

RECORD OF TECHNICAL CHANGE

Technical Change No. DOE/NV--659-ROTC 1 Page 1 of 2
Activity Name CAU 97 Yucca Flat/Climax Mine Corrective Action Investigation Plan Date: February 19, 2013

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

<u>Robert W. Andrews</u>	<u>Navarro-Intera LLC/UGTA Integration Manager</u>
(Name)	(Title)

Description of Change:

1. Page 225 of 315, Section 5.1.3.3 Contaminant Transport Model Development - Delete the paragraph:

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

and replace with the paragraph:

"The simulation of radionuclide transport with the CAU model can be performed with the traditional solution of the three-dimensional advective dispersion equation (called the reactive transport model in FEHM), however more efficient particle tracking routines such as the *sptr* subroutine in FEHM or Walkabout (Painter, 2011) when used in combination with PLUMECALC (Robinson et al., 2012) are suitable codes for forecasting the contaminant boundary. The routines in FEHM_sptr and Walkabout have been determined to be suitable to calculate the advective-dispersive transport using steady state heterogeneous flow fields developed from FEHM. PLUMECALC has been determined to be a suitable code to calculate contaminant concentrations down gradient from contaminant sources including the effects of radioactive decay, matrix diffusion, fracture sorption and matrix sorption. The justification for using either FEHM_sptr or Walkabout and PLUMECALC is provided in Rev 1 of the *Evaluation of Software Errors and Issues, and Software Impact Assessment for Frenchman Flat* (N-1, 2012)."

2. Page 304-307 of 315, Section 9.0, References - Add the following new references:

N-1, see Navarro-Intera, LLC.

Navarro-Intera, LLC. 2012. *Evaluation of Software Errors and Issues, and Software Impact Assessment for Frenchman Flat, Nevada National Security Site, Nye County, Nevada*. Rev. 1, N-1/28091--063. Las Vegas, NV.

Painter, S.L. 2011. *User's Manual for Walkabout V1.0*. Los Alamos, NM: Los Alamos National Laboratory, LA-UR-11-01952.

Robinson, B.A., Z.V. Dash, and S.L. Painter. 2011. *User's Guide for the PLUMECALC Application*, Version 2.3. Los Alamos, NM: Los Alamos National Laboratory.

Justification:

The CAIP for the Yucca Flat/Climax Mine CAU (DOE/NV-659; DOE/NV, 2000) states that the only code identified for use in contaminant transport modeling for the Yucca Flat/Climax Mine CAU is FEHM (Zyvoloski et al., 1997). The CAIP notes that this method is unlikely to result in an accurate solution and thus a large number of one-dimensional transport solutions along pathlines will be relied on. The CAIP notes that alternative approaches will be proposed.

Subsequent to the CAIP, additional codes using alternative approaches have been determined to be acceptable for

forecasting contaminant boundaries, including PLUMECALC (Robinson et al., 2012) when used with either FEHM_sptr or Walkabout (Painter, 2011). The justification for PLUMECALC has been documented in the *Phase II Transport Model of Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada* (NNES, 2010). The justification for using PLUMECALC with either FEHM_sptr or Walkabout has been documented in the *Evaluation of Software Errors and Issues, and Software Impact Assessment for Frenchman Flat* (N-I, 2012). Additional justification is provided in Appendix K of the Final Rev 0 of the *Yucca Flat/Climax Mine CAU Flow and Transport Model* document (N-I, 2013). Based on these analyses, PLUMECALC V2.3.2 when used in combination with either FEHM_sptr or Walkabout is determined to be appropriate for forecasting contaminant boundaries for the Yucca Flat/Climax Mine CAU.

References cited in Justification:

DOE/NV, see U.S. Department of Energy, Nevada Operations Office.

N-I, see Navarro-Intera, LLC.

NNES, see Navarro Nevada Environmental Services, LLC.

Navarro-Intera, LLC. 2012. *Evaluation of Software Errors and Issues, and Software Impact Assessment for Frenchman Flat, Nevada National Security Site, Nye County, Nevada*. Rev. 1, N-I/28091--063. Las Vegas, NV.

Navarro-Intera, LLC. 2013. Written communication. Subject: *Yucca Flat/Climax Mine CAU Flow and Transport Model, Nevada National Security Site, Nye County, Nevada*. Final Rev 0, February. Las Vegas, NV.

Navarro Nevada Environmental Services, LLC. 2010. *Phase II Transport Model of Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada*, Rev.1, N-I/28091--004, S-N/99205--122. Las Vegas, NV.

Painter, S.L. 2011. *User's Manual for Walkabout V1.0*. Los Alamos, NM: Los Alamos National Laboratory, LA-UR-11-01952.

Robinson, B.A., Z.V. Dash, and S.L. Painter. 2011. *User's Guide for the PLUMECALC Application*, Version 2.3. Los Alamos, NM: Los Alamos National Laboratory.

U.S. Department of Energy, Nevada Operations Office. 2000. *Corrective Action Investigation Plan for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada Test Site, Nevada*, DOE/NV--659. Las Vegas, NV.

Zyvoloski, G.A., B.A. Robinson, Z.V. Dash, and L.L. Trease. 1997. *User's Manual for the FEHM Application - A Finite-Element Heat- and Mass-Transfer Code*, LA-13306-M. Los Alamos, NM: Los Alamos National Laboratory.

The task time will be (Increased) (Decreased) (Unchanged) by approximately 0 days.

Applicable Activity-Specific Document(s): *Yucca Flat/Climax Mine CAU Flow and Transport Model*

Approved By: /s/ Wilhelm R. Wilborn
Activity Lead

Date 2/19/2013

/s/ Wilhelm R. Wilborn
for EM Operations Manager

Date 2/28/2013

/s/ Chris T. Andres
NDEP

Date 2/28/2013

RECORD OF TECHNICAL CHANGE

Technical Change No. DOE/NV-659-ROTC 2

Page 1 of 2

Activity Name Underground Test Area

Date 6/16/14

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

Sam Marutzky

(Name)

UGTA Project Manager

(Title)

Description of Change:

Corrective Action Investigation Plan for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada Test Site, Nevada, Rev. 0 (DOE/NV- - 659), Page 265 of 315, *Groundwater Sampling and Analysis*, Section 6.1.5.2 (Field and Laboratory Activities):

Remove:

“The groundwater samples will be analyzed for the following constituents:

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

Replace with:

“The groundwater characterization samples will be analyzed for the constituents presented in Table 6-2. Associated analytical methods and requirements for the collection and analysis of groundwater characterization samples are also included in the table.

