologic Data | Bob Andrews, Navarro-Intera |
| 11:20 - 12:00 | Yucca Flat Physical Transport Data | John Pickens, INTERA |
| LUNCH (60 min) | | |
| 1:00 - 1:40 | Yucca Flat Radionuclide Sorption ($K_d$) and Colloid Data | Mavrik Zavarin, Lawrence Livermore National Laboratory |
| 1:40 - 2:25 | Yucca Flat Groundwater Contamination Data | Irene Farnham, Navarro-Intera |
| BREAK (20 min) | | |
| 2:45 - 4:45 | Hydrologic Source Term: Principles and Overview | Andy Tompson, Lawrence Livermore National Laboratory |
| BREAK (15 min) | | |
| 5:00 - 5:30 | Discussion | |
| 5:30 - 5:40 | Field Trip Logistics | |
| END OF DAY 2 | | |

## Agenda for Wednesday, April 9

| Time | Topic |
|---|---|
| 6:45 - 6:00 | Field Trip – Convene at Atomic Testing Museum (~11 hours) |
| END OF DAY 3 | |

# Tour Agenda

***Depart Atomic Testing Museum in Las Vegas at 6:45 am***

- Stop #1: USGS Core Library, Mercury
- Stop #2: Frenchman Flat overlook
- View of: Frenchman Playa to the east (*info in this booklet*)
- Stop #3: News Nob
- Stop #4: Well ER-6-1
- Lunch
- Stop #5: U1a Complex
- Stop #6: BILBY crater
- Stop #7: Yucca fault scarp
- Stop #8: ICECAP (U-7cd) tower
- Stop #9: U-10i (BYE) crater
- Stop #10: SEDAN crater
- Stop #11: Area 12 Camp, T-Tunnel access road
- Optional Stop: Syncline Ridge (*info in this booklet*)
- Optional Stop: Apple II houses (*info in this booklet*)

***Arrive back in Mercury at approximately 4:30 pm***

***Depart Mercury at 4:45 pm, arrive Las Vegas at 5:30 pm (Centennial Hills Park and Ride, Lot 3) and 6:15 pm at the Atomic Testing Museum***

# The U.S. Department of Energy

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Yucca Flat/Climax Mine CAU Peer Review Kickoff Meeting

April 7–11, 2014 - Las Vegas, Nevada

## Agenda for Thursday, April 10

| Time | Topic | Presenter |
|---|---|---|
| 8:00 - 8:05 | Welcome to Day 4 | Sam Marutzky, Navarro-Intera |
| 8:05 - 8:20 | Introduction to Yucca Flat/Climax Mine Flow and Transport Models | Ed Kwicklis, Los Alamos National Laboratory |
| 8:20 - 9:20 | Climax Mine Sub-CAU Flow and Transport Models | Matt Reeves and Karl Pohlmann, Desert Research Institute |
| 9:20 - 10:00 | Yucca Flat Unclassified Source Term and Allocation | Pete Martian, Navarro-Intera |
| BREAK (15 min) | | |
| 10:15 - 11:30 | Yucca Flat Unsaturated Zone Flow and Transport Models | Ed Kwicklis, Los Alamos National Laboratory |
| LUNCH (90 min) | | |
| 1:00 - 2:15 | Yucca Flat Saturated Alluvial/Volcanics Flow and Transport Models | Elizabeth Keating, Los Alamos National Laboratory |
| 2:15 - 3:10 | Yucca Flat Lower Carbonate Aquifer (LCA) Flow Model | Bob Andrews, Navarro-Intera |
| BREAK (15 min) | | |
| 3:25 - 5:00 | Yucca Flat Lower Carbonate Aquifer (LCA) Transport Model | Bob Andrews, Navarro-Intera |
| 5:00 - 5:30 | Discussion | |
| END OF DAY 4 | | |

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Yucca Flat/Climax Mine CAU Peer Review Kickoff Meeting

April 7–11, 2014 - Las Vegas, Nevada

## Agenda for Friday, April 11

| Time | Topic | Presenter |
|---|---|---|
| 8:00 - 10:00 | Peer Review Panel - Working Session (Closed) | PEER REVIEW PANEL |
| BREAK (15 min) | | |
| 10:15 - 10:20 | Welcome to Day 5 | Sam Marutzky, Navarro-Intera |
| 10:20 - 11:20 | Flow and Transport Model Summary and Concepts for Model Evaluation | Ed Kwicklis, Los Alamos National Laboratory |
| 11:20 - 11:30 | Yucca Flat/Climax Mine Peer Review – Next Steps | Bill Wilborn and Bob Andrews, NNSA/NFO and Navarro-Intera |
| 11:30 - 12:30 | Preliminary Observations | PEER REVIEW PANEL |
| 12:30 - 12:40 | Farewell | Bill Wilborn, NNSA/NFO |
| END OF DAY 5 | | |

# The U.S. Department of Energy

Welcomes You To...

Yucca Flat/Climax Mine Peer Review Kickoff Meeting

April 7–11, 2014 - Las Vegas, Nevada

## Presenters and Attendees

| Affiliation | Name<br>Presenter (P), Attendee (A) |
|---|---|
| Nevada Division of Environmental Protection (NDEP) | Chris Andres (P)<br>Britt Jacobson (A)<br>Mark McLane (A) |
| National Nuclear Security Administration Nevada Field Office (NNSA/NFO) | Scott Wade (P)<br>Rob Boehlecke (P)<br>Bill Wilborn (P)<br>Kathryn Knapp (A)<br>Bruce Stolte (A)<br>Tiffany Lantow (A) |
| Navarro-Intera, LLC (N-I) | Sam Marutzky (P)<br>Bob Andrews (P)<br>John Pickens (P)<br>Peter Martian (P)<br>Irene Farnham (P)<br>Greg Ruskauff (A)<br>Dave Taylor (A)<br>Venus Blumenstein (A) |
| Desert Research Institute (DRI) | Karl Pohlmann (P)<br>Chuck Russell (A)<br>Jenny Chapman (A)<br>Matt Reeves (A) |
| Los Alamos National Laboratory (LANL) | Ed Kwicklis (P)<br>Elizabeth Keating (P)<br>Kay Birdsell (A) |
| Lawrence Livermore National Laboratory (LLNL) | Gayle Pawloski (P)<br>Andy Tompson (P)<br>Mavrik Zavarin (P) |

# The U.S. Department of Energy

Welcomes You To...

Yucca Flat/Climax Mine Peer Review Kickoff Meeting

April 7–11, 2014 - Las Vegas, Nevada

## Presenters and Attendees

| Affiliation | Name<br>Presenter (P), Attendee (A) |
|---|---|
| National Security Technologies, LLC (NSTec) | Sig Drellack (P)<br>Lance Prothro (P)<br>Ken Ortego (A) |
| Nevada Site Specific Advisory Board (NSSAB) | Bill Sears (A)<br>Donna Hruska (A) |
| U.S. Geological Survey (USGS) | Joe Fenelon (P)<br>Wayne Belcher (P)<br>Robert Graves (A) |

# Appendix C

# Corrective Action Unit (CAU) 97: Yucca Flat/Climax Mine (YF/CM) Peer Review Clarification: Letter from Wilborn to Marutzky, October 9, 2014

(4 Pages)

**Department of Energy**
National Nuclear Security Administration
Nevada Field Office
P.O. Box 98518
Las Vegas, NV 89193-8518

OCT 9 2014

Sam J. Marutzky, Project Manager
Underground Test Area
Navarro-Intera
P. O. Box 98952
Las Vegas, NV 89193-8952

CORRECTIVE ACTION UNIT (CAU) 97: YUCCA FLAT/CLIMAX MINE (YF/CM) PEER REVIEW CLARIFICATION

During the October 6 – 8, 2014, meeting with the YF/CM Peer Review committee, it was clear that the questions posed to the committee (listed below) required some clarification in order to focus the review on the use of the model at this point in the Underground Test Area (UGTA) strategy.

1. *Are the approaches, assumptions, and results consistent with the use of the models as decision tools for meeting Federal Facility Agreement and Consent Order (FFACO) regulatory requirements?*

   a. *Are the models of sufficient scale/resolution to adequately forecast contaminant transport in the YF/CM setting?*

   b. *Have the key processes been included in the models?*

   c. *Are the flow and transport modeling results and uncertainties technically sound and defensible?*

   d. *Are the conceptual models used in the different flow and transport models sufficiently consistent to provide representative integrated model results?*

2. *Are the datasets and modeling results adequate for a transition to model evaluation studies in the Corrective Action Decision Document/Corrective Action Plan (CADD/CAP) stage—the next stage in the UGTA strategy for the YF/CM CAU?*

The clarification relates to defining the purpose and goal and the associated level of confidence required in the model and the model results necessary to advance from the Corrective Action Investigation (CAI) stage to the CADD/CAP stage. Clarification is needed to identify the FFACO regulatory requirements that the modeling approaches, assumptions, and results are meant to support (Question 1) and what constitutes dataset and modeling result adequacy for a transition to model evaluation studies (Question 2) at this point in the UGTA FFACO strategy.

Clarification begins with the discussion of the goals and objectives of the CADD/CAP stage presented in the FFACO (1996, as amended):

> The first two steps in the CADD/CAP stage require the National Nuclear Security Administration Nevada Field Office (NNSA/NFO) and the Nevada Division of Environmental Protection (NDEP) negotiation and identification of CAU regulatory boundary objectives and initial use restriction boundaries. After these objectives and boundaries are identified, the CADD/CAP is developed which includes a model evaluation strategy to perform the following:
>
> 1. *Continue the process of model evaluation with an increased focus on assessing the reliability of model results.*
>
> 2. *Test contaminant boundary forecasts and the uncertainty in contaminant boundary forecasts through data collection, which may include additional drill-hole exploration and focused testing and sampling.*
>
> 3. *Build confidence that the results from modeling of flow and contaminant transport can be used for regulatory decisions required for CAU closure. (FFACO, Appendix VI, page 29-30)*

In essence, the model and associated model results need to be sufficient to (a) negotiate and identify CAU regulatory boundary objectives, (b) negotiate and identify initial use restriction boundaries, and (c) develop a model evaluation strategy that focusses on the reliability of the model results, uncertainty in contaminant boundary forecasts and that builds confidence in the model results for CAU closure.

The details of the implementation of the model evaluation strategy are not explicitly defined in the FFACO, but have been developed for the Frenchman Flat CADD/CAP (NNSA/NSO, 2011). The model evaluation strategy defined in the Frenchman Flat CADD/CAP consists of a series of five steps involving key uncertainty (model evaluation target) identification, data collection, and model refinement (Figure 1, enclosed). Model adequacy to meet the CAU closure objectives (i.e., determining regulatory boundaries, finalizing use restriction boundaries, and developing a monitoring program) is addressed in the final step of the CADD/CAP stage after any necessary model refinements have been made.

At the end of the CAI stage, the model approaches, assumptions, and results must be sufficient to support the initial step of the CADD/CAP stage. As noted in the Frenchman Flat CADD/CAP (page 44, step 1):

> *"The CADD/CAP <u>model evaluation process begins with model uncertainty identification and prioritization</u> <u>by the modeling team with the support of others</u> with additional expertise, if necessary. The initial evaluation (i.e., evaluation that follows the CAI stage) <u>begins with an assessment of the model uncertainties</u>*

*identified in the contaminant transport model report. The uncertainties are identified by sensitivity and uncertainty analyses, including evaluation of alternative conceptual models. A list of model evaluation targets is developed for the key uncertainties and data-collection activities are identified that could best address those targets."*

As a result of the above summary of FFACO regulatory requirements and the description of the first step in model evaluation strategy, the clarification can be summarized as follows:

*The model and supporting information should be sufficiently complete that the key uncertainties can be adequately identified such that they can be addressed by appropriate model evaluation studies. The model evaluation studies may include data collection and model refinements conducted during the CADD/CAP stage. One major input to identifying "key uncertainties" is the detailed peer review provided by independent qualified peers.*

Please communicate this clarification to the Peer Review committee. If you have any questions, please contact me at (702) 295-3188.

for /s/ Robert F. Boehlecke
Bill R. Wilborn
UGTA Activity Lead

EMO:10862.CD

Enclosure:
As stated

cc w/encl. via e-mail.:
N-I Central Files
NSTec Correspondence Management
R. F. Boehlecke, NFO
FFACO Group, NFO
NFO Read File

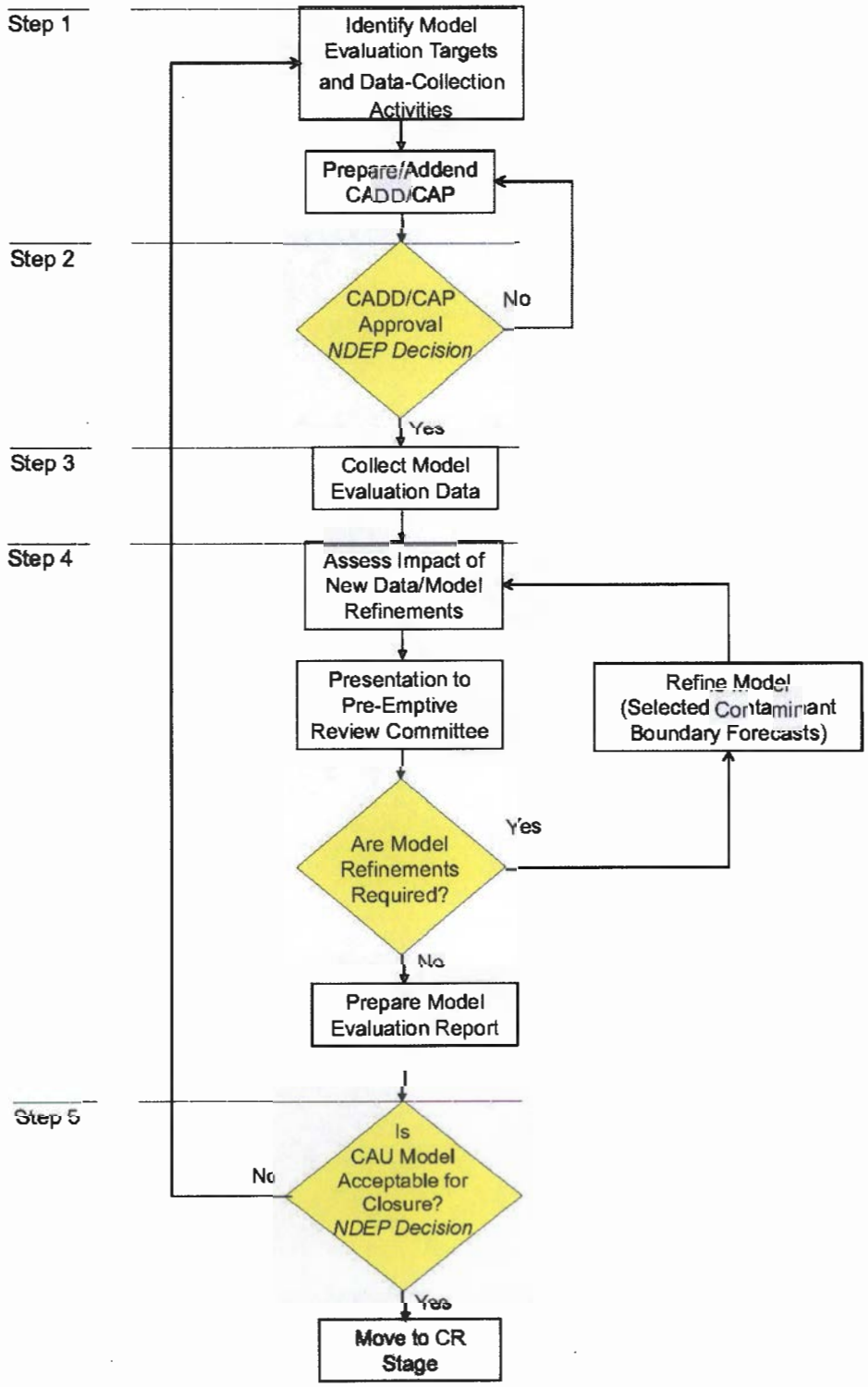


Figure 1 CADD/CAP Model Evaluation Process (NNSA/NSO, 2011)

# Appendix D

# Steady-State Head Targets

# D.1.0 STEADY-STATE HEAD TARGETS

The wells presented in this appendix are the only wells used for steady-state targets in N-I (2013). As noted in the recommendations of this report, there are other wells that should be included as targets. The peer review team recommends a thorough review of the available data to identify more targets and additional fieldwork to gather more calibration data. Data for the graphs displayed in this appendix are from the USGS Data Series 533, *Database of Groundwater Levels and Hydrograph Descriptions for the Nevada Test Site, Nye County, Nevada* (Elliott and Fenelon, 2013), obtained via a link provided by R. Andrews on May 23, 2014. The graphs for each well display all data for the well on the left graph, and the data selected and averaged to obtain the steady-state target head on the right. X-axes are all the same. Y-axes are the same for all wells on the west side and all wells on the east side; however, the range differs for the west and east side.

Problems:

- The values selected for determining the steady-state average seem to be arbitrary, and the procedure for selection does not appear to be consistent from well to well.
- As recognized by N-I (2013), some of the wells show a gradual upward trend starting in the 1980s. This was deemed to be small enough to be a minor trend in a long-term steady condition.
- If the values represent a long-term steady condition, then (after removal of outliers that represent recovery, measurement error, and response to a detonations) either all the values should be averaged, or preferably all of the data points (with previously noted deviations omitted) could be used, and the numerous residuals at each location would provide a realistic representation of the difference between measured and simulated heads.
- It is not appropriate to combine heads from different time periods (the temporal midpoints of the averaged values range from 1961 to 2003) to represent a steady-state flow field when conditions are changing over time. In this case the transient change in head is substantial relative to the difference in head over the area of interest (e.g., about 5-ft rise over about 15 years in ER-6-2 (2,444.6 ft above mean sea level [amsl] in 1994 and 2,449.6 ft amsl in 2009) with about 30 ft difference in head on the west side of the faults).

### D.1.1 Summary of the Data Selected for Each Steady-State Target

Wells on the west side of major faults approximately in order from north to south:

- **UE-10j 2380** — All data were averaged. Midpoint approximately 1971.
- **WW-2 3422** — Mid-range of late data were averaged. Midpoint approximately 2000.
- **TW-D** — Mid-range of late data were averaged. Midpoint approximately 1996.
- **UE-1q 2600** — Mid-range of late data were averaged. Midpoint approximately 2001.
- **UE-1h** — Mid-range of late data were averaged. Midpoint approximately 1992.
- **ER-6-2** — Mid-range of late data were averaged. Midpoint approximately 1998.

Wells on the east side of major faults approximately in order from north to south:

- **U10L-1** — Recovery omitted, then all data were averaged. Midpoint approximately 1975.
- **UE-7nS** — Spikes were omitted, then mid-range data were averaged. Midpoint approximately 1988.
- **ER-7-1** — Mid-range of late data were averaged. Midpoint approximately 2003.
- **UE-7aa** — Recovery omitted, then all data were averaged. Midpoint approximately 1970.
- **U-3cn5** — Mid-range data were averaged. Midpoint approximately 1988.
- **TW-E** — Recovery & spikes removed, mid-range early data averaged. Midpoint approximately 1962.
- **ER-3-1**-2 shallow — Mid-range of early data were averaged. Midpoint approximately 1994.
- **ER-6-1** main 2243 — Mid-range of data were averaged. Midpoint approximately 1997.
- **WW-C** — All data were averaged. Midpoint approximately 1961.

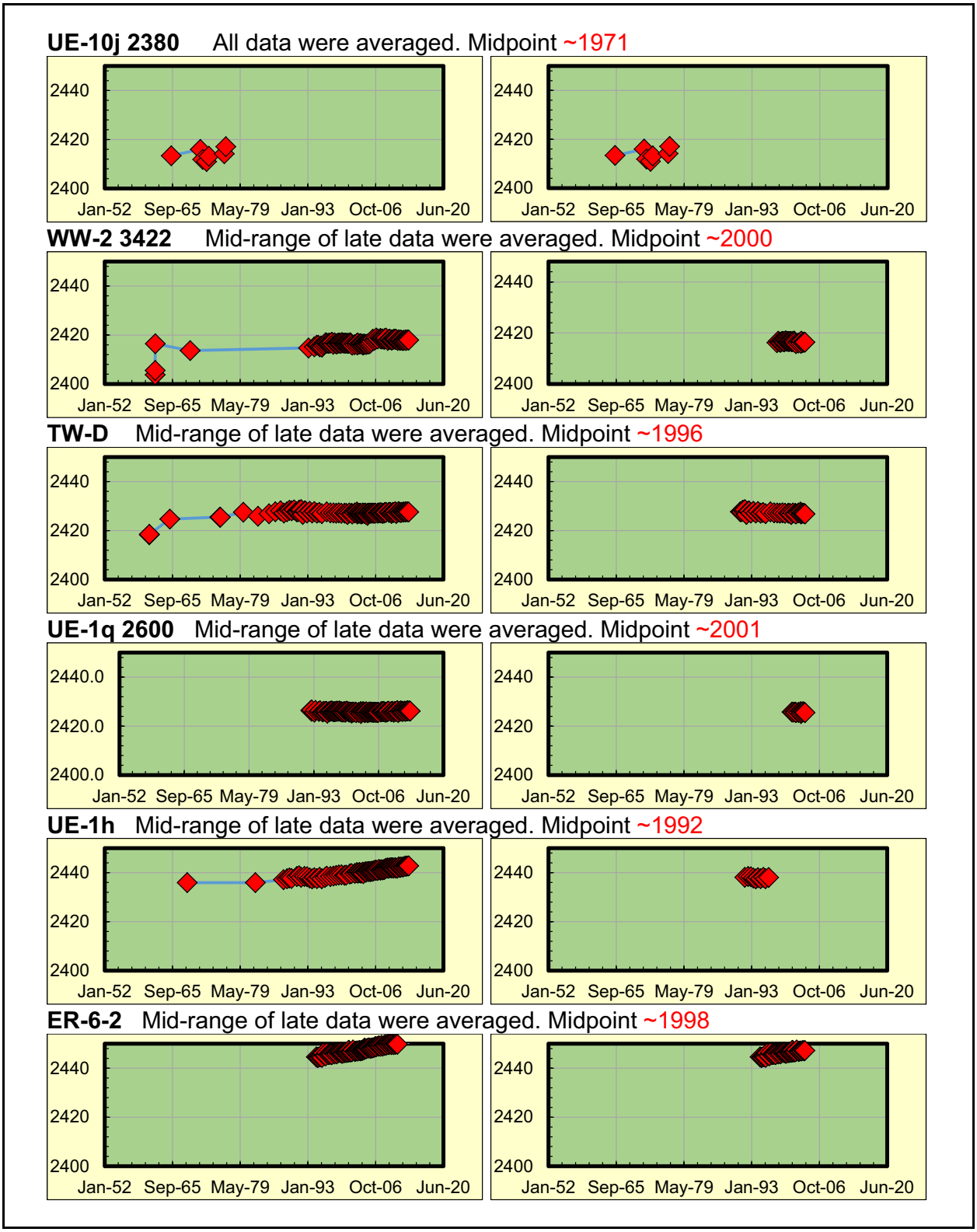


***Figure D-1***
***West Side North to South***

Note: All data are shown on left, data averaged for steady state on right.

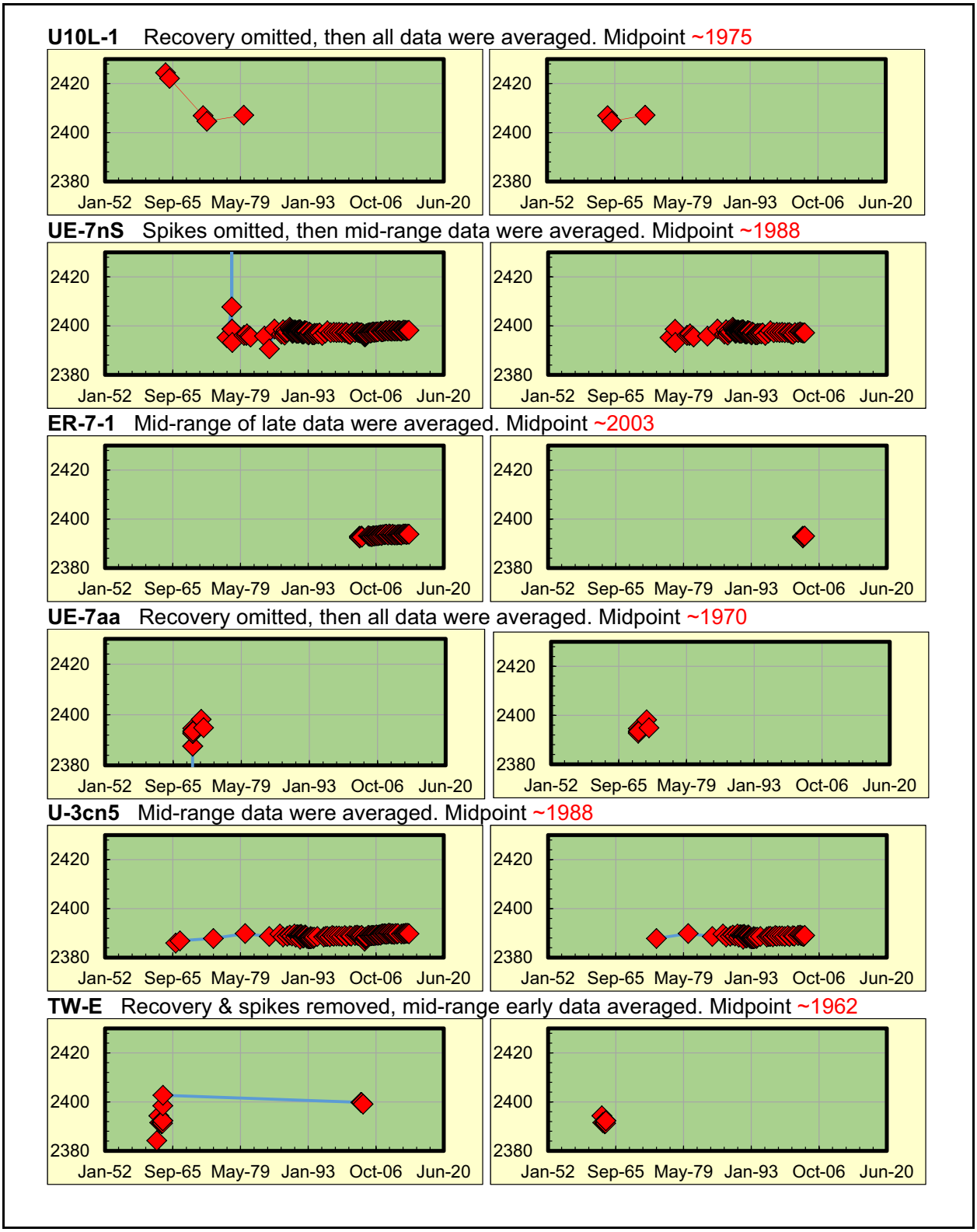


***Figure D-2***
***East Side North to South***

Note: All data are shown on left, data averaged for steady state on right.

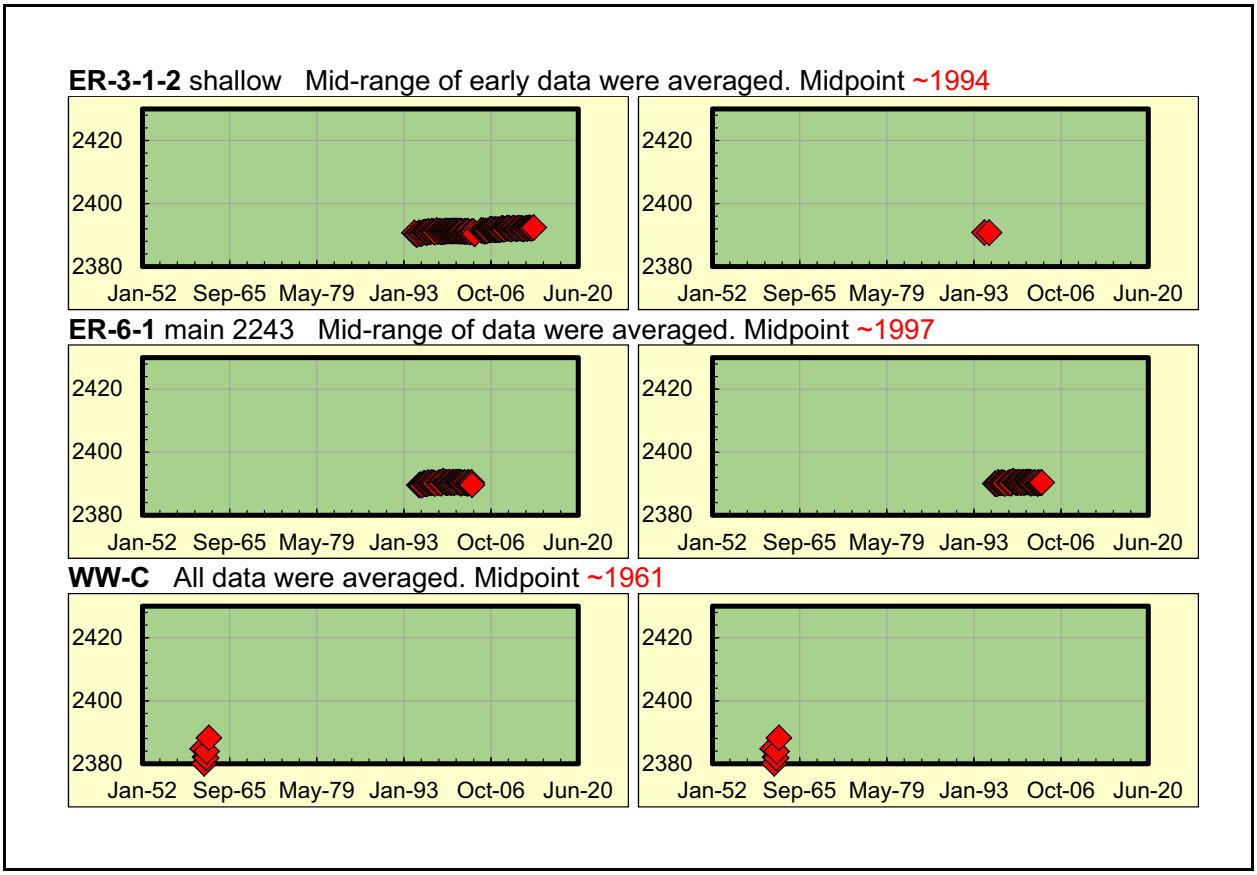


***Figure D-2 (continued)***
***East Side North to South***

Note: All data are shown on left, data averaged for steady state on right.

## D.2.0 REFERENCES

Elliott, P.E., and J.M. Fenelon. 2013. *Database of Groundwater Levels and Hydrograph Descriptions for the Nevada Test Site Area, Nye County, Nevada*, Data Series 533, Version 4.0. Reston, VA: U.S. Geological Survey.

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# Appendix E

# Cumulative Distribution Function for Parameters Used in the N-I 2013 LCA Model

# E.1.0 Cumulative Distribution Function for LCA Flow Model Hydraulic Conductivity Values

The CDFs in this appendix were supplied by N-I (Andrews, 2014a and b). The straight line represents the initial hydraulic conductivity distribution specified by the N-I modeling team based on Table 5-8 of N-I (2013). The blue line represents the CDF of the initial hydraulic conductivity values selected by the NSMC procedure for the base-case flow model. The red line represents the CDF of the resulting calibrated hydraulic conductivity values for the 83 runs that had a calibration objective function of less than 10 m. The green triangle indicates the value of the hydraulic conductivity value for the parameter in the "fast" flow model, NSMC run 46.