Insert Table 6-2 “*Groundwater Characterization Sample Analysis Parameters*”(see attached)

Page 285 of 315, Section 6.3.3.2 Fluid Sampling and Analysis, Paragraph 4 – 2nd sentence:

“Groundwater characterization samples are collected from the newly installed wells at the completion of well development and periodically thereafter until the well is taken out of service or until monitoring is no longer required.”

Replace with:

“Groundwater characterization samples are collected from the newly installed wells at the completion of well development and testing.”

Page 286 of 315, Section 6.3.3.2 Fluid Sampling and Analysis, Paragraph 1 - Delete last two sentences:

“All groundwater samples are then sent to an analytical laboratory to be analyzed for the parameters listed in Table 5-1 of the UGTA QAPP (DOE/NV, 2000). The analyses listed in this table include metals, major ions, general chemistry, age and migration parameters, radiological indicator parameters, nuclear fuel products, and other radionuclides.”

Replace with:

"Groundwater characterization samples will be analyzed for the parameters listed in Table 6-2."

Justification:

The current version of the UGTA Quality Assurance Plan does not contain the table of analytical parameters (Table 5-1) referenced in the previous Quality Assurance Project Plan (QAPP). This ROTC replaces the reference to Table 5-1 in the QAPP with a table of analytical parameters in the CAIP (Table 6-2). Further the Corrective Action Investigation Plan for Corrective Action Unit 97: Yucca Flat/Climax Mine (DOE/NV—659, Rev. 0 provided a bulleted list of generalized groups of analytical parameters (e.g., radioisotopes) and a limited number of specific parameters (e.g., Cl-36, He-3) for which groundwater characterization samples will be analyzed. The addition of Table 6-2 provides appropriate detail regarding specific analyses required for characterization samples and the required analytical methods. The table also identifies those parameters that are presently considered optional analyses and not required for all groundwater characterization suites collected from wells in Yucca Flat.

The task time will be (Increased) (Decreased) (Unchanged) by approximately 0 days.

Applicable Activity-Specific Document(s):

Corrective Action Investigation Plan for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada Test Site, Nevada, Rev. 0 (DOE/NV - - 659)

Approved By:

/s/ Wilhelm R. Wilborn

Date

6/17/2014

Activity Lead

/s/ Robert F. Boehlecke

Date

6/17/14

EM Operations Manager

/s/ Chris T. Andres

Date

6/18/14

NDEP

Table 6-2
Groundwater Characterization Sample Analysis Parameters

Parameter	Analytical Method	Sample Volume and Container Type	Laboratory	Filtration	Preservative	Holding Time
Metals						
Aluminum Arsenic Barium Cadmium Calcium Chromium Iron Lead Lithium Magnesium Manganese Potassium Selenium Silicon Silver Sodium Strontium	SW-846 6010	1-L polyethylene	Commercial	1-L nonfiltered for total analysis	HNO ₃ to pH<2	180 days
Uranium	SW-846 6020					
General Chemistry						
Chloride	EPA 300.1	(1) 1-L polyethylene	Commercial	Filtered	Cool to ≤ 6 °C	28 days
Fluoride						
Bromide						
Sulfate						
pH	EPA 150.1	(1) 1-L polyethylene	Commercial	Nonfiltered	Cool to ≤ 6 °C	ASAP
EC	EPA 120.1					28 days
Carbonate/ Bicarbonate	EPA 310.2					14 days
Radioisotopes						
Gamma Scan	EPA 901.1	(1) 1-L polyethylene	Commercial	Nonfiltered	HNO ₃ to pH<2	180 days
Tritium ^a	EPA 906.0 or equivalent	(1) 250-mL amber glass	Commercial	Nonfiltered	None	180 days
Tritium ^b (Low Level)	EPA 906.0 (Low Level)	(3) 1-L polyethylene	Commercial	Nonfiltered	None	180 days

Table 6-2
Groundwater Characterization Sample Analysis Parameters

Parameter	Analytical Method	Sample Volume and Container Type	Laboratory	Filtration	Preservative	Holding Time
Gross Alpha Gross Beta	EPA 900.0	(1) 1-L polyethylene	Commercial	Nonfiltered	HNO ₃ to pH<2	180 days
¹⁴ Carbon	EPA EERF C-01	(1) 1-L amber glass	Commercial	Nonfiltered	None	180 days
³⁶ Chlorine	Lab Specific SOP-724	(2) 1-L amber glass	Commercial	Nonfiltered	None	180 days
⁹⁰ Strontium	ASTM D5811-00 or EPA 905.0	(1) 1-L polyethylene	Commercial	Nonfiltered	HNO ₃ to pH<2	180 days
¹²⁹ Iodine	EPA 902.0 / Lab Specific SOP-753	(2) 1-L amber glass	Commercial	Nonfiltered	None	180 days
^{238,239/240} Plutonium	HASL 300 Se-03/G-01	(2) 1-L polyethylene	Commercial	Nonfiltered	HNO ₃ to pH<2	180 days
⁹⁹ Technetium	HASL 300 TCW-02	(1) 1-L polyethylene	Commercial	Nonfiltered	HNO ₃ to pH<2	180 days
Tritium ^b (Low Level)	SOP-UGTA-121	(1) 1-L amber or clear glass	LLNL	Nonfiltered	None	Indefinite
⁹⁹ Technetium ^c	SOP-UGTA-111	(1) 4-L or (2) 2-L pre-cleaned HDPE	LLNL	Nonfiltered	None	Indefinite
¹²⁹ Iodine ^c	SOP-UGTA-123	(2) 1-L amber glass	LLNL	Nonfiltered	None	Indefinite
^{238,239/240} Plutonium ^c	SOP-UGTA-135	(2) 1-L amber glass	LLNL	Nonfiltered	None	Indefinite
Age and Migration Parameters						
^{δ13} Carbon and TIC/TOC	SOP-UGTA-116	(6) 40 ml amber glass VOA	LLNL	Filtered	Cool to ≤ 6°C	180 days
		(6) 40 ml amber glass VOA		Nonfiltered	HgCl ₂ , Cool to ≤ 6°C	