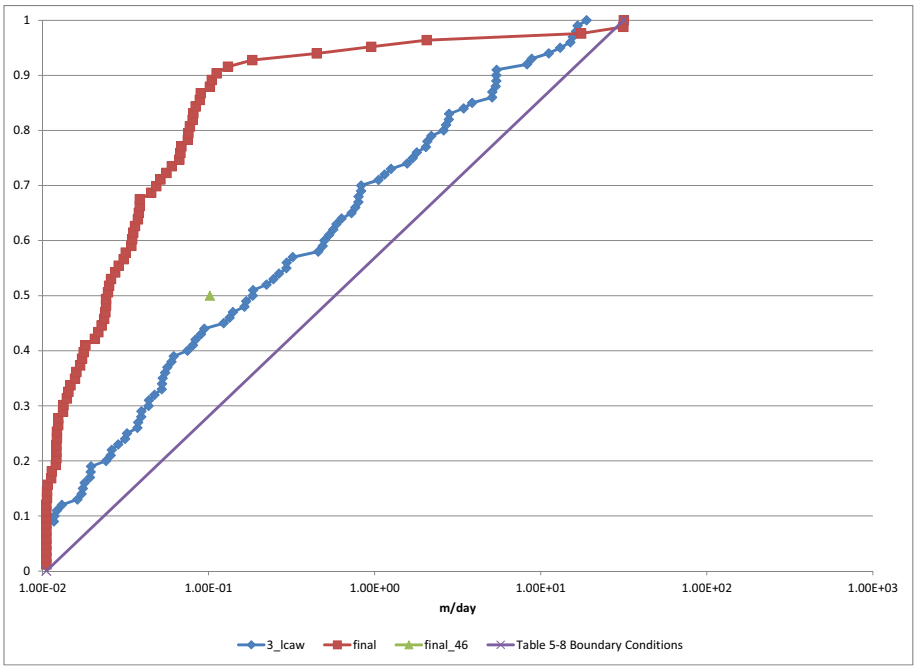



**Figure E-1**
**LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 3_lcaw)**

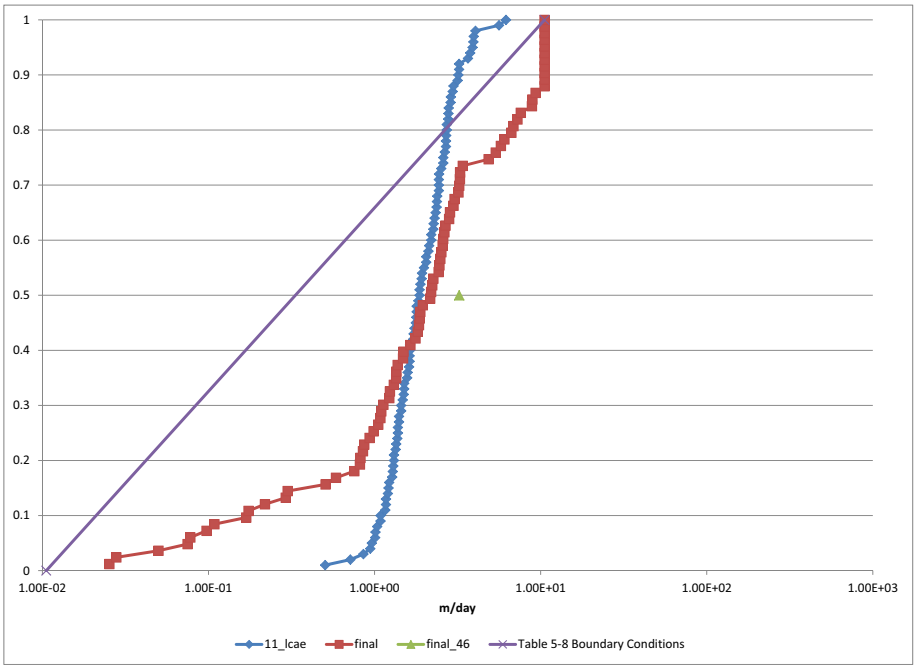



***Figure E-2***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 11_lcae)***

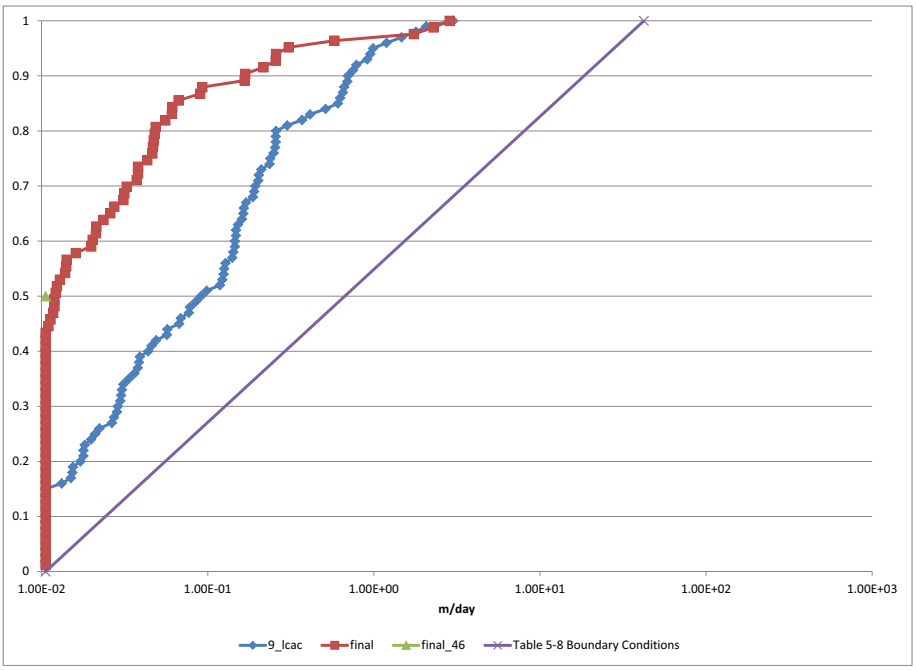



***Figure E-3***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 9_lcac)***

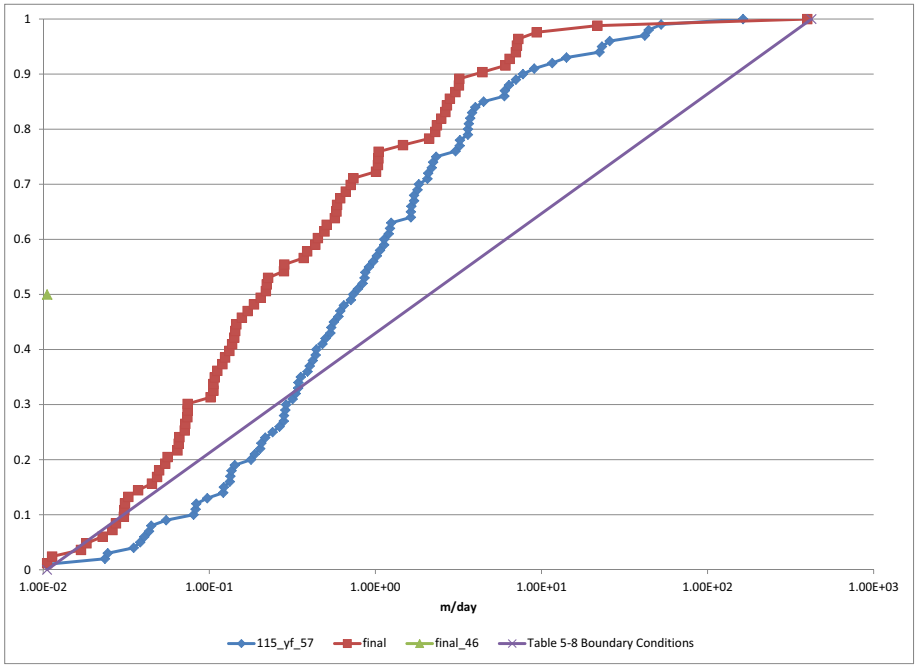



***Figure E-4***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 115_yf_57)***

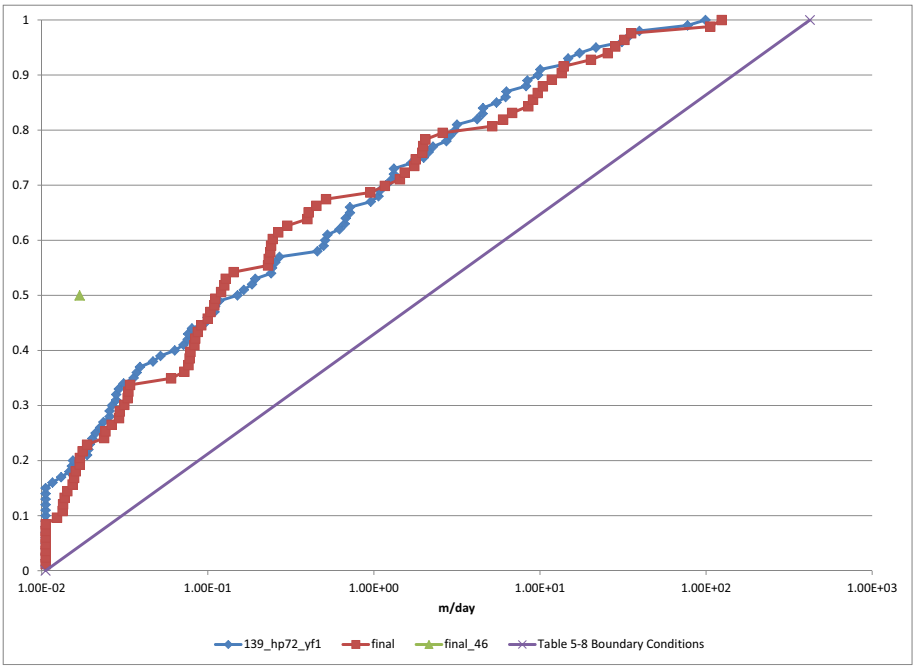



***Figure E-5***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 139_hp_72_yf1)***

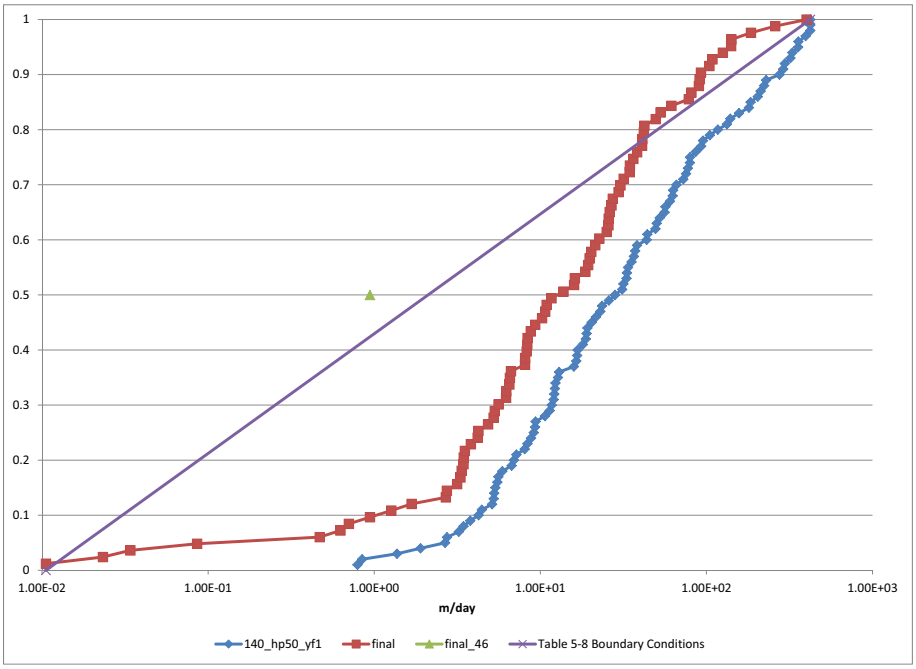



***Figure E-6***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 140_hp50_yf1)***

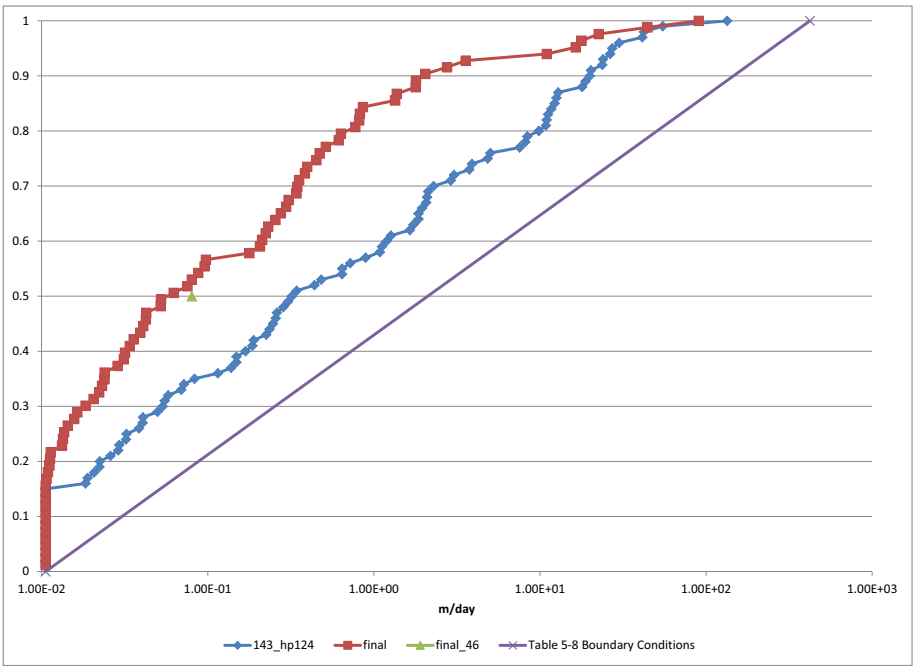



***Figure E-7***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 143_hp124)***

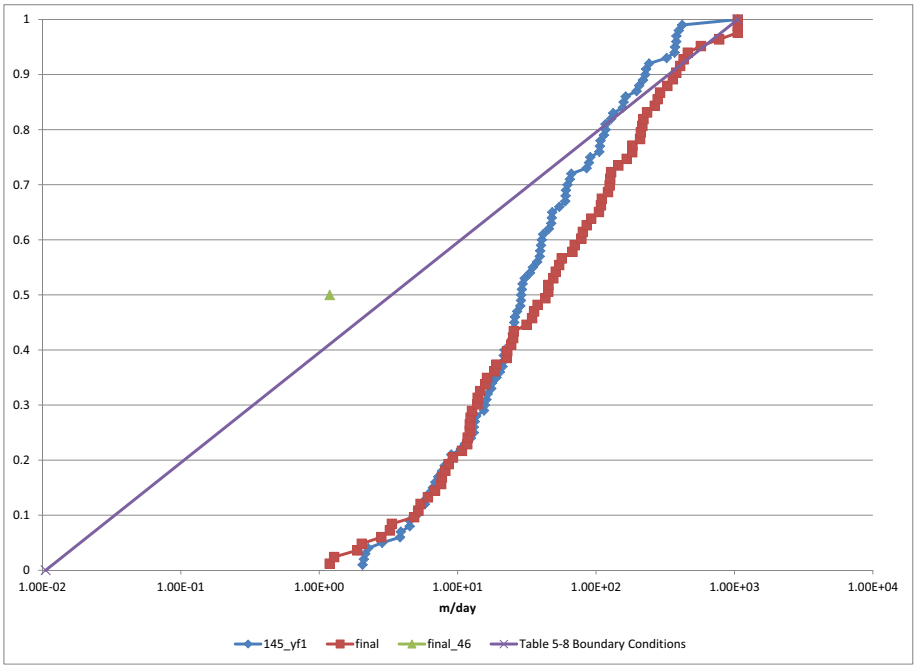



***Figure E-8***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 145_yf1)***

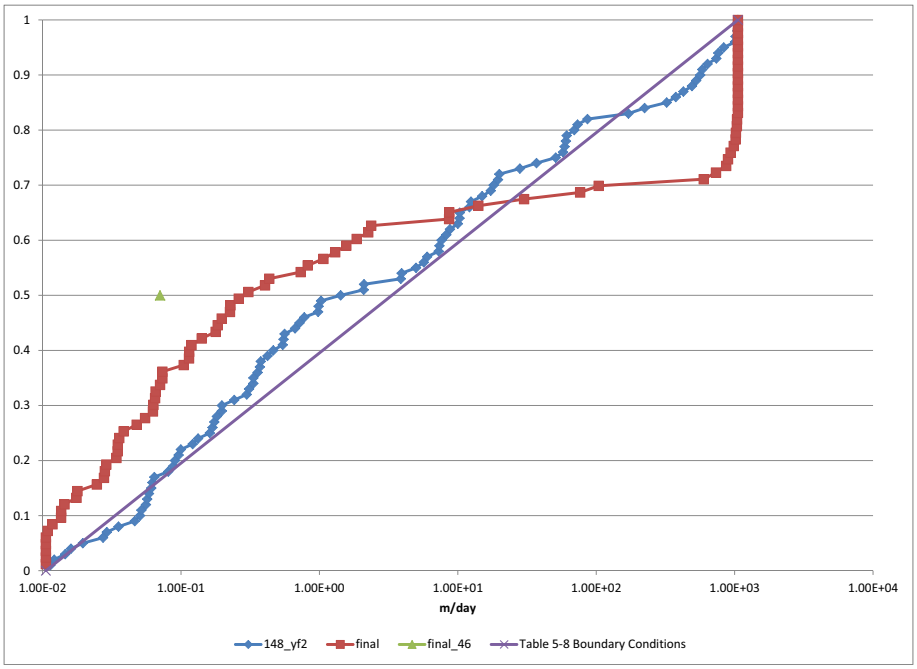



***Figure E-9***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 148_yf2)***

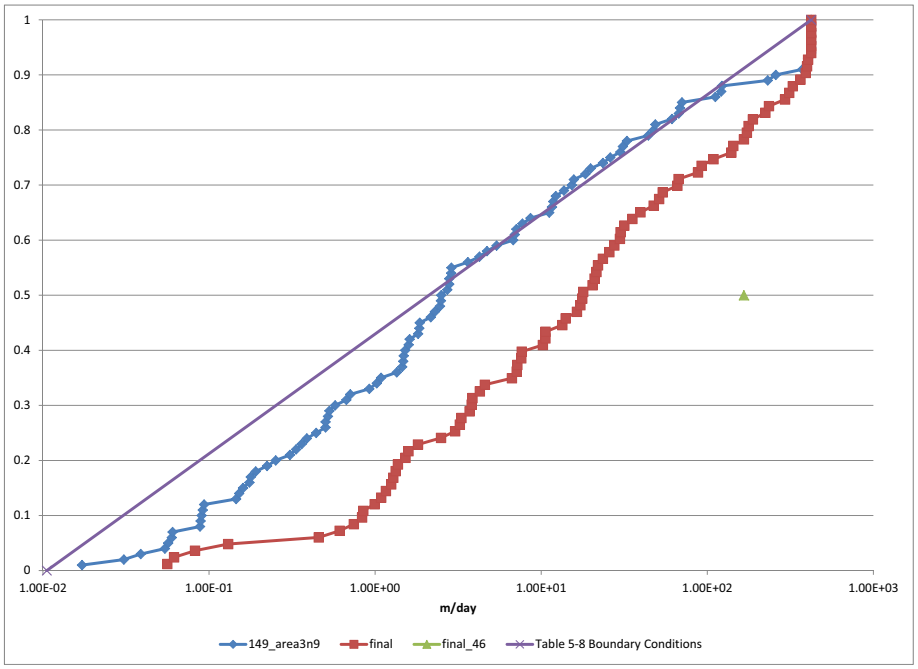



***Figure E-10***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 149_area3n9)***

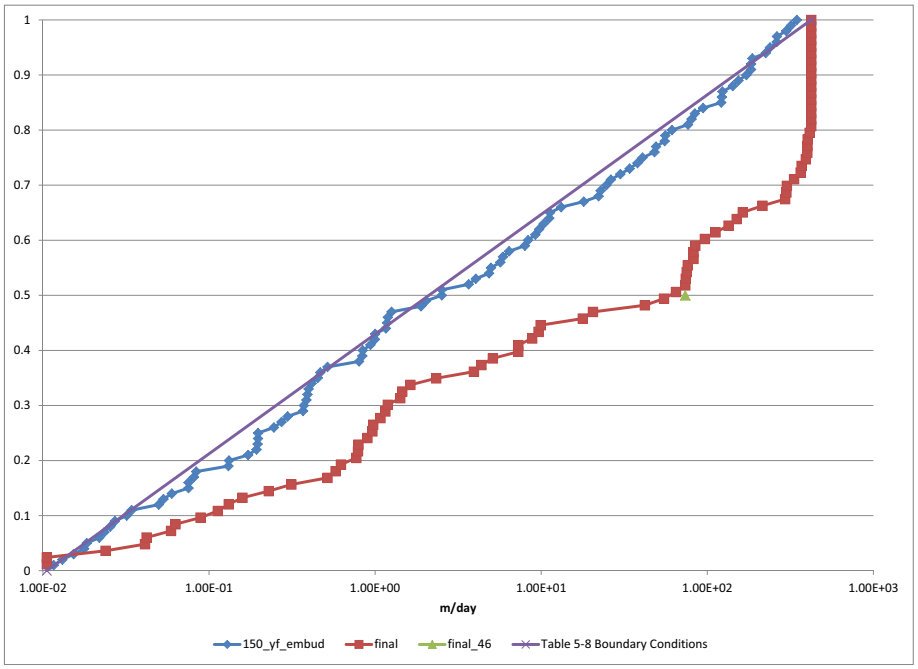



***Figure E-11***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 150_yf_embud)***

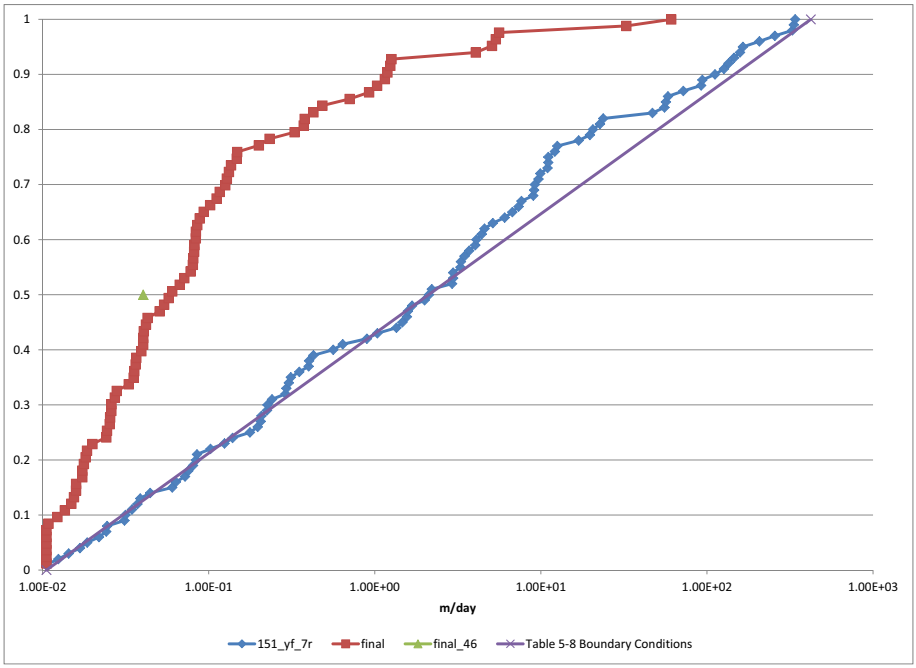



***Figure E-12***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 151_yf_7r)***

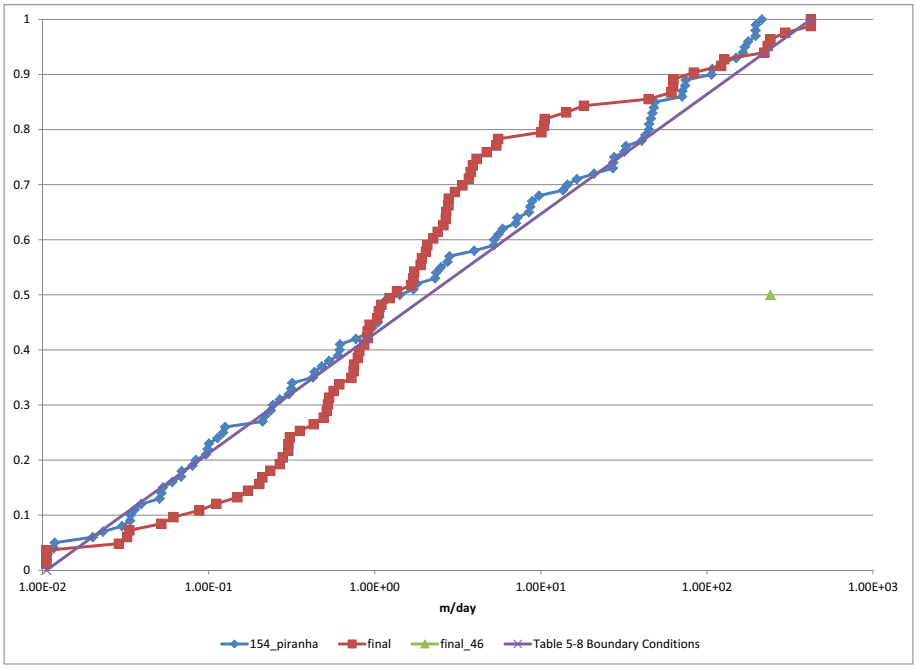



***Figure E-13***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 154_piranha)***

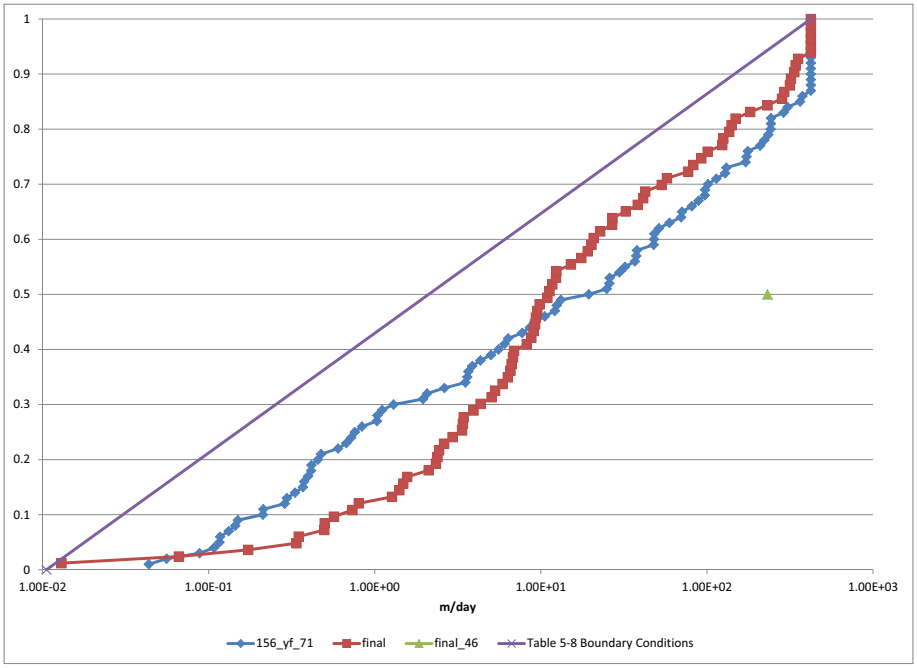



***Figure E-14***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 156_yf_71)***

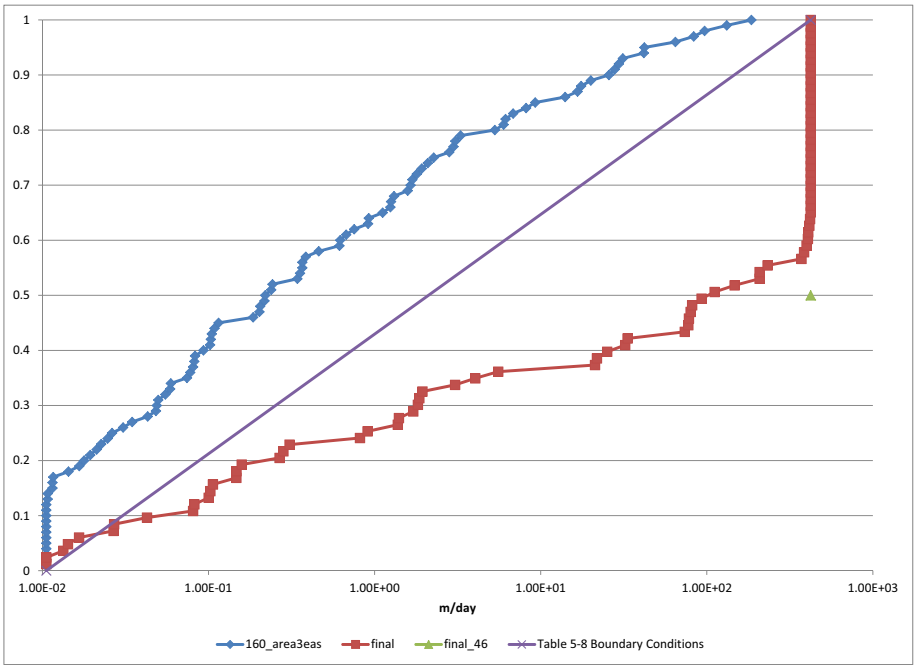



***Figure E-15***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 160_area3eas)***

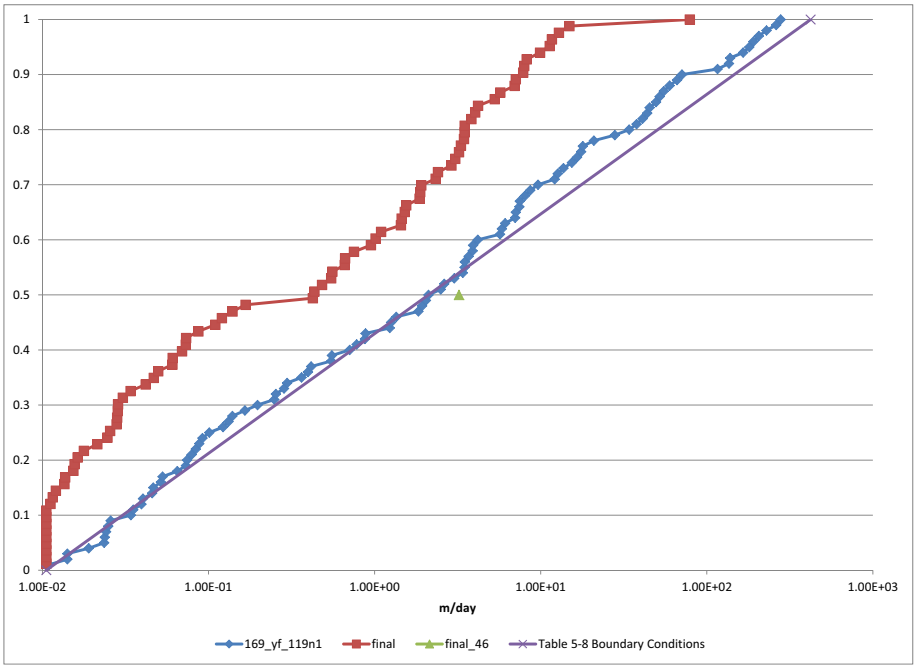



***Figure E-16***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 169_yf_119n1)***

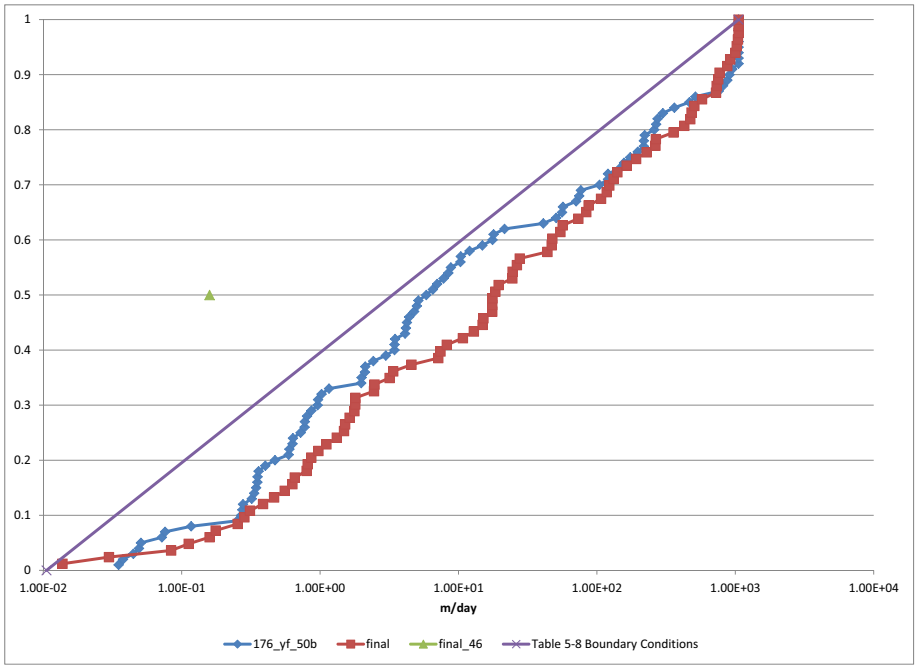



***Figure E-17***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 176_yf_50b)***

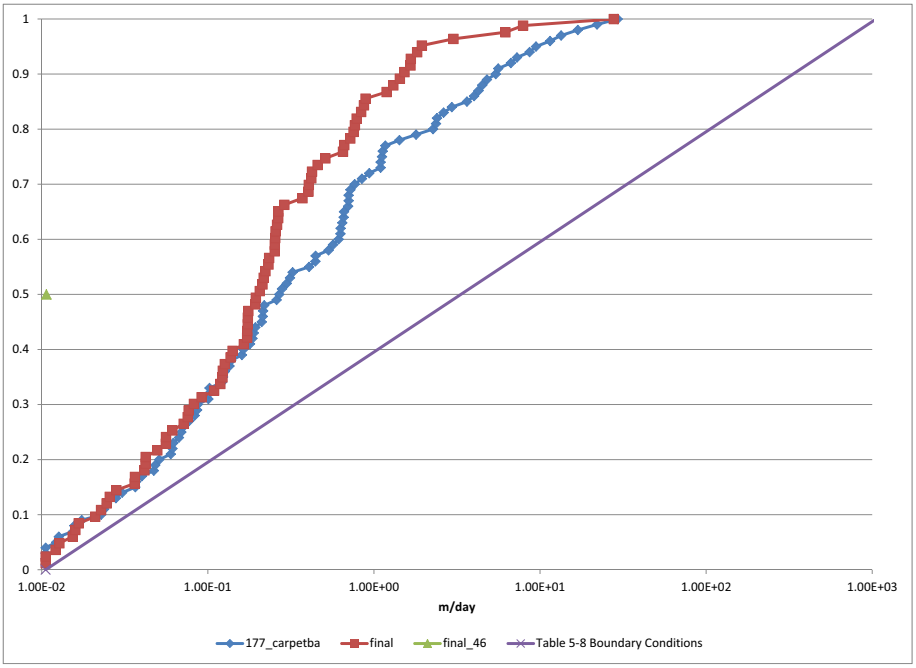



***Figure E-18***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 177_carpetba)***

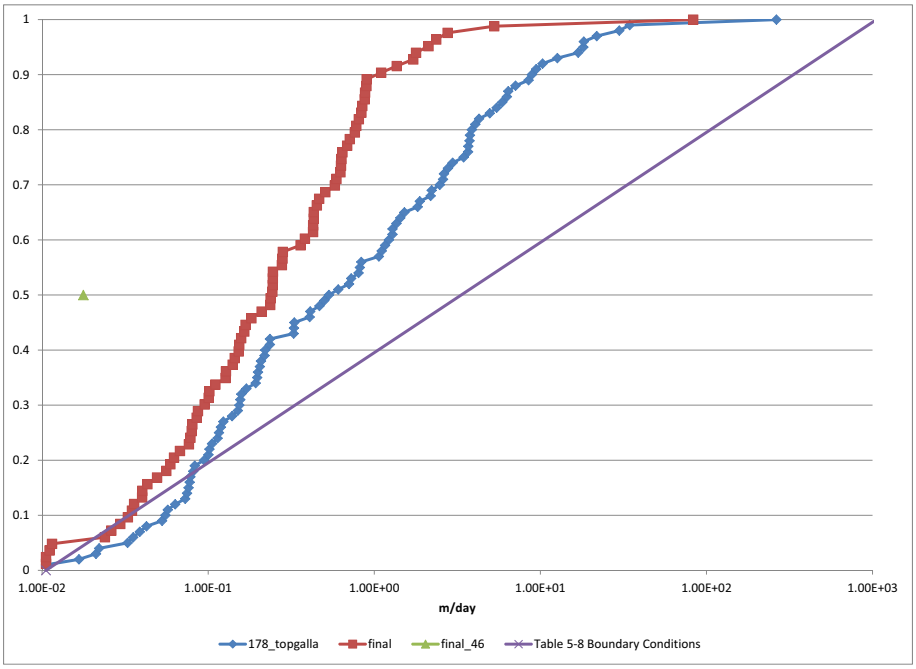



***Figure E-19***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 178_topgalla)***

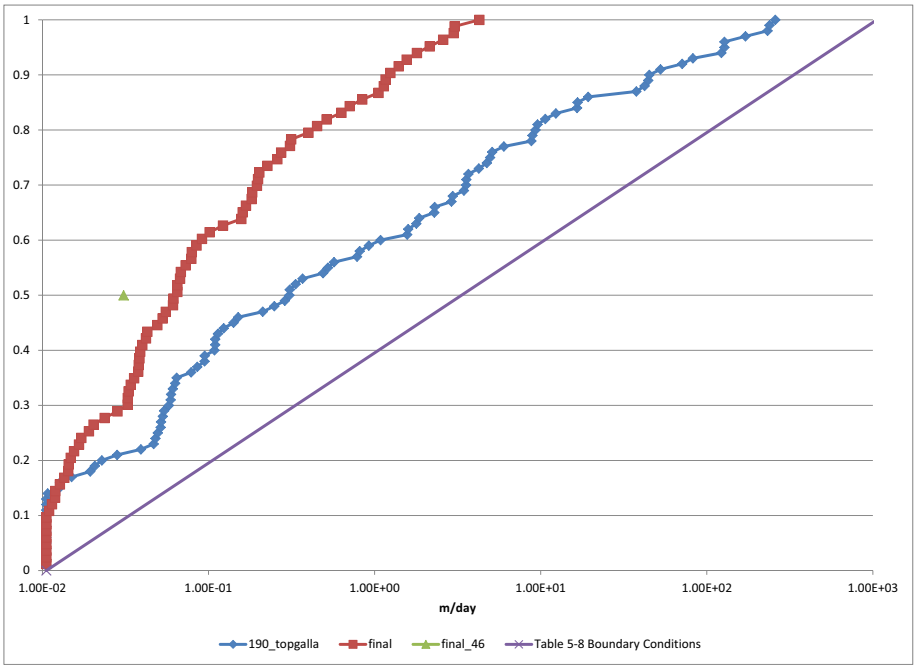



***Figure E-20***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 190_topgalla)***

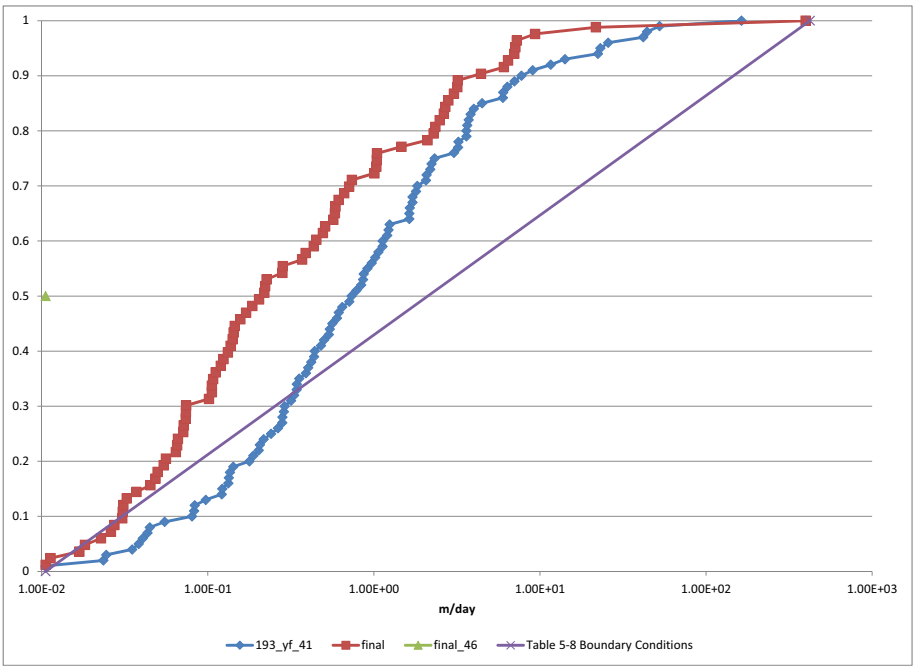



***Figure E-21***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 193_yf_41)***

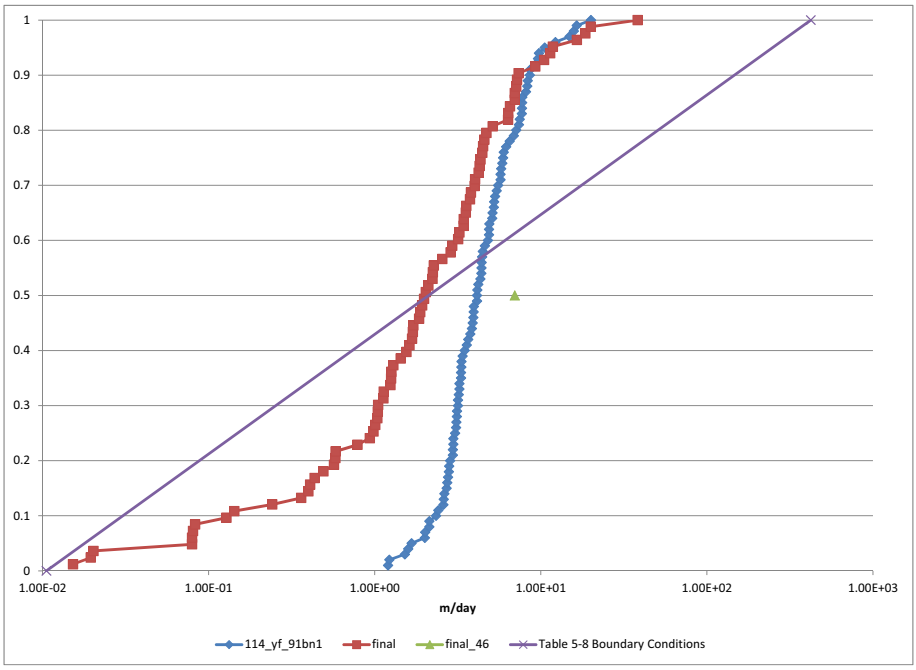



***Figure E-22***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 114_yf_91bn1)***

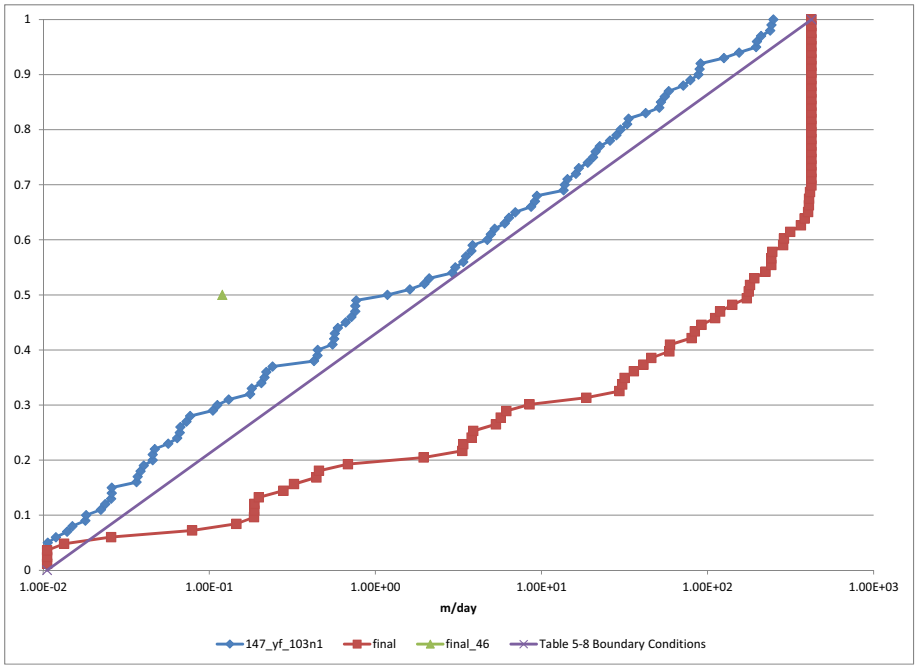



***Figure E-23***
***LCA Base-Case Flow Model Hydraulic Conductivity Distributions (Parameter 147_yf_103n1)***

## E.2.0 REFERENCES

Andrews, R., Navarro-Intera, LLC. 2014a. Email to Jonathan Price and peer review team titled "RE: Yucca Flat - LCA cdfs" with attached figure "YF_NSMC_initial_parameters_tv02.pdf," 15 October. Las Vegas, NV.

Andrews, R., Navarro-Intera, LLC. 2014b. Email to Eileen Poeter and peer review team titled "RE: Yucca Flat - LCA cdfs" with attached figures "yf_flt_traceatwt_ann_20141016_007.pdf," "work_032_plan(3).png," and "YF_NSMC_initial_parameters_tv03.pdf," 17 October. Las Vegas, NV.

N-I, see Navarro-Intera, LLC.

Navarro-Intera, LLC. 2013. *Phase I Flow and Transport Model Document for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada National Security Site, Nye County, Nevada.* Rev. 1, N-I/28091--080, Las Vegas, NV.