Table 6-2
Groundwater Characterization Sample Analysis Parameters

Parameter	Analytical Method	Sample Volume and Container Type	Laboratory	Filtration	Preservative	Holding Time
¹⁴ Carbon (Inorganic)	SOP-UGTA-116 SOP-UGTA-136	(1) 125 ml amber glass w/septa	LLNL	Nonfiltered	HgCl ₂ , Cool to ≤ 6°C	Indefinite
Dissolved Organic Carbon ^b	SM 5310C	(2) 125-mL factory baked, pre-cleaned, amber glass	DRI	Filtered (DRI numbered, pre-cleaned, 0.45 μm groundwater cartridge)	Cool to ≤ 6°C	28 days
¹⁴ Carbon (Organic) ^b	SOP Carbon-14 Analyses Revision 1.0 NSF-Arizona AMS Facility	(5) 1-L precleaned amber glass	DRI	Filtered (DRI numbered, pre-cleaned, 0.45 μm groundwater cartridge)	Cool to ≤ 6°C	Indefinite
³⁶ Chlorine	SOP-UGTA-115 SOP-UGTA-120	(1) 1-L polyethylene w/(1) 125 ml polyethylene CI field blank as provided by lab (1) 125 ml polyethylene	LLNL	Nonfiltered Filtered	Cool to ≤ 6°C	Indefinite 180 days
Noble Gases ^{b, d} (incl. ³ He)	SOP-UGTA-122	(2) copper tubes	LLNL	Nonfiltered	None	180 days
δ ² Hydrogen	SOP-UGTA-128	(1) 30 ml glass	LLNL	Nonfiltered	None	180 days
δ ¹⁸ Oxygen						
Chloro-fluorocarbons ^b	GCE23	Glass bottle with foil-lined cap	USGS	Nonfiltered	Maintain at room temperature	~ 180 days
N ₂ , Ar, CO ₂ , CH ₄ , O ₂ ^(b)	GC152/GC153	150 mL septum bottle with rubber-type stopper (supplied by USGS lab)	USGS	Nonfiltered	Cool to ≤ 6°C	3 Months

Table 6-2
Groundwater Characterization Sample Analysis Parameters

Parameter	Analytical Method	Sample Volume and Container Type	Laboratory	Filtration	Preservative	Holding Time
SF ₆ ^b	GCE28	1-L plastic coated amber glass bottle with polyseal cone lined cap	USGS	Nonfiltered	Maintain at room temperature	3 months

^a Tritium analysis to be performed with higher detection levels (~ 300 pCi/L). This sample may be collected from groundwater where the tritium activities are known or are expected to exceed low level tritium analysis thresholds established by the laboratories.

^b Optional sample analysis. Samples may be analyzed by a single or multiple participating laboratories based on the requested parameter. Optional analysis allows for non-standard analytical methods to attain desired detection limits or unique sampling objectives (e.g., chlorofluorocarbons, N₂, Ar, CO₂, CH₄, O₂, and SF₆ for determining recently recharged groundwater).

^c Optional analysis to be conducted only for groundwater samples with known or expected tritium concentrations equal to or exceeding 5,000 pCi/L.

^d Optional analysis to be conducted only for groundwater samples with known or expected tritium concentrations less than 5,000 pCi/L.

Note: For commercial laboratory analysis the most current EPA or equivalent accepted standard laboratory analytical methods may be used as appropriate to attain specified detection limits. All analysis performed by commercial and non-commercial laboratories must be compliant with the Underground Test Area Activity Quality Assurance Plan Nevada National Security Site, Nevada.

°C = Degrees Celsius
AMS = Accelerator Mass Spectrometry
Ar = Argon
ASTM = American Society of Testing Materials
CH₄ = Methane
Cl = Chlorine
CO₂ = Carbon dioxide
DRI = Desert Research Institute
EPA = Environmental Protection Agency
H₂SO₄ = Sulfuric Acid
HCl = Hydrochloric Acid
HDPE = High-density Polyethylene
HgCl₂ = Mercuric Chloride
HNO₃ = Nitric Acid
L = Liter
LLNL = Lawrence Livermore National Laboratory

mL = Milliliter
µm = Micrometer
N₂ = Nitrogen
NaOH = Sodium Hydroxide
NSF = National Science Foundation
O₂ = oxygen
pCi/L = Picocuries per Liter
SF₆ = Sulfurhexafluoride
SOP = Standard Operating Procedure
TIC = Total Inorganic Carbon
TOC = Total Organic Carbon
USGS = U.S. Geological Survey
VOA = Volatile Organic Analysis
ZnAc = Zinc Acetate

RECORD OF TECHNICAL CHANGE

Technical Change No. DOE/NV-659-ROTC 3

Page 1 of 2

Activity Name Underground Test Area

Date November 26, 2014

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

Sam Marutzky

(Name)

UGTA Project Manager

(Title)

Description of Change:

Corrective Action Investigation Plan for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada Test Site, Nevada, ROTC 2

Remove:

"The groundwater characterization samples will be analyzed for the constituents presented in Table 6-2. Associated analytical methods and requirements for the collection and analysis of groundwater characterization samples are also included in the table."

Replace with:

"Sampling and analysis will be performed according to location type as shown in Table 6-2. Additional analyses will be performed as needed."

Remove:

Table 6-2 "*Groundwater Characterization Sample Analysis Parameters*"

Replace with:

Table 6-2, "*Sample Location Type Definitions and Analyte*" (see attached)

Remove:

"Groundwater characterization samples will be analyzed for the parameters listed in Table 6-2."

Replace with:

"Groundwater samples will be analyzed according to location type as shown in Table 6-2. Additional analyses will be performed as needed."

Justification:

This ROTC describes sampling and analyses that will take place during the rest of the corrective action investigation stage. It provides a table that summarizes sample location types and analytical parameters required for each location type (Table 6-2).