# Appendix F

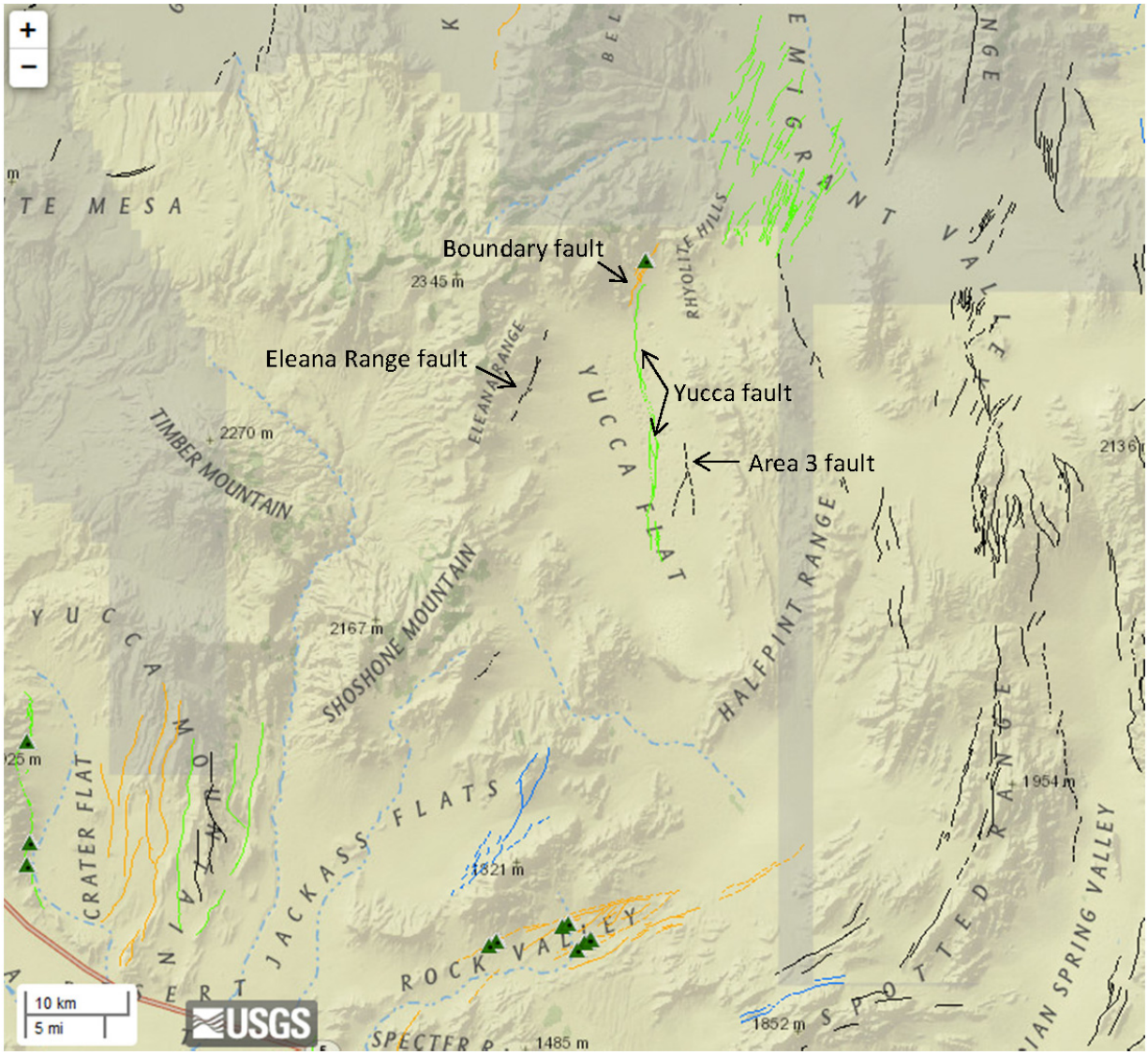
# Potential for Flow of Surface Water into Fractures in the Alluvium

# F.1.0 Potential for Flow of Surface Water into Fractures in the Alluvium

The peer review team recognizes that there is sufficient information to suspect that surface water may flow into and along fractures in the alluvium at Yucca Flat, particularly along faults and in fault zones. This appendix summarizes information regarding this potential.

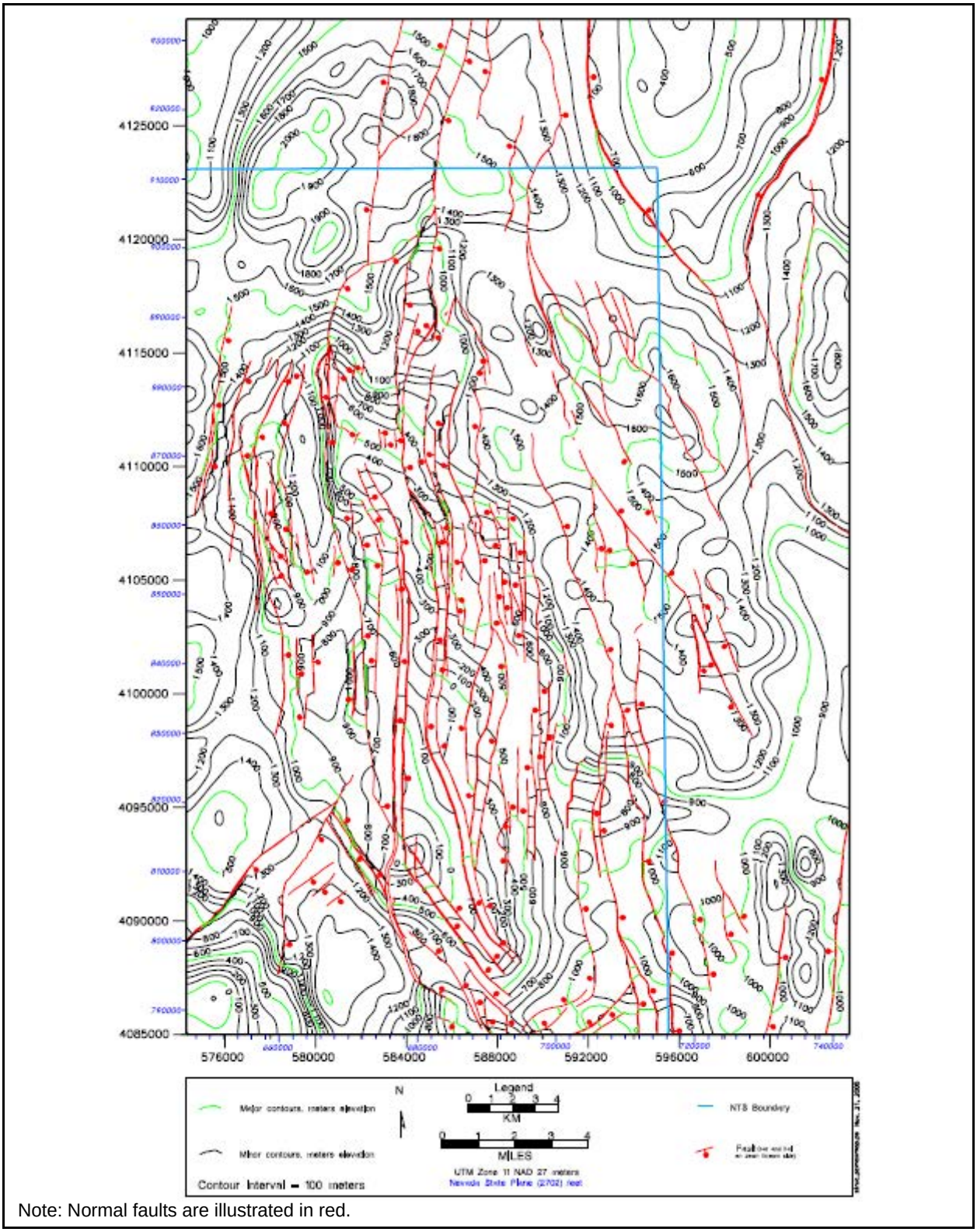
At least some faults in Yucca Flat cut through the alluvium in the valley and have been mapped at the surface. The USGS, in its Quaternary fault database, characterized young tectonic faults in the Yucca Flat area (USGS, 2014). The Yucca fault in the middle of Yucca Flat moved (in a major, pre-testing earthquake) at least once in the last 130,000 years; the Boundary fault at the north end of the valley, near the Comstock stock, moved in the last 15,000 years; and the Area 3 fault in the southeastern part of the valley and the Eleana Range fault on the western side of the valley moved at least once during the last 1.6 million years (Figure F-1). All these faults have estimated slip rates of less than 0.2 mm/yr. Although other faults that are recognized as cutting Tertiary volcanic rocks in the subsurface of Yucca Flat were not mapped in the USGS fault database as cutting the surface, the pattern of surface-breaking faults in the valley immediately to the northeast of Yucca Flat (the Emigrant Valley North faults, with movements in the last 130,000 years and slip rates of less than 0.2 mm/yr) is similar in spacing between faults to the pattern of subsurface faults in Yucca Flat (Figure F-2). In the NBMG compilation of Quaternary faults in Nevada, dePolo (2008) agreed with the USGS' characterization of these faults.

The faults in Yucca Flat are likely to move during future earthquakes, and the displacement may cause portions of the faults to become conduits for surface water to flow through the alluvium. The Yucca fault has had multiple displacements during the Quaternary, as demonstrated by the maximum scarp height near the north end of Yucca Flat (Barnes et al., 1963). Johnson and Hibbard (1957) documented 75 ft (23 m) of displacement at this location, where compact fanglomerate occurs on the west (footwall) side of the fault, and unconsolidated alluvium occurs on the east side (hanging wall). Typical maximum surface displacements during individual earthquakes in the Basin and Range Province are in the range of 1 to 6 m, which suggests that several earthquakes have occurred on the Yucca fault during the last 2.6 million years. Johnson and Hibbard (1957) and the mapping by Barnes




Explanation: Orange lines are surface traces of faults for which the most recent movement was within the last 15,000 years; green lines are faults younger than 130,000 years; dark blue lines are faults younger than 750,000 years; and black lines are faults that are younger than 1.6 million years. Light blue, dashed lines are streams, many of which are ephemeral.

***Figure F-1***
***Quaternary Faults in and near Yucca Flat as Mapped by the USGS in the Quaternary Fault and Fold Database of the United States***
Source: USGS, 2014




Note: Normal faults are illustrated in red.

***Figure F-2***
***Structure Contour Map On the Top of the Pre-Tertiary Surface Generated by the EarthVision Model***

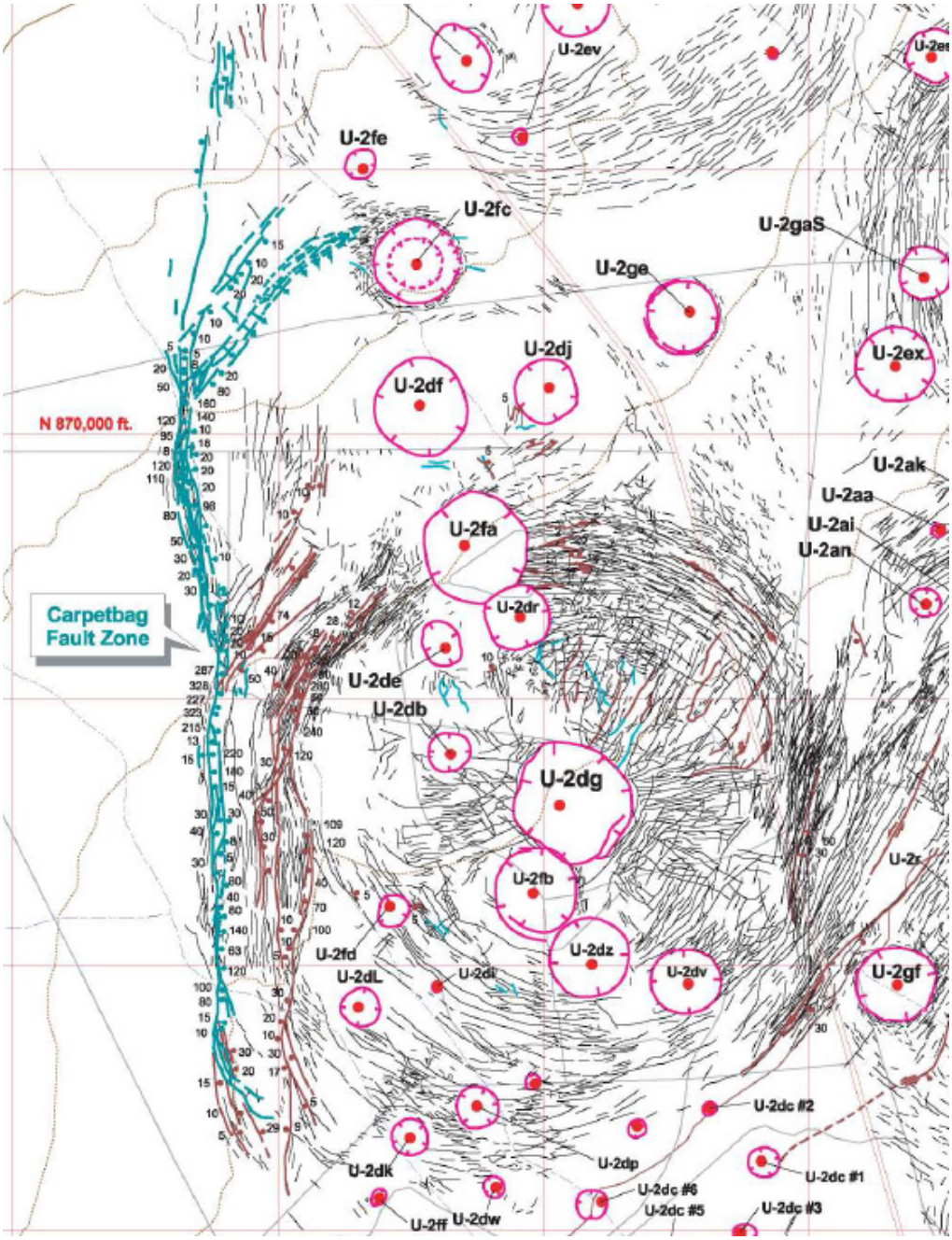
Source: BN, 2006, Fig. 3-4

et al. (1963) demonstrated that displacements of Quaternary units decrease to the south and die out beneath valley-fill deposits at the south end of Yucca Flat, although Johnson and Hibbard (1957) hypothesized that the fault probably continues south of the valley to connect with a bedrock fault in Yucca Pass.

The geophysical characterization of faults by Asch et al. (2008) indicated that, in addition to the main faults (Yucca, Carpetbag, and Topgallant faults), other faults appear to cut alluvium and nearly reach the surface. BN (2006) include approximately 178 normal faults in the hydrostratigraphic model of Yucca Flat (Figure F-2). Most of these faults cut the Tertiary volcanic rocks in Yucca Flat and potentially cut alluvium. Furthermore, many faults were (re)activated by nuclear detonations (Grasso, 2000). The Carpetbag fault has particularly impressive features related to the CARPETBAG detonation (December 17, 1970; announced yield of 220 kt), including up to 3.38 m (Grasso, 2000) of vertical displacement (Figures F-3 and F-4) and open fissures (Figure F-5) in alluvium.

Fissures (cracks) have intermittently developed on the surface of Yucca Lake, including ones that opened before nuclear testing or groundwater pumping (Carr, 1974). Fissures could have opened on Yucca Lake as the result of tectonic creep (movement without the sudden, second-long displacement of the ground during an earthquake), natural dessication, or groundwater withdrawal. Thordarson et al. (1967) hypothesized that pumping from water wells A, B, and C may have contributed to dewatering of the playa sediments and opening of fissures, but fissures existed before 1950, before any significant pumping occurred in the area.

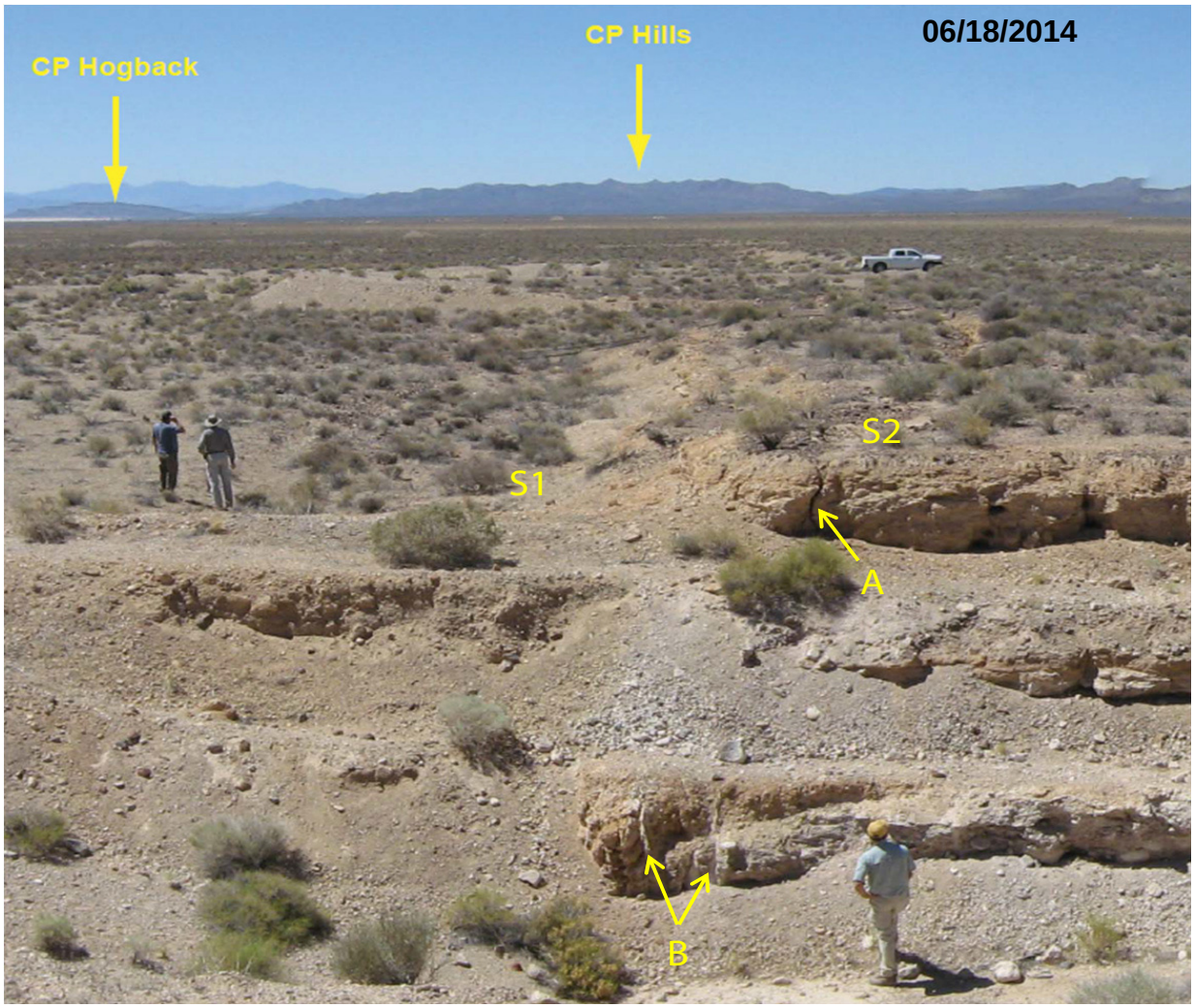
The fissures appear to be associated with faults (Carr, 1974; McKeown et al., 1976; Doty and Rush, 1985), as are many fissures in alluvium observed elsewhere in Nevada, including Las Vegas Valley (Bell, 1981; Bell and Price, 1993), where they are linked to groundwater withdrawal and related land subsidence. Carr (1974) argued for a tectonic origin for the fissures on Yucca Lake for several reasons. The most compelling evidence for tectonic creep is (1) the alignment of a pre-1950 fissure with a mapped Quaternary fault (McKeown et al., 1976) and (2) opening before any significant groundwater withdrawals. The fissures on Yucca Lake are also oriented generally north–northeast, more or less perpendicular to the current orientation of least principal stress (extension) in the region (N50˚W, as determined by Carr [1974], to N60˚W–N65˚W, as determined by Stock et al. [1985], at Yucca Mountain to the southwest of Yucca Flat).




Explanation: Mapped craters (purple), working point epicenters (red), faults with vertical displacement (brown with balls on the downthrown side and displacement in centimeters; teal for the Carpetbag fault), faults with lateral displacement (with arrows indicating relative motion), pressure ridges (blue), and surface cracks (black).

Note: The CARPETBAG detonation was at U-2dg.

***Figure F-3***
***Surface Effects from Underground Detonations in the Vicinity of CARPETBAG***
Source: Modified from Grasso, 2000




Note: Looking south at the trench dug across the Carpetbag fault. The ground surface (point S1 on the downthrown side and point S2 on the upthrown side) was displaced down-to-the-east (left). A nearly vertical, open fissure, caused by the detonation, is visible at A, and nearly vertical calcite-filled fissures, presumably related to pedogenic fracture filling after Quaternary fault movement, are visible at B.

***Figure F-4***
***Photograph of Ground Displacement Caused by the CARPETBAG Detonation***
Source: Photo by L. Prothro, NSTec

Note: This is the southward extension of the fissure at point A in Figure F-4.

***Figure F-5***
***Photograph of Open Fissure in Alluvium on the Upthrown Side of the Carpetbag Fault***
Source: Photo by L. Prothro, NSTec

Doty and Rush (1985) documented that between 1974 and 1977, approximately 5 million cubic feet of surface water flowed into a mile-long (1.6-km-long) northeast-striking crack that opened in 1969 on Yucca Lake. Over the years, sedimentation of fine-grained material had sealed the crack at the surface, although Doty and Rush (1985) noted extensions of the crack approximately 230 m northeast into the alluvium, beyond the northeast edge of the playa. On June 18, 2014, four members of the peer review team participated in a geological field trip to the Yucca Flat area. Lance Prothro took the peer review team to Yucca Lake, where he pointed out that the 1969 fissure described by Doty and Rush (1985) now extends as a series of discontinuous northeast-striking vertical fissures from the edge of the most recent playa sediments for approximately 0.8 km (0.5 mi) to the northeast (Figure F-6). Near the dirt road on the northeast side of the playa, collapse of surficial sediment into the fissure, which presumably has been widened by infiltration of surface water, has created sinkholes (Figure F-7). Sig Drellack has written a report about the potential hazard of the sinkholes (Drellack, 2014), but the extent of the post-1969 fissures northeast of the playa has not been documented on a map.

According to Ed Kwicklis in a 2014 conversation, faults in the alluvium were dismissed as important conduits for water flow based on the arguments in the groundwater flow model for Frenchman Flat (SNJV, 2006), largely that the faults would be sealed by either deformation (grinding, smearing) along the fault planes or infilling of fine-grained sediments. Whether the faults that cut the alluvium in Yucca Flat have been sealed after movement during earthquakes or after movement related to nuclear detonations is uncertain. Continued opening due to tectonic creep along the faults, however—particularly along segments favorably oriented relative to the direction of least principal stress—is possible and perhaps likely, given the observations of fissures on Yucca Lake.

Carr (1974) observed that detonation-induced movements along the Yucca fault occurred on a series of largely left-stepping en echelon segments, consistent with a component of right-lateral slip (Figure F-8). Those segments that have strikes that are roughly perpendicular to the current orientation of least principal stress would be most likely to have open fractures, which may allow surface water to flow down to the underlying bedrock units.

The peer review team for the Frenchman Flat area (N-I, 2010) highlighted earthquake faulting in its report and noted (p. 8-2 to 8-3): “Throughout the Basin and Range province, ample evidence exists that young normal faults provide major conduits for fluid flow. These results consistently indicate that the hydraulically conductive fractures at depth are those oriented as “critically stressed faults”

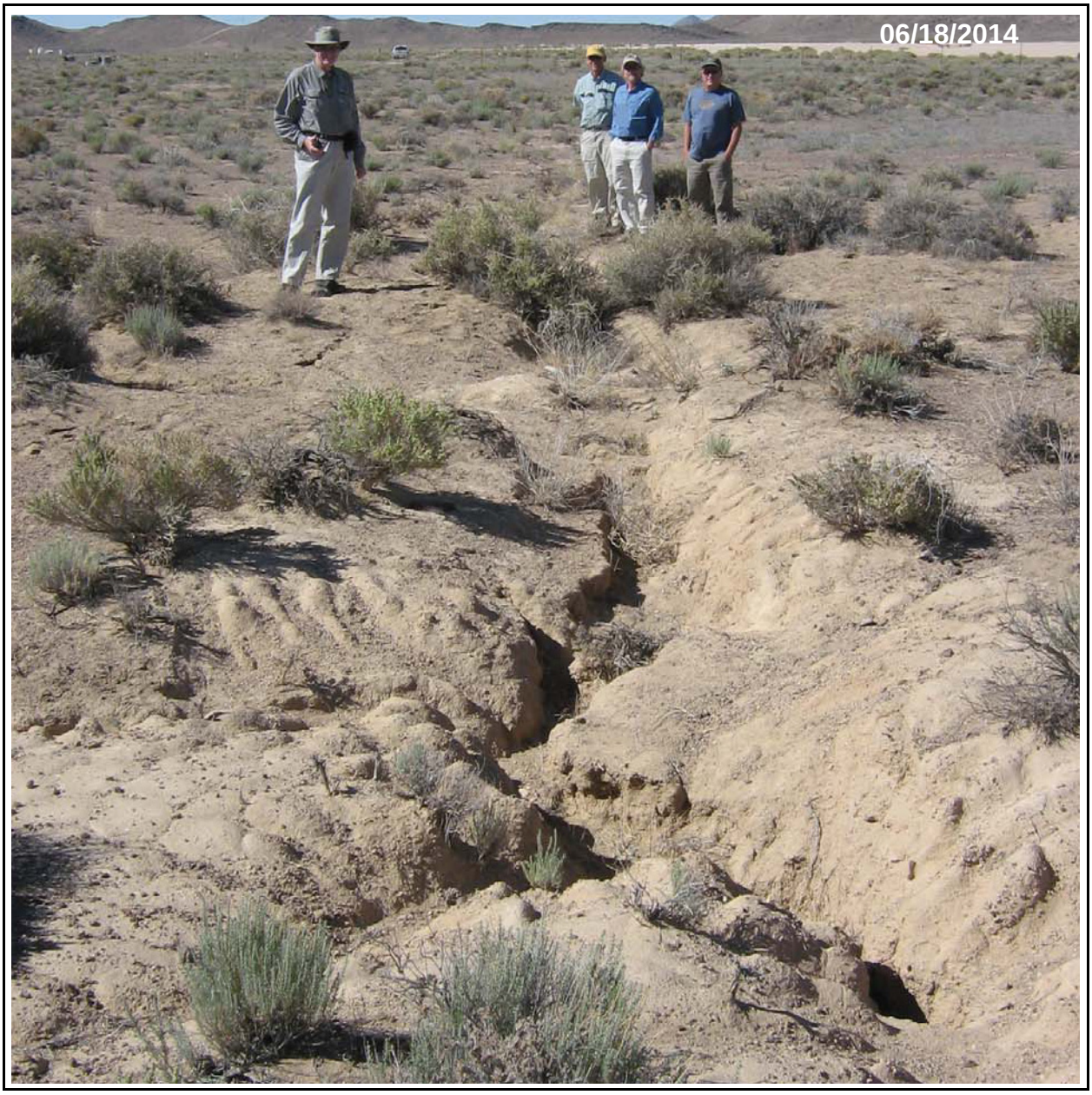
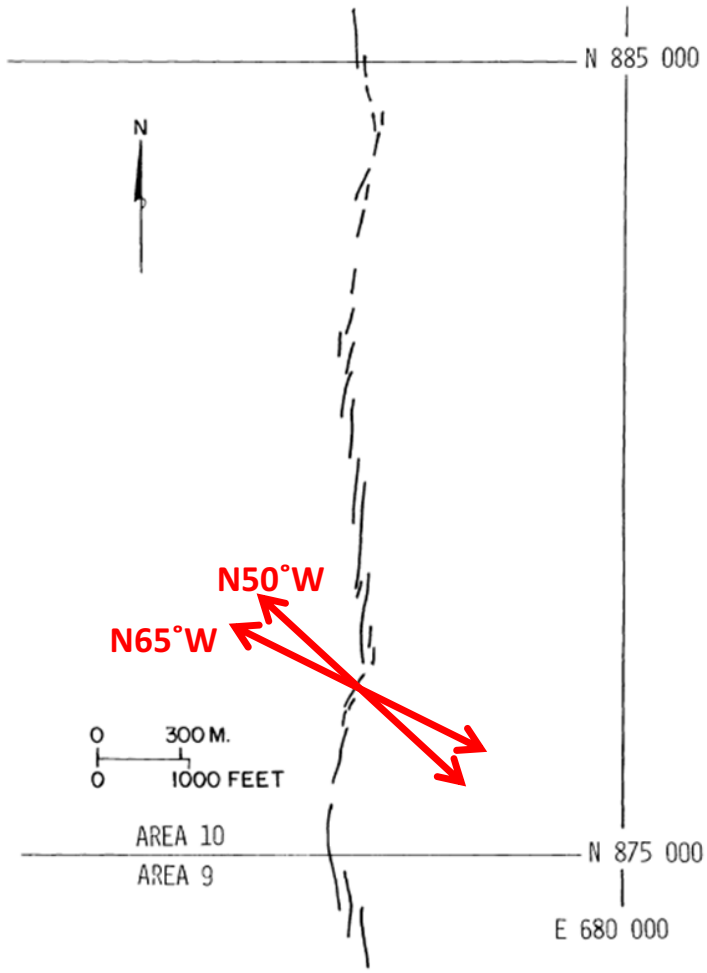



***Figure F-6***
***Photograph of Fissure in Alluvium Northeast of the Yucca Lake Playa, Looking South–Southwest toward the Playa***
Source: Photo by L. Prothro, NSTec

Note: Sinkhole is visible at point A. The south edge of a second sinkhole is visible at point B.

***Figure F-7***
***Photograph of Sinkhole That Formed Over a Widened Fissure near the Margin of the Yucca Lake Playa Looking South***
Source: Photo by L. Prothro, NSTec




Note: The red arrows are added to illustrate the direction of least principal stress (between N50° W and N65° W)

***Figure F-8***
***Detonation-Induced Scarps along a Section of the Yucca Fault***
Source: Modified from Carr, 1974

(i.e., those fractures optimally oriented for failure in the present-day stress regime) (Barton et al., 1995).” They also noted (p. 8-3): “While active faults can act as conduits for flow, they may also act as barriers, particularly in alluvium. While positive head differences in geothermal areas drive hot, deep waters to the surface along basin-bounding faults, a negative head difference could also drive fluids down such a fault.”

Penfield et al. (2010) documented numerous hot and warm springs within and on the edges of alluvial valleys in Nevada, several of which appear to be associated with Quaternary faults (NBMG, 2014). These observations suggest that warm water moves upward, along the faults, into the alluvium, and, in some cases, flows at the surface in springs located along the faults. Presumably Quaternary faults in alluvium can also act as conduits for surface water to flow downward.

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# Appendix G

# Interpretation of Geochemistry and Environmental Isotopes

# G.1.0 INTERPRETATION OF GEOCHEMISTRY AND ENVIRONMENTAL ISOTOPES

Geochemistry is used to support or corroborate two aspects of the flow and transport modeling. First, mass balance models based on conservative components of the water such as Cl and its stable isotopes (deuterium [$^{2}H$] and $^{18}O$) are used to suggest sources and flow paths of groundwater in the Yucca Flat system, especially in the LCA. More comprehensive mass balance models including mineral-water reactions have been developed for selected groups of wells using the NETPATH and PHREEQC codes. These codes evaluate the effect of water mixing and mineral-water reactions on solutes, particularly dissolved inorganic carbon (DIC) and its $^{14}C$ content. Second, the radioisotopes $^{14}C$ and $^{36}Cl$, which are formed in the atmosphere, are used to estimate the time since the water in a given sample was recharged or last in contact with the atmosphere or soil air.

The water chemical and isotopic data are given in SNJV (2006a and b), and the mass balance modeling is described in detail in SNJV (2006b).The relatively few water samples available and the complexity of the flow system resulting from the extensive faulting means that the results of the mixing calculations are, for the most part, non-unique. That is, equally good models for the origins of the given water sample can be constructed with different choices of starting waters. This is recognized in the flow and transport modeling report in that the results are used only qualitatively to indicate consistency with flow paths based on regional geology and hydrology. None of the numerical mixing ratios developed in the mass balance modeling described in SNJV (2006b) are used quantitatively in developing the flow and transport model. Given the non-uniqueness in the mixing results and uncertainties in the supporting data that were not considered, this is appropriate.

Ages and flow rates have been deduced from $^{14}C$ and $^{36}Cl$ contents of water samples as described in SNJV (2006b), N-I (2013, Appendix L), and Kwicklis and Farnham (2014). Considerable supporting information must be available before isotope ages can be relied upon. This includes the following:

- Initial isotope concentrations
- Effects of geochemical reactions on the isotopic composition of the groundwater
- Effects of mixed water sources
- The extent to which the rate of isotope flow is retarded relative to the rate of water flow

These topics are addressed in the flow and transport model report and supporting documents. However, several of them are not addressed consistently within the flow and transport report nor between the report and its supporting documents. Possible effects of these inconsistencies on the conclusions of the flow and transport modeling report are not certain but are explored below.

### G.1.1 Interpretation of Isotope Data

#### G.1.1.1 Initial Isotope Concentrations

Both $^{14}C$ and $^{36}Cl$ are produced in the atmosphere by reactions of cosmic rays with atmospheric gases. As the cosmic ray flux has varied with time, so have the concentrations of these isotopes in the atmosphere.

The initial $^{14}C$ contents of samples of known ages increased from their nominal level of 100 percent modern carbon (pmc) before the advent of fossil fuel burning and nuclear testing; to about 110 pmc at about 10 ka before the present (BP); and then more rapidly to about 140 pmc at about 20 ka (Clark and Fritz, 1997, Fig. 8-4; Plummer et al., 1997, Fig. 3). Uncertainties in $^{14}C$ contents of 10 and 40 pmc correspond to uncertainties in ages of 0.9 and 4.2 ka, respectively. The $^{14}C$ content of the atmosphere reached about 200 pmc in the 1960s following atmospheric testing of thermonuclear devices in the northern hemisphere earlier in that decade. The effects of cosmic ray and anthropogenic changes on initial $^{14}C$ contents were not evaluated. There is no evidence of high $^{14}C$ levels such as were produced in the 1960s by weapons testing in any samples.

$^{36}Cl$ is usually reported as the ratio $^{36}Cl/Cl$. Its value in the atmosphere has varied with time due to changes in the cosmic ray flux and to high neutron fluxes from weapons testing. Before testing began, the $^{36}Cl/Cl$ ratio in southern Nevada was about $500 \times 10^{-15}$ and, because of increased cosmic ray flux, it was much higher at times greater than 10 ka BP, from 800 to $1{,}200 \times 10^{-15}$ (Clark and Fritz, 1997, Fig. 8-7; Plummer et al., 1997, Fig. 3; Tyler et al., 1996, Fig. 6). Atmospheric levels of $^{36}Cl$ increased greatly following atmospheric testing in the South Pacific. These high concentrations are not evident in soil water in the region (Tyler et al., 1996), but even a small amount of such water in drilling fluid could have increased the $^{36}Cl$ concentration of groundwater samples. This possibility was not evaluated.

Section 4.2.5 and Fig. 4-6 of N-I (2013) indicate that waters in the UCCU and LCCU tend to have $^{36}$Cl/CL ratios above $500 \times 10^{-15}$, suggesting they represent recharge that occurred at least 10 ka BP. This is consistent with the conclusion of Walvoord et al. (2002) (cited by E. Kwicklis in the April 2014 peer review meeting) that there has been no recharge in the last 10,000 years.

### G.1.2 Effects of Geochemical Reactions on the Isotopic Composition of Groundwater

#### G.1.2.1 $^{36}$Cl

The half-life of $^{36}$Cl is so long ($3 \times 10^5$ years) that decay in waters like these with much lower ages need not be considered. Likewise, *in situ* production of $^{36}$Cl (Lehmann et al., 1993) is not likely to be significant except as associated with the detonations. Thus, the only factors influencing the $^{36}$Cl/Cl ratios of these waters will be the values in recharge and any increases in $^{36}$Cl-free Cl from dissolution of Cl in the formations. Dilution by formation Cl is evident in a graph of $^{36}$Cl/Cl versus 1/Cl on which the data can be represented by a straight line passing through the origin (N-I, 2013, Appendix L, Fig. L-1; Kwicklis and Farnham, 2014, Fig. 9). To correct for formation Cl and determine the initial $^{36}$Cl/Cl content of the waters, values for waters with measured $^{36}$Cl/Cl ratios below $500 \times 10^{-15}$ were corrected for dilution by assuming an initial Cl content of 7 milligrams per liter (mg/L).

As discussed in Section G.1.4, this assumption leads to an initial $^{36}$Cl/Cl value indicating recharge before 10 ka BP. Choosing a a higher value would indicate more recent recharge.

#### G.1.2.2 $^{14}$C

The chemistry of $^{14}$C in groundwater is complicated because of uncertainty in the composition of the soil-air source of $^{14}$C to the water, nature of reactions between groundwater and $^{14}$C-free material in the aquifer during flow, and composition of those reactants. A general model of carbon isotope behavior in groundwater is available (Wigley et al., 1978 and 1979) but is useful in its complete form only if the geochemical evolution of water is well understood. The NETPATH code, which includes the general carbon isotope model, requires data on the chemical evolution of the water and on the properties of reactive minerals if it is to be applied successfully. Inverse modeling with the PHREEQC code does not include isotope fractionation associated with loss of carbonate from the solution, but its most recent version (PHREEQC Version 3) provides output that can be used directly by NETPATH to make such calculations (Parkhurst and Appelo, 2013). SNJV (2006b) describes

elaborate NETPATH and PHREEQC models made to investigate possible sources of water to selected wells and to help define conceptual flow paths. These models are also used to adjust the $^{14}C$ contents of DIC as required to calculate $^{14}C$ ages.

Models for $^{14}C$ based on simple dissolved carbon and carbon isotope mass balances are also widely used (e.g., Clark and Fritz, 1995). These have been in use since the 1960s, but they can be derived from the general model of Wigley et al. (1978) when certain simplifications are made (e.g., Pearson, 1989; Pearson et al., 1991, Chapter 5).These simple models are used in N-I (2013, Appendix L) and Kwicklis and Farnham (2014) with general agreement between the results using either total carbon or carbon isotope mass balances. Differences in the ages calculated using the two models are generally less than 5 ka for samples from the AA, VA, and TCU units and for the LCA (SNJV, 2006b, Appendix L, Figs. L-5 through L-7; Kwicklis and Farnham, 2014, Fig. 6). It is not clear whether the groundwater $^{14}C$ ages given in these two documents and shown in Fig. 5-14 of the flow and transport report (N-I, 2013) are based on the elaborate NETPATH and PHREEQC modeling of SNJV (2006b) or on the simpler calculations in the two documents. In either case uncertainty seems to have been neglected because in all the $^{14}C$ age figures, ages are given to the nearest year. Showing ages to the nearest ka or even to the nearest 5 ka would be more appropriate.

As discussed below, there are a number of problems with the mixing calculations and data supporting them. There may be more uncertainty in the resulting mixing proportions and $^{14}C$ ages than are given in the report. Until these uncertainties are properly estimated, the $^{14}C$ ages from SNJV (2006b) should be used with caution. On the other hand, $^{14}C$ ages based on simple mass balances as described in N-I (2013, Appendix L) and Kwicklis and Farnham (2014) appear to be useful within a few thousand years.