The task time will be (Increased) (Decreased) (Unchanged) by approximately 0 days.

Applicable Activity-Specific Document(s):

DOE/NV-659-ROTC2, Corrective Action Investigation Plan for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada Test Site, Nevada, ROTC 2

Approved By:

11/11/14
/s/Robert F. Boehlecke

Date

11/26/14

Activity Lead

Br. Bill Wilborn

/s/Robert F. Boehlecke

Date

11/26/14

EM Operations Manager

/s/Chris Andres

Date

12/1/14

NDEP

Table 6-2
Sample Location Type Definitions and Analytes
 (Page 1 of 2)

Location Type	Definition	Analytes ^a
Characterization ^b	Used for system characterization or model evaluation	• Alkalinity, pH, specific conductance • Anions (Br, Cl, F, SO₄) • Total metals (Ag, Al, As, Ba, Ca, Cd, Cr, Fe, K, Li, Mg, Mn, Na, Pb, Se, Si, Sr, U) • Gross alpha and gross beta • Gamma emitters (²⁶Al, ⁸⁴Nb, ¹³⁷Cs, ¹⁵²Eu, ¹⁵⁴Eu, ²³⁵U, ²⁴¹Am, ²⁴³Am) • ³H (standard and/or low-level) ^c • ¹⁴C, ³⁶Cl, ⁹⁹Tc, ⁹⁰Sr, ¹²⁹I, ^{238/239/240}Pu
Source/Plume	Located within the plume from an underground nuclear test (i.e., test-related contamination present), and COCs detected above standard measurement levels (e.g., ³ H >300 pCi/L)	• ³H (standard), ¹⁴C, ³⁶Cl, ⁹⁹Tc, ¹²⁹I (plus ⁹⁰Sr and ¹³⁷Cs in LCA samples)
Early Detection	Located downgradient of an underground test or Source/Plume well, and no COCs detected above standard measurement levels (i.e., ³ H <300 pCi/L)	• ³H (low-level)
Distal	Outside the Early Detection area ^d	• ³H (standard)
Community	Located on BLM or private land; used as a water supply source or is located near one	• ³H (standard)

Table 6-2
Sample Location Type Definitions and Analytes
 (Page 2 of 2)

Location Type	Definition	Analytes ^a
Inactive	Not currently sampled but available for sampling if conditions warrant	None

^a Required analyses performed by a commercial lab certified by NDEP.

^b Characterization locations will transition to another type when a sufficient baseline (a minimum of three samples) is established to support categorization.

^c Standard ³H analytical methods achieve a minimum detection limit of approximately 300 pCi/L; low-level ³H analytical methods achieve detection limits as low as 1 pCi/L.

^d The Early Detection area is defined as the area directly downgradient of an underground nuclear test where COCs have not been detected above levels detectable using standard analytical methods.

Ag = Silver

Al = Aluminum

Am = Americium

As = Arsenic

Ba = Barium

Br = Bromide

C = Carbon

Ca = Calcium

Cd = Cadmium

Cl = Chlorine

Cr = Chromium

Cs = Cesium

Eu = Europium

F = Fluorine

Fe = Iron

³H = Tritium

I = Iodine

K = Potassium

Li = Lithium

Mg = Magnesium

Mn = Manganese

Na = Sodium

Nb = Niobium

Pb = Lead

Pu = Plutonium

Se = Selenium

Si = Silicon

SO₄ = Sulfate

Sr = Strontium

Tc = Technetium

U = Uranium

BLM = Bureau of Land Management

COC = Contaminant of concern

NDEP = Nevada Division of Environmental Protection

pCi/L = Picocuries per liter

Nevada
Environmental
Restoration
Project

DOE/NV--659



Corrective Action Investigation Plan
for Corrective Action Unit 97:
Yucca Flat/Climax Mine,
Nevada Test Site, Nevada

Controlled Copy No.: ____

Revision No.: 0

September 2000

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Environmental Restoration
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**CORRECTIVE ACTION INVESTIGATION PLAN
FOR CORRECTIVE ACTION UNIT 97:
YUCCA FLAT/CLIMAX MINE
NEVADA TEST SITE, NEVADA**

DOE Nevada Operations Office
Las Vegas, Nevada

Controlled Copy No.: ____

Revision No.: 0

September 2000

Approved for public release; further dissemination unlimited.

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**CORRECTIVE ACTION INVESTIGATION PLAN
FOR CORRECTIVE ACTION UNIT 97:
YUCCA FLAT/CLIMAX MINE
NEVADA TEST SITE, NEVADA**

Approved by: /s/ Robert M. Bangerter Date: 9/27/00
Robert M. Bangerter, Project Manager
Underground Test Area Project

Approved by: /s/ Janet Appenzeller-Wing Date: 9/27/00
 R. C. Wycoff, Division Director
Environmental Restoration Division

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List of Acronyms and Abbreviations

δ	Delta
μm	Micrometer(s)
^{106}Ru	Ruthenium-106
^{125}Sb	Antimony-125
^{129}I	Iodine-129
^{13}C	Carbon-13
^{137}Cs	Cesium-137
^{14}C	Carbon-14
^{18}O	Oxygen-18
$^{18}\text{O}/^{16}\text{O}$	Oxygen-18/Oxygen-16
^{237}Np	Neptunium-237
^{238}U	Uranium-238
^{239}Pu	Plutonium-239
^{240}Pu	Plutonium-240
^{241}Am	Americium-241
3-D	Three-dimensional
^3He	Helium-3
^{36}Cl	Chlorine-36
^{85}Kr	Krypton-85
$^{87}\text{Sr}/^{86}\text{Sr}$	Strontium-87/Strontium-86
^{90}Sr	Strontium-90
^{99}Tc	Technetium-99
AA	Alluvial Aquifer
ALARA	As-low-as-reasonably achievable
amsl	Above mean sea level
ASTM	American Society for Testing and Materials