The flow system of Yucca Flat is not well defined either in terms of permeability or head distribution compared to other regional aquifer systems in which $^{14}C$ has been employed successfully to evaluate groundwater flow rates. The fact that flow paths between individual sampling points are ill-defined lowers the confidence one might have in flow rates estimated from $^{14}C$ age differences. There is one group of wells, however, that are demonstrably connected: well ER-7-1 with wells ER-6-1 and ER-6-2#2. The MWAT showed the rapid connections among these wells. Furthermore, the chemistry and isotopic properties of water from all three are virtually identical. The only significant difference among them is in their measured $^{14}C$ contents, which are 5.3 pmc for well ER-7-1 and 2.2+/-0.2 and

2.4 pmc for wells ER-6-1 and ER-6-1 #2, respectively. Because of the chemical and isotopic identity of the wells, the $^{14}C$ age differences between them can be calculated directly from the measured $^{14}C$ data. This difference equals 6.9 ka, which agrees with the differences calculated using NETPATH and PHREEQC modeling (6.5 to 7.3 ka, respectively [SNJV, 2006b, Section 7.5]) and by the simpler method used in N-I (2013, Appendix L) and by Kwicklis and Farnham (2014) (6.2 to 6.9 ka). Based on a 10-km distance, these correspond to $^{14}C$ travel rates from 1.4 to 1.7 m/yr.

### G.1.3 Effects of Mixing

The isotopic and chemical properties of groundwater in the NNSS have long been explained by mixing of waters from different recharge areas. The early conceptual flow models (e.g., Winograd and Friedman, 1972; Winograd and Thordarson, 1975) were based on mass balances of conservative constituents such as $^{2}H$. This approach has been extended in SNJV (2006b) to complex mass balances involving many constituents and mineral-water reactions that are solved by the codes NETPATH and PHREEQC.

A number of questions arise in connection with these models that, taken together, cast doubt on the reliability of the results. These include questions about the sources of the water samples, about the analyses themselves, and about some of the assumptions in the mixing models.

The borehole intervals from which samples were taken and the HSUs represented are frequently not well defined. In only one borehole were water samples taken from distinct, well separated depth intervals so that the variation of chemistry with depth could be determined. This is UE-10-j in which three intervals were sampled:

-3: 691.1-699.0 m; Cl = 12.8 mg/L; $^{14}C$ = 13 pmc

-2: 732.3-740.1 m; Cl = 16.0 mg/L; $^{14}C$ = 11 pmc

-1: 765.0-773.0 m; Cl = 23.9 mg/L; $^{14}C$ = 7 pmc

The increasing Cl and decreasing $^{14}C$ concentrations with depth are consistent with recharge from above. The differences between the top and the bottom samples would also be consistent with considerably different travel distances and times for water in the two samples despite the relatively

small depth interval between them. Two samples were collected from the top and bottom intervals. They agree well suggesting that the results are reliable.

At the other extreme are two boreholes, UE-1b and UE-1c, each with long open intervals spanning two HSUs. Samples were taken from these boreholes but no packers or borehole flowmeters were used, so it is not known which parts of the open intervals yielded the water collected nor even which HSU the samples represent. Instead of rejecting these samples because they lacked provenance, each was interpreted twice as if two samples had been taken from each borehole, one from each HSU. This is physically unreasonable. The samples must represent water from either one unit or the other or a mixture of the two. In the absence of any borehole data on the source of the water to the wells during pumping the samples cannot be assigned to either unit.

There are also uncertainties in the chemical data and other model parameters. Many of these uncertainties appear to have been underestimated; for others no uncertainties were considered. Thus, uncertainties in the mixing ratios and $^{14}C$ adjustments calculated from them are likely to be underestimated. For example:

- A pH uncertainty of 0.2 was used in the modeling. Differences between laboratory and field pH values for a number of samples are larger than this (SNJV, 2006b, Table A.1-3), so the uncertainty range should be larger.

- It appears that some samples collected for cation analysis were not filtered and/or acidified in the field, because the field charge balance (C/B Field) of many samples in Table A.1-1 of SNJV (2006b) is negative and larger than C/B Lab. Such a pattern commonly results from carbonate precipitation during sample storage leading to lower laboratory-than-field calcium contents and, often, lower laboratory-than-field alkalinity values.

- Saturation states of common minerals for the samples as analyzed are given in SNJV (2006b, Table 5-1). It is not stated whether these are based on field or laboratory data. Also, there is no discussion or mention of the thermochemical databases used in the modeling.

- Inverse modeling in PHREEQC includes parameter uncertainty. Because of the lack of analytical data, most aluminum and iron values were calculated from the solubilities of kaolinite and amorphous ferric hydroxide. In this case, sulfate uncertainty should include the uncertainty in the properties of ferric hydroxide. The report did not explain which silicate phase was used.

- Different isotopic compositions are used for the minerals calcite and dolomite in the NETPATH and the PHREEQC modeling. According to Morse (2002), NETPATH results are very sensitive to variations in the mineral $^{13}C$ values used.

- In the NETPATH and PHREEQC modeling, the water is assumed to react simultaneously with both volcanic and carbonate HSUs. This seems unrealistic for waters moving only in the LCA.

- PHREEQC modeling produced many possible reaction paths and corrected $^{14}C$ ages for each mixing problem posed (SNJV, 2006b). The uncertainties in the age reported for each problem are based on the statistics of these ages. The results appear to include many cases that differ only in the extent of reactions with minor silicate phases, which do not influence the $^{14}C$ age corrections. The statistics based on all mixing results therefore are likely to underestimate the uncertainties in the corrected ages.

### G.1.4 Retardation

It is commonly assumed that both dissolved Cl and DIC move at the same rate as water, so ages and flow rates based on $^{14}C$ and $^{36}Cl$ are the same as those of water and no retardation correction is needed. This is generally acceptable for retardation due to water-rock reactions such as sorption, but may not be true in dual porosity flow systems where matrix diffusion also provides a mechanism for solute retardation.

Matrix diffusion is treated unevenly and inconsistently in N-I (2013) when inferring groundwater flow rates from $^{14}C$ and $^{36}Cl$. Because Cl is virtually always treated as an ideal tracer, retardation is not considered when interpreting groundwater $^{36}Cl$ contents. However, while it is correct to assume that Cl will not be retarded by water rock reactions, it will be as susceptible to retardation by matrix diffusion as any solute. Matrix diffusion will not affect the concentration of stable Cl isotopes at steady-state, but retardation of $^{36}Cl$ might be evident. The amount of such retardation could be evaluated theoretically. For example, Sanford (1997) shows that the extent of retardation depends on the relative thicknesses of the stagnant and flowing zones and on the decay constant of the isotope of interest. This might permit estimation of both $^{14}C$ and $^{36}Cl$ retardation for a geometry typical of that used to model the LCA.

In N-I (2013, Appendix L) and Kwicklis and Farnham (2014), $^{14}C$ ages of DIC of samples from the LCA are compared with $^{36}Cl/Cl$ ratios from $^{14}C$-dated pack-rat middens (Plummer et al., 1996) to demonstrate that both isotopes move at the same rate, and that $^{14}C$ is not retarded. The resulting water flow rate in the LCA is 1 to 2 m/yr rather than the 10 to 20 m/yr calculated by the base-case flow model (p. 1-50, p. 5-32). To make this comparison the measured $^{36}Cl/Cl$ ratios had to be corrected for the effect of dissolution of formation Cl. This was done by adjusting all ratios below $500 \times 10^{-15}$ (virtually all the LCA samples) to an initial Cl content of 7 mg/L. This is lower than the Cl content of

any LCA sample except UE-1c—which, as noted above, may not be representative of the LCA. Based on the correlation between $^{36}Cl/Cl$ and Cl shown in Kwicklis and Farnham (2014, Fig. 9) and in N-I (2013, Appendix L, Fig. L-1), this concentration leads to a $^{36}Cl/Cl$ ratio of $800 \times 10^{-15}$, closer to values expected in water recharged at times greater than 10 ka than values expected in more recently recharged water—that is, between about 10 ka BP and the advent of atmospheric weapons testing. This is interpreted to show that $^{14}C$ is not retarded. Choosing an initial value of 11 mg/L would lead to a $^{36}Cl/Cl$ ratio of $500 \times 10^{-15}$, the recent value. In this case, the age relationship between groundwater and pack-rat $^{36}Cl/Cl$ ratios would be offset, and the conclusion would be that $^{14}C$ is retarded relative to Cl.

Additional evidence on $^{14}C$ retardation is available from the Ash Meadows flow system. Ash Meadows springs discharge from regional flow in the LCA and are chemically and isotopically very like waters sampled from wells in the LCA in Yucca Flat and Frenchman Flat. In particular, the carbonate chemistry and isotopic composition of these wells, if treated as were the Yucca Flat data, would lead to ages in the 20 to 30 ka range like those of ER-6-1, ER-5-4, and WW-C1, for example. However, other evidence indicates that the Ash Meadows spring waters have travel times from recharge of probably less than 2 ka and certainly less than 7 ka. This evidence is summarized by Winograd et al. (2006) and includes the time resolution of the paleoclimatic record in vein calcite from Devils Hole and the $^{14}C$ contents of DOC. From the Ash Meadows data, a fair conclusion would be that $^{14}C$ in DIC in the LCA is retarded by about 3 to 10. This contradicts the conclusion of N-I (2013, Appendix L) that there is no retardation, and would mean that the “ages” in e.g., Fig. 5-14 of N-I (2013) are 3 to 10 times too high.

This retardation indicated by the Devils Hole data is mentioned in N-I (2013, Section 5.2.6.2) leading to: “Given it is conservative to not underestimate the groundwater velocity, the flow model comparison assumes the velocities estimated from the $^{14}C$ age dating are considered to represent retarded age dates and the unretarded age dates are reduced and velocity estimates increased.” Certainly in the base case for the transport modeling $^{14}C$ is treated as unretarded. This would lead to results inconsistent with the Ash Meadows $^{14}C$ data but, as stated in the report, could be justified on the grounds of conservatism.

In summary, the attempt to use environmental $^{14}C$ and $^{36}Cl$ as natural analogues for the behavior of these isotopes generated by the testing is laudable but the results are ambiguous.

***Recommendation:*** *Field data bearing on retardation should be reevaluated and every effort made to reach a simple, consistent interpretation. First, the conclusion that there is no retardation based on the comparison of the $^{36}Cl/Cl$ values is dependent on the choice of initial Cl concentrations used to adjust the measured $^{36}Cl/Cl$ ratios of the water samples. This concentration should be examined carefully and strong justification provided for the value finally chosen. Second, the Devils Hole/Ash Meadows data should be examined in the same manner as the Yucca Flat data to more precisely evaluate retardation in that system. Finally, if results of such a study show that there is retardation in Ash Meadows but not in Yucca Flat, an explanation should be sought for such a profound difference in the behavior of two otherwise similar flow systems. Finally it should be made clear whether the rates of groundwater flow supporting the modeled transport of detonation-derived radionuclides are more similar to those based on retarded or on unretarded $^{14}C$ flow rates.*

### G.1.5 Dissolved Organic Carbon

The peer review team questions the correctness and relevance of groundwater ages based on DOC. These data and ages are given in Section 3.2.3.1, Table 3-3, of the Geochemical Evaluation supporting document (SNJV, 2006b). While they are also referred to in Section 5.0 of that document, they are not compared and contrasted with other groundwater age information and they are not mentioned at all in the Flow and Transport document.

Studies of the $^{14}C$ contents of DOC in groundwater from Southern Nevada, principally from the Ash Meadows flow system, have been made by Thomas (1996) and Morse (2002). $^{14}C$ contents were sensitive to the molecular weight fraction of the DOC on which they were measured, with those of the heaviest fraction being the most reliable indicators of water age. $DO^{14}C$ values of Ash Meadows springs suggest travel times of 2 to 7 ka, consistent with values based on ages of vein calcite in Devils Hole (Winograd et al., 2006) but considerably below the ages of 10 to greater than 20 ka from $^{14}C$ data on DIC. (Note, though, that $DI^{14}C$ ages developed by Thomas (1996) based on NETPATH geochemical modeling can be as low as a few hundred years.)

The data on Yucca Flat samples are not described well enough to know whether they meet the criteria outlined by Thomas and by Morse to be useful for interpretation as $DO^{14}C$ ages. For example, were the sample collection procedures adequate and were the analyses made on the appropriate molecular weight fractions? Regardless of what the results represent, they and the ages given for them are sufficiently inconsistent internally to disqualify them. Samples from ER-6-1 and ER-6-1 #2 have virtually identical chemistry. Their DOC contents and $DO^{14}C$ values differ significantly, however. Good practice would first attribute this to difficulties in sampling/sample preparation/analysis and

only after the results had been replicated would one seek a geochemical explanation for the difference. (It is of interest, though, that the DOC of ER-6-1 is three times that of ER-6-1 #2, while the DO$^{14}$C of the former is about one-third of the latter. This would be the case if two-thirds of the DOC of ER-6-1 was derived from $^{14}$C-free DOC from the formation or from borehole contamination such as oil or grease. As discussed elsewhere in these comments, the DI$^{14}$C age difference between ER-7-1 and both ER-6-1 and ER-6-1 #2, which is as reliable as any of the age differences proposed for Yucca Flat wells, is about 6.9 ka. The difference between DO$^{14}$C ages of ER-7-1 and ER-6-1 #2 in Table 3-3 is 9.0 ka, which is similar. However, the large differences in the DOC contents and DO$^{13}$C values of these two wells indicate that the differences in their DO$^{14}$C contents are probably due as much to geochemical reactions and/or contamination as they are to $^{14}$C decay, so little weight should be given to ages calculated from them).

> ***Recommendation:*** *The existence of DO$^{14}$C data needs to be mentioned but no age interpretations should be reported, unless it can be demonstrated that the data are sound and that the interpretive methods are appropriate.*

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# Appendix H

# Summary of Recommendations

# H.1.0 INTRODUCTION

Recommendations explained in Section 6.0 of this report are repeated in this appendix to allow readers to view them together. The numbered headings are preserved for ease of finding the text that was written as justification for the recommendations (e.g., Section H.6.1 in this appendix corresponds with Section 6.1 in the main document).

# H.6.0 KEY UNCERTAINTIES

## H.6.1 Uncertainty in Model Domain/Boundary Conditions

### H.6.1.1 Western Boundary

The peer review team recommends inclusion of the Rainier Mesa area in the model and use of head data from that area as calibration targets (including the semi-perched springs that reflect saturated groundwater heads) to improve the representation of the flow field and build confidence in model predictions.

### H.6.1.2 Southern Boundary

The peer review team recommends that to better delineate the full extent of the contaminant boundary, future model simulations should extend the domain farther to the south to capture all areas where there is greater than a 5 percent probability of exceeding the MCL.

### H.6.1.3 Northern Boundary

Multi-well hydraulic testing and water sampling at the northern Yucca Flat boundary should be undertaken to investigate inflow from the north, including the fracture/fault hydraulic properties of rocks that occur along the northern extension of the Boundary/Yucca fault across the topographic divide to the north (Comstock stock, LCA, contact-metamorphosed LCA, and overlying Tertiary volcanic rocks).

#### H.6.1.4 Water Table Boundary and AA/VA Flow Direction

The peer review team recommends contouring simulated water levels in the AA/VA system and comparing the simulated contours to the horizontal gradients and flow directions shown in Fenelon et al. (2012) and in Fig. 4-2 of N-I (2013) to build confidence in the reasonableness of the predicted fluxes into the LCA. Given the poor quality of the available head data, especially due to its transient nature, the uncertainty associated with flux to the LCA resulting from uncertain spatially variable hydraulic heads and gradients in the AA/VA should be examined.

#### H.6.1.5 Hydraulic Connection between Aquifers

The peer review team recommends that the uncertainty associated with the consistency of the upper boundary of the LCA model and the lower boundary of the AA/VA model be considered in future simulations of the contaminant boundary. One suggestion is to follow common convention for modeling multi-aquifer systems separated by an aquitard and model them together. This approach would ensure continuity of heads between aquifers where they are connected at the faults. The coupled model grid can be fairly coarse, at least much coarser than the decoupled models that were used for both flow and transport predictions of the contaminant boundary. Once the models are coupled, then all the head data within the combined multi-aquifer system can be used for calibration. The flux leaking into the LCA from the coarse-grid coupled aquifer model would help constrain further calibrations with the fine-grid flow and transport model. Use of the most recent USGS regional modeling (Faunt, 2012) for establishing head boundaries in the local-scale flow model of Yucca Flat is recommended.

### H.6.2 Model Calibration

#### H.6.2.1 Poorly Posed Calibration

The peer review team recommends the problem be better posed by coupling the aquifers in one model; including more calibration targets (e.g., [1] AA/VA heads, [2] heads and springs east of the groundwater divide on Rainier Mesa, and [3] heads Fenelon identified as representative of the regional carbonate aquifer such as UE-8e, UE-10 ITS 3 (2160), UE-10bf, UE-10 ITS 5 before the measurement in 1972, U-7a, WW-C-1, and ER-3-1—this list provides examples and, as such, is not a compulsory nor comprehensive list); collecting additional calibration data via field activity; and simplifying the parameterization of the model.

#### H.6.2.2 Lack of Steady-State Head Data

The peer review team recommends calibrating a coupled model of the aquifers, including more calibration targets, resurveying the well heads to ensure both the accuracy of the targets and to determine whether the measuring point may have changed with time, as well as completely representing the data that were used to develop steady-state targets. To completely represent the data, use all the data points (with deviations due to recovery and measurement errors omitted) as targets, and present a residual at each location for every measurement that has been recorded over the years. This would provide a realistic representation of the difference between measured and simulated heads.

#### H.6.2.3 Use of Parameter Bounds

The peer review team recommends reducing the number of parameters through re-parameterization, removing bounds from the parameters, including more calibration targets, and adjusting the model conceptualization and construction if the estimated parameter values are not reasonable. Parameters should not be constrained for the calibration. The resulting estimated parameter values should be compared with equivalent values measured in the field. Substantial differences between the parameter values estimated by the calibration and the values measured in the field are an indication that there is a problem with model conceptualization or construction, and such clues should be used to improve the model.

#### H.6.2.4 Omission of Available Calibration Data

The peer review team recommends using an expanded model domain and more calibration targets including those that do not fit the conceptual model of a flat potentiometric surface in the LCA. An attempt should be made to include features in the model that will generate heads similar to the targets. The residuals related to all of the measurements (excluding outliers that are likely errors and recovery conditions) should be presented. A critical review of all calibration data with respect to water levels, thermal effects, well completions, geophysical logs, and core and cuttings should be undertaken to clarify the conceptual model. Head data from all wells should be reevaluated to confirm the location of targets in the AA/VA/TCU/LAC, to determine whether each head measurement represents normal pressurization, and to assess whether the well completion is sufficient to ensure there is minimal

communication between zones. If results of the reassessment are inconclusive, single-point piezometers should be installed in key areas as determined from the analysis.

#### H.6.2.5 Using the Jacobian to Determine Weights for Targets

The peer review team recommends determining weights for each target by evaluating the quality of the target data based on well construction and measurement procedures.

#### H.6.2.6 Field Measurements of Hydraulic Conductivity Not Honored in the Calibrated Model

The peer review team recommends that parameters be estimated without bounds, and the estimated parameter values be compared with equivalent values measured in the field. Substantial differences between the parameter values estimated by the calibration and the values measured in the field are an indication that there is a problem with model conceptualization or construction. These clues should be used to improve the model. If the parameters are unreasonable, adjust the model conceptualization and/or construction.

### H.6.3 Uncertainty in Hydraulic Properties and Pathways

#### H.6.3.1 Country Rock

##### H.6.3.1.1 Aquifer Testing

The MWAT at ER-6-1 (1) provided the only calibration data that somewhat reduce the non-uniqueness of the Yucca Flat model calibration yet renders only seven of the many model parameters identifiable (all in the vicinity of the MWAT) and (2) did not test the central or western portions of Yucca Flat. Consequently, the peer review team recommends additional large-scale MWATs in the central and western portion of Yucca Flat to assess hydraulic properties of the country rock and faults, and to evaluate boundary conditions. Otherwise, there is little basis to justify setting such markedly lower permeabilities in the LCA west and central zones, compared with the permeability in the LCA east and ER-6-1 MWAT results.

#### H.6.3.1.2 Model Permeabilities Inconsistent with Field Measurements

The peer review team recommends honoring the available hydraulic properties data for the country rock in assessing uncertainty in the extent of the contaminant boundary. Unless the field-measured hydraulic conductivity data are weighted more heavily in parameterizing the model, the available information suggests that the southern extent of the contaminant boundary will be underestimated. The choice of NSMC run 46 as the "fast" scenario in evaluating the extent of the contaminant boundary seems to be misleading. The peer review team recommends reevaluation of the choice of a "fast" scenario and additional simulations to account for other uncertainties described elsewhere in this report.

#### H.6.3.1.3 Preferential Flow

The peer review team recommends a thorough examination of all the field data relevant to the question of whether karst features do exist and are continuous below the water table. This would include reviews of drill logs (e.g., lost circulation, rod drops), geologists notes, borehole flowmeter data, geophysical logs (televideo logs, caliper, others), outcrop descriptions, and stratigraphic correlations of anomalous features. New monitor wells should be analyzed specifically with karst features in mind. Determine whether the karst features do or do not exist, and if they cannot be ruled out, include alternative flow and transport simulations that do include karst features.

### H.6.3.2 Faults

It is unlikely that the only multi-well test in Yucca Flat identified the highest value of fault damage-zone permeability. The peer review team therefore recommends that the range considered for modeling extend well above the highest measured value. Given that none of the major faults have been investigated in the field, include alternative models with permeable faults and no impermeable core to determine their effect on the flow field and transport.

The peer review team recommends assigning increased permeability to the material that is currently simulated as country rock near the major faults in the analysis of uncertainty.

The peer review team recommends that the effect of greater fault permeability in the AA/VA model should be explored in CADD/CAP, and if model tests show that fault permeability in the AA/VA

system is relevant to the LCA contaminant boundary prediction, field data should be collected to characterize AA/VA fault behavior.

The peer review team recommends that the uncertainty in the contaminant boundary due to all the faults serving as permeable pathways to the LCA be evaluated, and alternative models include faults without impermeable cores.

The peer review team recommends including an alternative conceptual model that has no or many fewer minor faults in the LCA; this may require allowing flow and transport to occur between the AA/VA and LCA via the TCU (fractured) as described further below, in addition to the major faults. For example, flow in the LCA in Yucca Flat was recently modeled without faults by Halford (2012).

#### H.6.3.3 Tuff Confining Unit

The peer review team recommends that uncertainty in the contaminant boundary include an alternative conceptual model for analysis of the importance of flow across a TCU that is not impermeable but rather honors the available data on hydraulic properties of the TCU.

Given the importance of the TCU to isolate much of the radionuclide inventory, the peer review team recommends developing new data and hydraulic field testing to determine the lateral continuity of the TCU as an effective hydraulic barrier to vertical transport.

#### H.6.3.4 Effective Porosity

Evaluate the uncertainty in the extent of the contaminant boundary due to effective (fracture) porosity of the TCU.

#### H.6.3.5 Potential for Flow of Surface Water into Fractures in the Alluvium

Modeling should include the reasonable and conservative approach that would permit faults to be local zones of preferential flow through the unsaturated and saturated alluvium into the underlying stratigraphic units.

Field measurements are recommended to ascertain the degree to which fissures contribute to enhanced local recharge and local groundwater flow directions, including the earth fissures near Yucca Lake and the fissures associated with faults that extend to the surface in the alluvium.

#### H.6.3.6 Anisotropy and Preferential Flow in the Unsaturated Zone

During the CADD/CAPP process, data collection efforts should be undertaken at those craters determined via field testing or modeling to have high rates of enhanced recharge to determine the maximum depth of recent infiltration and possible flow through preferential pathways to detonation cavities.

### H.6.4 Source Term and Mass Flux to the LCA

#### H.6.4.1 No Uncertainty Associated with the RST

The peer review team suggests that uncertainties in the RST values be included in the modeling. It would be possible to evaluate unclassified RST uncertainties by comparing the unclassified inventory of each detonation calculated as above with the corresponding classified inventories from Miller et al. (2002). The distribution of differences would evaluate the uncertainties in the unclassified RST values based on the average CAU inventories without revealing any information about individual classified RST values.

#### H.6.4.2 Uncertainties in Partition Factors Are Not Well Defined Particularly for Cavities in Carbonate Rock

Develop arguments supporting the relevance of IAEA partitioning data to tests in silicate rock at the NNSS by examining what differences would be expected between partitioning in cavities in seawater-saturated basalt and partitioning in cavities in unsaturated or fresh-water saturated rhyolite. That is, should one expect consistency between the IAEA partition factors and those from the CHANCELLOR test?

Provide support for the partition factors used in interpreting carbonate tests. This could include theoretical considerations, laboratory examination of cavity debris, and/or—most convincing—collection and interpretation of field data from a carbonate test like those that were available to Rose et al. (2011) for the CHANCELLOR test.

#### H.6.4.3 Water Flow into Cavities

Given that liquid transport from the cavities is the dominant mechanism for downward movement, the peer review team recommends a concerted effort to measure and monitor enhanced-recharge-driven transport in and below detonation cavities, with emphasis on detonations within the TCU.

#### H.6.4.4 Uncertainty in the Exchange Volume Not Fully Captured

The peer review team recommends that the uncertainty analysis of the contaminant boundary include the effects of extending the exchange volume to at least 5 $R_c$.

#### H.6.4.5 Possible Chimney and Cavity Pathway to the LCA

The peer review team recommends that the uncertainty analysis of the contaminant boundary include breaches from detonations not only within 5 $R_c$ but also include a greater range in the permeability enhancement assigned to the damage zone. Where possible, consider evaluating whether post-shot holes can be used to test the field permeability of the damage zones *in situ*.

### H.6.5 Transport

#### H.6.5.1 Values Used for Pu Retardation Are Not Well Supported and May Be Too High

The Pu $K_d$ values used for modeling should be decreased to reflect the lower end of the measured range, and values lower than those measured should be used to evaluate the uncertainty associated with the lowest measurement. This would be a more conservative approach than emphasizing the high end of the range as is now done. Sensitivity analyses would also be useful to determine at what a range of retardation values Pu transport would be a concern.

With respect to additional data, site-specific data should be collected to develop a better mechanistic understanding of Pu retardation processes and improve the representation of the *in situ* chemical conditions in which the retardation takes place in Yucca Flat. In addition, evaluation of existing data should continue to determine whether it is possible that retardation values can reach levels that the modeling indicates may cause concerns.

#### H.6.5.2 Melt-Glass Dissolution Is Largely Neglected

Include melt-glass dissolution in UZ models that allow for enhanced flow.

Consider additional processes affecting cavity-debris behavior in the LCA model. Include an instant-release case among the sensitivity analyses, similar to that in the AA/VA model.

### H.6.6 Simulating Critical Observations

#### H.6.6.1 Field Measured $^3$H Concentrations Are Not Simulated by the N-I (2013) Model

The peer review team recommends the following actions to address $^3$H observations:

- Simulate a sub-region of the model encompassing an unexpectedly high measured concentration using many more particles to determine whether the reason for the mismatch is the low number of particles used to represent $^3$H transport.
- Simulate a sub-region of the model encompassing an unexpectedly high measured concentration using smaller block sizes.
- Determine what processes could lead to the observed apparent lateral transport of $^3$H in the AA/VA and incorporate them into the model.
- Evaluate whether the timing of the sampling or the nature of the completion of the non-detect wells may be such that $^3$H occurrences were missed.
- Given that there are so few contaminant data in the LCA, results of comparisons are mixed, and contaminant movement in the LCA is expected to follow discrete pathways, the next step is to gather field data that will define the current extent of contamination to better evaluate the simulations and adjust the model to better represent the field system.

#### H.6.6.2 Crater-Infiltration Data Are Not Well Matched in the Model

Determine why the modeled crater-recharge estimates do not match well the limited observations, and ensure that the crater-recharge model is conservative in its estimates of enhanced recharge.

### H.6.6.3 Geochemical and Environmental Isotopes Not Fully Evaluated

The choice of initial Cl concentrations used to adjust the measured $^{36}Cl/Cl$ ratios should be examined carefully, and strong justification should be provided for the value finally chosen.

The behavior and interpretation of $^{14}C$ in the Yucca Flat and Ash Meadows flow systems should be compared and contrasted. If results of such a study indicate retardation in Ash Meadows but not in Yucca Flat, an explanation should be sought for such a profound difference in the behavior of two otherwise similar flow systems. Finally, it should be made clear whether the rates of groundwater flow supporting the modeled transport of detonation-derived radionuclides are more similar to those based on retarded or on unretarded $^{14}C$ flow rates.

The existence of $DO^{14}C$ data needs to be mentioned, but no age interpretations should be reported unless it can be demonstrated that the data are sound and that the interpretive methods are appropriate.

### H.6.6.4 Interpretation of Temperature Data

Investigate and explain temperatures at the water table; use the temperature data to inform the calibration of the coupled flow model that integrates flow in the AA/VA and LCA (recommended in Section 6.2.1); and incorporate water fluxes that may be indicated by the temperature data into the determination of the contaminant boundary.

### H.6.6.5 Realistic Geologic Features

Realistic geologic features (normal faults cutting the Paleozoic strata; variable dips on normal faults; fault intersections and active faults as higher permeability zones; alternative interpretations of faults based on geophysical data; narrow fault cores; gaps in the fault cores; lack of fault cores for some faults; and attitude of LCA strata, including high-permeability layers) should be incorporated in the model as computational capabilities, software, and data improve.

### H.6.6.6 Other Sources of Data Are Available but Unused

Data from the surrounding DOE and DoD facilities need to be reviewed and used to further constrain water levels, boundary fluxes, and estimates of hydraulic properties of the LCA.

Among other approaches discussed in previous sections of this report, the peer review team recommends building confidence in the Yucca Flat model by using the Yucca Flat modeling approach to simulate single-test detonations outside Yucca Flat in similar geological units where there has been groundwater monitoring (e.g., the 40-kt RULISON test in 1969 in Colorado, the 200- to 1,000-kt FAULTLESS test in 1968 in central Nevada, or the 12-kt SHOAL test in 1963 in northern Nevada).

### H.6.7 Uncertainty Assessment

#### H.6.7.1 Current Evaluation Does Not Capture the 95th Percentile

The peer review team recommends an approach where models that represent combinations of values from the upper end of their parameter distributions (those that would enhance transport) are generated manually and explored. Such exploration would start with the alternative flow model scenarios (including those listed in Section 6.7.2*)* using the most extreme parameters. For example, very high values for continuous, high hydraulic conductivity zones from the northern to the southern boundary and passing through sources would be held constant while other values are adjusted to determine whether an acceptable calibration can be obtained. If it cannot, the process would be repeated with a substantially lower value of continuous high hydraulic conductivity, and if that calibration is successful, then the difference (in log space) between the values of hydraulic conductivity would be halved until the maximum acceptable continuous high hydraulic conductivity value for the pathway is identified. A sampling scheme that captures combinations of parameter values from the portion of the transport parameter distributions that would enhance transport should be coupled with the faster flow fields.

#### H.6.7.2 Expected Alternative Flow Models Were Not Included

The peer review team recommends the models listed in this section be evaluated as described in Section 6.7.1 and the “fast” flow fields from many strong source locations be used in combination with source and transport parameters that result in the most distant locations of MCL exceedance.

#### H.6.7.3 Limited Number (100) of NSMC Realizations of the Flow Model Produced Parameter Value Combinations That Do Not Capture the 95th Percentile of Parameter Combinations That Lead to Rapid Transport

Use the manual modification of a bias sampling approach as described in Section 6.7.1 to capture fast flow fields without excessive numbers of simulations. Confirm that the calibrated hydraulic conductivities are consistent with maximum field measurements. This requires increasing the range of considered permeabilities to include values beyond that measured in the spinner logs in wells ER-6-1 and ER-6-1 #2.

#### H.6.7.4 Limited Calibrated Flow Models Used to Evaluate Transport Uncertainty

More flow fields (relative to the previous stage, which included only three) should be considered for the transport uncertainty evaluation, and biased sampling of transport parameters (in the direction that enhances transport) should be used to limit the number of transport simulations required to capture the 95th percentile. Additional flow fields should be generated by considering alternative conceptual models as described in Section 6.7.2 and associated parameters that lead to fast transport from source locations to the south end of Yucca Flat.

#### H.6.7.5 Limited Alternative Models Used to Evaluate Relevant Detonations

Alternative source terms need to be considered with associated flow conditions that move radionuclides rapidly to the LCA (e.g., breaches, high infiltration) and rapidly through the LCA (continuous high-permeability zones connected to source locations) in order to capture the upper end of the cases that will provide the 5 percent exceedance of MCLs.

#### H.6.7.6 Limited Range of Transport Parameters Values Used to Evaluate Transport Uncertainty

Pu isotopes need to be included in the transport model with combinations of lower $K_d$ values and higher mass in the source term than presently specified in the uncertainty analysis. Improve the estimates of matrix diffusion or expand the evaluated uncertainty range such that the simulations will have little doubt of capturing the upper 5 percent tail of the contaminant boundary. Include higher values of dispersivity in the uncertainty evaluation. The range of dispersivity included in the

uncertainty analysis needs to be commensurate with the degree of heterogeneity in the hydraulic conductivity field incorporated in future models.

#### H.6.7.7 Mesh Refinement Not Necessarily Conservative

Evaluate higher level meshes to determine definitively the mesh-refinement level for which there is no change in the contaminant boundary.

### H.6.8 Unforeseen Uncertainties and the Need for Extended Peer Review

#### H.6.8.1 New Concerns and Approaches Will Likely Arise

The peer review team recommends that DOE initiate a wider "vetting" of the models and monitoring, and continued review of assumptions and rationale for choices made in data gathering, inclusion, and exclusion.

The peer review team recommends that DOE should consider annual or biennial independent and external review of the hydrologic modeling, testing, and characterization efforts at Yucca Flat. This would foster development of new conceptual models; would lead to efficiencies in developing characterization plans, as it would provide an independent and unbiased assessment of the efficacy of new characterization efforts; and would help focus DOE efforts on critical characterization gaps. An outside evaluation could take, as this peer review team has been able to do, a "30,000-foot" view of the conceptual flow model and characterization efforts in a continuous manner to help guide efforts to close the most important knowledge gaps and build model confidence.

#### H.6.8.2 Climate Change

As climate models are refined in the future, modeling should evaluate whether long-term climate change and associated extreme weather events would have a significant impact on the transport of radionuclides from Yucca Flat.

### H.6.9 Location of Radionuclide Plumes—Recommendations for Monitor Wells and Testing/Sampling Programs during the CADD/CAP Stage

#### H.6.9.1 The Extent of Contamination Is Poorly Defined at Present

The peer review team recommends determining the bounds of contaminant migration in both the AA/VA and LCA aquifer systems. The emphasis should be on delineating the downgradient edge of the plume, targeting preferential geologic pathways (including faults) and placing monitor wells in the path predicted by the model for the year 2020, for example.

#### H.6.9.2 The Existing Observation Well Network Is Inadequate

The peer review team recommends a comprehensive formal review of existing data quality, including chemical sampling and laboratory testing methods. Going forward, a groundwater monitoring program should be maintained to collect samples for purposes such as evaluating model uncertainties and delineating contaminant boundaries. Existing observation wells included in the monitoring program should be flagged with appropriate data-quality designations. New monitor wells are recommended in the near field and far field downgradient of key detonations, especially west of Yucca fault; in one or more permeable fault zones; and at the southern end of Yucca Flat where contamination is anticipated based on modeling.

Initial CADD/CAP monitor wells should be sited with the goal of finding contaminant plumes and simultaneously collecting valuable hydraulic property data from the fault zones and country rock of the AA/VA, TCU, and LCA. The peer review team recommends at a minimum additional monitor wells for two purposes:

1. To further evaluate the nexus between large detonations and the LCA via major faults, such as in the vicinity of STRAIT and the Topgallant fault, or near the impacted AA/VA holes U-4uPS 2A/U-7ba PS 1AS and Yucca fault, and

2. To find the extent of contamination along expected pathways bordering the detonations on the south, between ER 6-1 and ER 6-2.

    - One well near the Topgallant fault and

    - One well near the junction of Yucca fault and other minor faults such as those extending south from BILBY.

- If either of the above two monitor wells show impacts, add two additional monitor wells to the south of Yucca Lake (e.g., near the outlet to CP Basin and Frenchman Flat).

Regarding construction of the wells, the peer review team recommends using angled drilling and doglegs when possible to cross the faults at multiple positions and investigate multiple issues with one hole.

In addition, the peer review team recommends resampling some of the drill-back holes and, as needed, sampling from new drill holes to understand whether radionuclides are migrating out of cavities. Drill holes near detonations with working points in and near the LCA may be most useful.

Furthermore, the peer review team recommends aquifer testing and sampling, and new drilling if necessary, to determine inflow to Yucca Flat from the north.

In addition to new monitor wells, existing wells may be used to better understand processes and decrease uncertainty in hydraulic and geochemical properties. The testing and sampling programs listed in Table H.6-5 should be undertaken in the CADD/CAP stage of the project to build confidence in the conservative nature of the predicted contaminant boundary. This list is neither exhaustive nor prioritized, and NNSA/NFO or NDEP may identify other key processes and pathways that require additional characterization during the next stage of work. The models should be used to identify additional data that would lead to the greatest reduction of uncertainty in the extent of the contaminant boundaries.

## Table H.6-5
## Recommended Non-exhaustive List of Testing and Sampling Programs to Better Characterize Key Pathways That Control the Contaminant Boundary

- Multi-well hydraulic testing on the central and western portions of the LCA to investigate both the fracture/fault hydraulic properties of the LCA and the vertical hydraulic continuity of the TCU. Water samples should be collected from known intervals and with time during testing in order to define the vertical as well as the horizontal distribution of water types and to define chemical changes (e.g., changing radionuclide concentrations) with the increasing aquifer volume sampled as pumping continues. Where appropriate, intervals should be packed off during sampling to prevent sample mixing due to vertical gradients.
- Multi-well hydraulic testing and water sampling at the northern boundary of the Yucca Flat to investigate inflow from the north, including the fracture/fault hydraulic properties of rocks that occur along the northern extension of the Boundary/Yucca fault across the topographic divide to the north (Comstock stock, LCA, contact-metamorphosed LCA, and overlying Tertiary volcanic rocks).
- Sampling and testing designed to maximize the ability to interpret data from hydraulic testing
  - Temperature profiling through the TCU to estimate vertical leakage
  - Lithologic logging (preferably of drill core) and geophysical logging of the TCU and LCA, with an emphasis on characterization of flow in fractures and faults in both units, and, in the case of the LCA, subsurface mapping of individual stratigraphic units that may contain karst or fracturing that would provide fast pathways
  - Packer testing to investigate hydraulic and chemical character of discrete preferred flow zones as well as the TCU
  - Spinner logs (as undertaken in ER-6-1) to investigate preferred flow zones
  - Head measurements at discrete depth intervals across the TCU and in the LCA to quantify the gradient
- Chemical data collected from discrete depth intervals and during pumping to define changes as boreholes are cleaned out and with increasing volume pumped:
  - Key radionuclides ($^{3}H$, $^{14}C$, $^{90}Sr$, $^{99}Tc$, $^{36}Cl$)
  - Major constituents (including field determinations) for charge balance (pH, major ions) as well as constituents required to assess equilibrium with formation minerals and aqueous speciation of radionuclides affecting their solubilities and sorption behavior

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