List of Acronyms and Abbreviations (Continued)

bgs	Below ground surface
BLM	U.S. Bureau of Land Management
BN	Bechtel Nevada
CADD	Corrective Action Decision Document
CAI	Corrective Action Investigation(s)
CAIP	Corrective Action Investigation Plan
CAP	Corrective Action Plan
CAS	Corrective Action Site(s)
CAU	Corrective Action Unit(s)
CFC	Chlorofluorocarbon(s)
CFR	<i>Code of Federal Regulations</i>
CL	Cathode luminescence
cm/yr	Centimeter(s) per year
cm	Centimeter(s)
cm ² /s	Square centimeter(s) per second
D	Deuterium
DEM	Digital Elevation Model(s)
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DoD	U.S. Department of Defense
DOE/NV	U.S. Department of Energy, Nevada Operations Office
DOE	U.S. Department Energy
DQO	Data Quality Objective(s)
DRI	Desert Research Institute
EPA	U.S. Environmental Protection Agency
ER	Environmental Restoration

List of Acronyms and Abbreviations (Continued)

ERP	Environmental Restoration Program
ET	Evapotranspiration
FFACO	<i>Federal Facility Agreement & Consent Order</i>
FMP	Fluid Management Plan
ft	Foot (feet)
ft/d	Foot (feet) per day
ft ² /s	Square foot (feet) per second
FY	Fiscal year
HASP	Health and Safety Plan
HRCES	Harry Reid Center for Environmental Science
HRMP	Hydrologic Resources Management Program
HRTEM	High-Resolution Transmission Electron Microscopy
HSU	Hydrostratigraphic unit(s)
I	Intrusives
IDW	Investigation-derived waste
in.	Inch(es)
in./yr	Inch(es) per year
ITLV	IT Corporation, Las Vegas
K _d	Distribution coefficient
km	Kilometer(s)
kt	Kiloton
LANL	Los Alamos National Laboratory
LCA	Lower carbonate aquifer
LCCU	Lower clastic confining unit
LLNL	Lawrence Livermore National Laboratory
LTHMP	Long-Term Hydrological Monitoring Program

List of Acronyms and Abbreviations (Continued)

m	Meter(s)
m/d	Meter(s) per day
m ³	Cubic meter(s)
m ³ /d	Cubic meters per day
MDA	Minimum detectable activity
MDC	Minimum detectable concentration
mg/L	Milligram(s) per liter
mi	Mile(s)
mrem/yr	Millirem(s) per year
mrem	Millirem(s)
Mt	Megaton
MWL	Meteoric water line
NDEP	Nevada Division of Environmental Protection
NEPA	<i>National Environmental Policy Act</i>
NTS	Nevada Test Site
OSHA	Occupational Safety and Health Administration
PAL	Preliminary action level(s)
pCi/L	Picocurie(s) per liter
pdf	Probability density function(s)
PPE	Personal protective equipment
QA	Quality assurance
QA/QC	Quality assurance and quality control
QAPP	Quality Assurance Project Plan
QC	Quality control
RadCon	Radiological Control
RCRA	<i>Resource Conservation and Recovery Act</i>

List of Acronyms and Abbreviations (Continued)

REOP	Real Estate/Operations Permit
RPP	Radiation protection program
RREMP	Radiological Environmental Monitoring Plan
RTTF	Residence Time Transfer Function
SDWA	<i>Safe Drinking Water Act</i>
SEM	Scanning electron microscopy
SMOW	Standard mean ocean water
SPTR	Streamline particle tracking
SSHASP	Site-specific Health and Safety Plan
SWNVF	Southwestern Nevada Volcanic Field
TCU	Tuff confining unit
TD	Total depth
TNT	Trinitrotoluene
TWG	Technical Working Group
TWG/MS	Technical Working Group Modeling Subcommittee
UCCU	Upper Clastic Confining Unit
UGTA	Underground Test Area
US-UK	United States and United Kingdom
USGS	U.S. Geological Survey
VA	Volcanic Aquifer
VCU	Volcanic Confining Unit
VOIA	Value of Information Analysis
WMP	Waste Management Plan
WW	Water Well
XRD	X-ray diffraction
ybp	Years before present

List of Acronyms and Abbreviations (Continued)

°C	Degree(s) Celsius
°F	Degree(s) Fahrenheit
‰	Per mil

List of Stratigraphic Unit Symbols

QTa	Old Alluvial Deposits
Tma	Ammonia Tanks Tuff
Tmr	Rainier Mesa Tuff
Tp	Paintbrush Group
Tpt	Topopah Spring Tuff
Tac	Calico Hills Formation
Tw	Wahmonie Formation
Tbg	Grouse Canyon Tuff
Tc	Crater Flat Group
Tn	Tunnel Formation
Tu	Volcanics of Big Dome
Tub	Tub Spring Tuff
To	Older Volcanics
Toy	Tuff of Yucca Flat
Tot	Tuff of Twin Peaks
Tx	Tuff Cones, Bullfrog Confining Unit or Belted Range Aquifer
Kg	Granitic Rocks
Op	Pogonip Group
Cbk	Bonanza King Formation

Note: This list is in geochronological order and is only applicable to [Tables 3-2](#) and [3-3](#).

1.0 Introduction

This Corrective Action Investigation Plan (CAIP) has been developed for Corrective Action Unit (CAU) 97: Yucca Flat/Climax Mine. The CAIP is a requirement of the *Federal Facility Agreement and Consent Order* (FFACO) (1996) agreed to by the State of Nevada, the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DoD). The FFACO was designed to address environmental restoration activities at DOE/NV facilities and sites including the underground testing area of the Nevada Test Site (NTS). This CAIP describes investigation activities that are currently planned for the Yucca Flat/Climax Mine CAU. These activities are consistent with the current Underground Test Area (UGTA) Project strategy described in Appendix VI of the FFACO (1996) and summarized in [Section 2.1.2](#) of this document. However, the UGTA strategy is currently under revision. Any additional investigation activities that may be proposed as a result of these revisions will be described in an addendum to this CAIP.

The Yucca Flat/Climax Mine CAU extends over several areas of the NTS ([Figure 1-1](#)) and constitutes one of several areas of the NTS used for underground nuclear testing in the past. The nuclear tests resulted in groundwater contamination in the vicinity as well as downgradient of the underground test areas. The CAIP describes the CAI to be conducted at the Yucca Flat/Climax Mine CAU to evaluate the extent of contamination in groundwater due to the underground nuclear testing.

The Yucca Flat and Climax Mine testing areas were originally defined as two separate CAUs in the FFACO: CAU 97 and CAU 100 (FFACO, 1996), but were later on combined into a single Corrective Action Unit (CAU 97). It was originally proposed to address each CAU individually because the geologic frameworks of the two areas are distinctly different. The Yucca Flat underground nuclear tests were conducted in alluvial, volcanic, and carbonate rocks; whereas, the Climax Mine tests were conducted in an igneous intrusion located in northern Yucca Flat. However, particle-tracking simulations performed during the regional evaluation (Section 5.5 of the regional model documentation package [IT, 1997b]) indicate that the local Climax Mine groundwater flow system merges into the much larger Yucca Flat groundwater flow system, during the 1,000-year time period of interest. These simulations indicate that groundwater flow paths passing through the underground nuclear tests of the Climax Mine CAU may enter northern Yucca Flat through the Lower Carbonate Aquifer (LCA). In addition, it is expected that smaller-scale contaminant transport modeling would

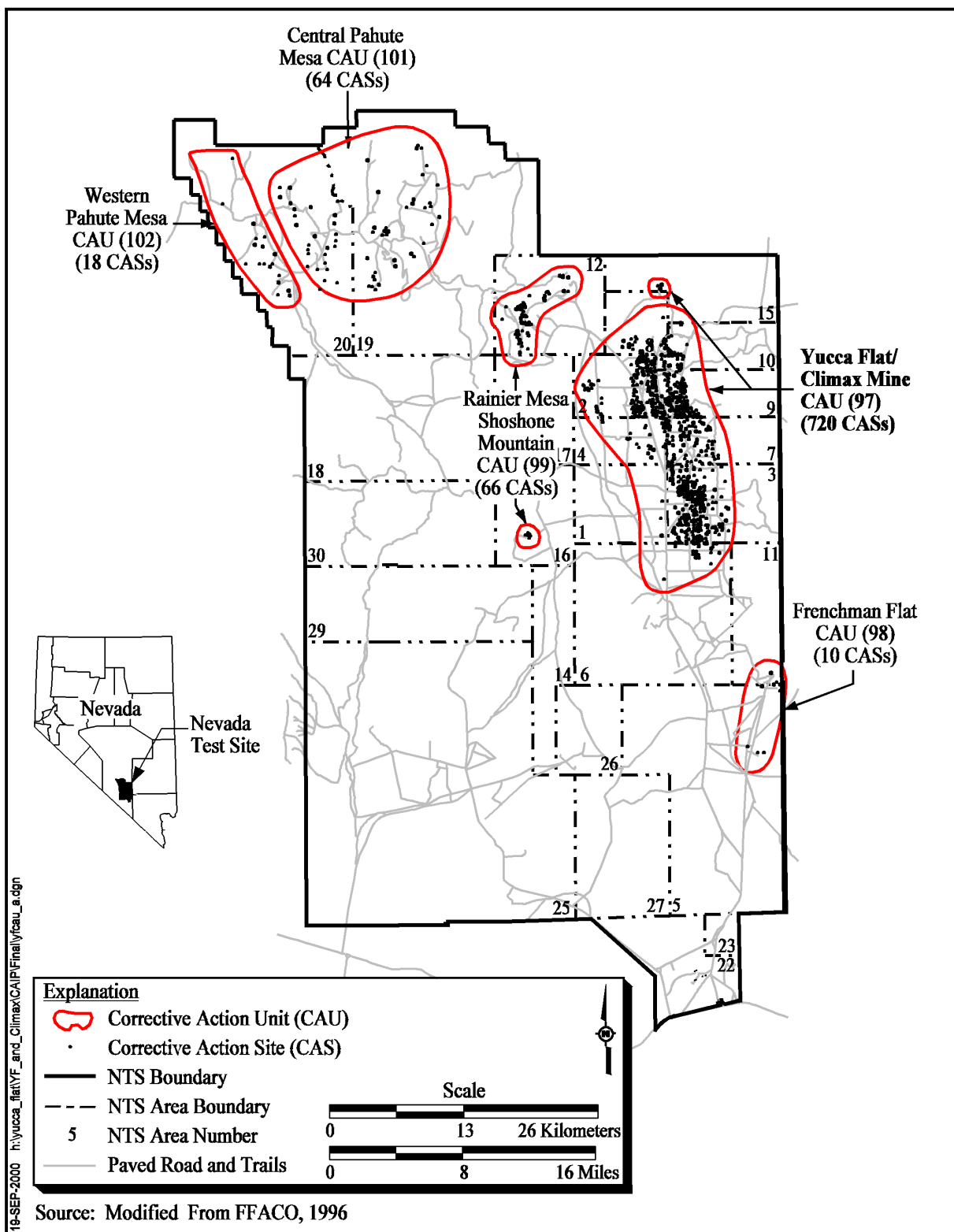


Figure 1-1
Location of the Yucca Flat/Climax Mine Corrective Action Unit
and Corrective Action Sites at the Nevada Test Site

also predict that contaminants from Climax Mine tests would enter the Yucca Flat groundwater flow system within the 1,000-year period of interest.

Additional considerations for addressing the two CAUs jointly include reductions in administrative costs and classification issues. As the result of these considerations, the U.S. Department of Energy, Nevada Operations Office (DOE/NV) has determined that the best way to proceed is to investigate the two CAUs simultaneously and, therefore, requested the two CAUs be combined by adding the Climax Mine Corrective Action Sites (CASs) to CAU 97. This request was accepted by the Nevada Division of Environmental Protection (NDEP) on March 21, 2000 (Liebendorfer, 2000).

The Yucca Flat/Climax Mine CAI will be conducted by the UGTA Project which is a part of the DOE/NV Environmental Restoration Project (ERP). The purpose and scope of the CAI are presented in this section, followed by a summary of the entire document.

1.1 Purpose

Based on the general definition of a CAI from Section IV.14 of the FFACO, the purpose of the CAI is “...to gather data sufficient to characterize the nature, extent, and rate of migration or potential rate of migration from releases or discharges of pollutants or contaminants and/or potential releases or discharges from corrective action units identified at the facilities...” (FFACO, 1996). For each UGTA CAU, a contaminant boundary delineating the portion of the groundwater system that may be unsafe for domestic and municipal use will be established (Appendix VI, FFACO [1996]). According to the UGTA strategy (Appendix VI of the FFACO), the CAI of a given CAU starts with the evaluation of existing data, and new data collection activities are generally contingent upon the results of the CAU modeling and may or may not be part of the CAI. The term “CAU model” as used in this document means groundwater flow and contaminant transport model for the Yucca Flat/Climax Mine CAU. Any other types of models referred to in this document are explicitly stated. However, the Yucca Flat/Climax Mine CAI includes new data collection prior to initiation of the CAU modeling to fill relevant data gaps identified during the regional evaluation (DOE/NV, 1997c) and the Yucca Flat/Climax Mine Value of Information (IT, 1999c).

Specific objectives of the CAI are as follows:

- Determine the characteristics of the groundwater flow system, the sources of contamination, and the transport processes to acceptable levels of uncertainty.
- Develop a credible numerical model of groundwater flow and contaminant transport for the Yucca Flat/Climax Mine CAU and downgradient areas.
- Develop stochastic predictions of the contaminant boundary at an acceptable level of uncertainty. Stochastic predictions are made using random sampling methods such as the Monte Carlo method. Numerous sets of model input parameters are sampled from estimated statistical distributions and used to predict a range of possible locations of the contaminant boundary. The range of possibilities for the location of the contaminant boundary reflects the uncertainties associated with the input parameters and defines the uncertainty associated with the location of the contaminant boundary.

1.2 Scope

The current scope of the Yucca Flat/Climax Mine CAI includes the following activities:

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

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

The CAU-scale groundwater flow and contaminant transport model will be constructed for an area encompassing the Yucca Flat/Climax Mine CAU. The potential CAU-model area encompasses the

Yucca Flat/Climax Mine CAU, Northwestern Frenchman Flat, CP Basin, Rock Valley, and the Amargosa Desert (Figure 1-2). The extent of the CAU-model area will be finalized after the data have been assessed. The final CAU-model area will depend on the predicted extent of contamination. The area of investigation encompasses the potential CAU-model area (Figure 1-2) and extends from the northeastern NTS boundary to the Amargosa Desert. It includes the Yucca Flat/Climax Mine CAU, northwestern Frenchman Flat, CP Basin, Rock Valley, and the Amargosa Desert (Figure 1-2). The area of investigation is defined as the region over which existing data will be collected and summarized for possible inclusion in the CAU modeling. This area is intentionally large and is intended to include all possible pathways for radionuclide migration from the Yucca Flat/Climax Mine CAU. The extent of the investigation area is not expected to increase during the CAI. However, if any increases do occur, NDEP will be informed.

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

1.3 Summary of the CAIP

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

1.3.1 Overview of Technical Elements of CAIP

The Yucca Flat/Climax Mine CAI will be conducted by DOE/NV with close involvement of NDEP throughout the entire process. The CAI will be conducted in five major sequential steps designed to be consistent with the UGTA strategy described in Appendix VI of the FFACO (1996) and summarized in Section 2.1.2 of this document. Figure 1-3 summarizes the five major steps and references the sections of the CAIP in which they are discussed. Documents generated to report on the technical findings of the CAI are also described at the end of this section.

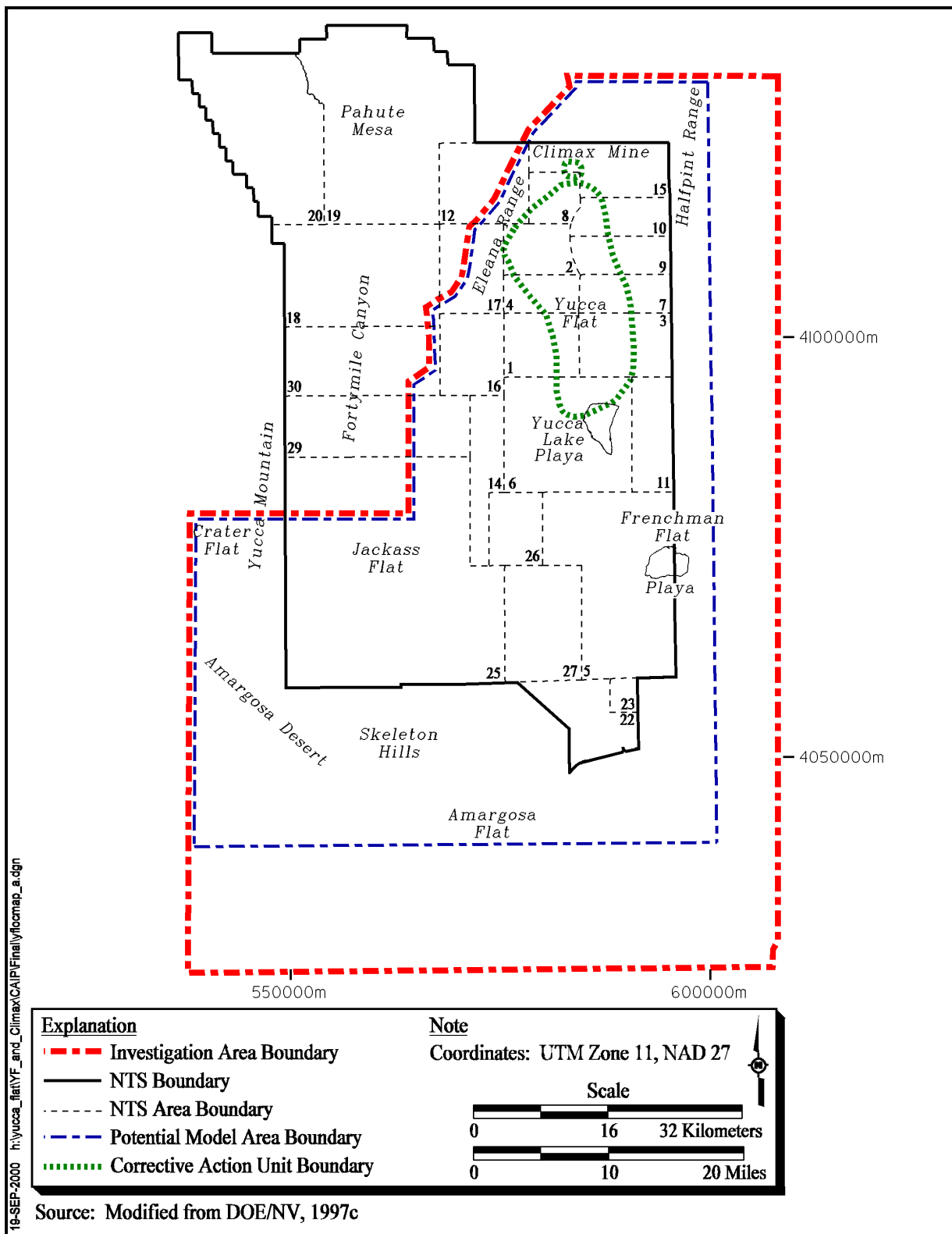


Figure 1-2
 Locations of the Yucca Flat/Climax Mine Investigation Area and Potential Model Area

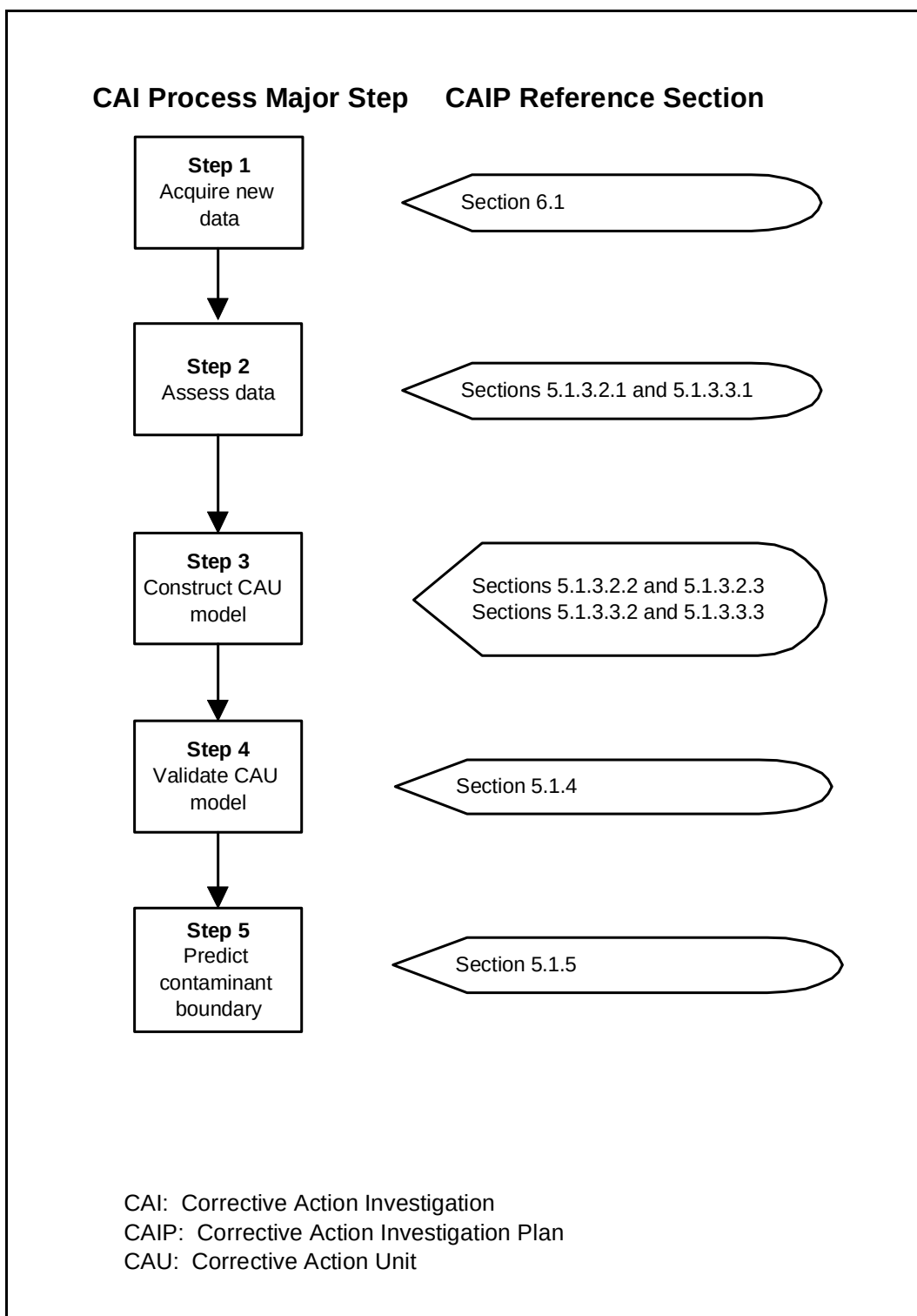


Figure 1-3
Overview of Technical Elements of the Yucca Flat/Climax Mine CAIP

1.3.1.1 Characterization Activities

Several characterization activities are included in the CAI to collect new data designed to reduce existing uncertainties in the current conceptual model. These following CAI activities were defined using the Data Quality Objectives (DQOs) process described in [Section 4.0](#), [Section 6.1](#), and [Appendix A](#):

- Mineralogy Study of the Tuff Confining Unit (TCU)
- Geophysical Interpretation of the Paleozoic Framework
- Analysis of Existing Seismic Data
- Hydrogeologic Investigation of Wells ER-6-1 and ER-6-2
- Isotope/Geochemistry Mass Balance Studies
- Analysis of Existing Tracer Test Data
- Laboratory Studies of Transport Processes
- Rainier Mesa Colloid Studies
- Analysis of Data for Phenomenological Models

These characterization activities will be conducted prior to the start of modeling. The plans for these activities are described in detail in [Section 6.0](#).

1.3.1.2 Assessment of CAU-Related Data

Following completion of the characterization activities, the existing and newly acquired data will be assessed, and used to refine the current conceptual groundwater flow and transport model. The existing data described in [Section 3.0](#) will be supplemented with historical data acquired from public and private sources and data from on-going characterization and monitoring programs not assessed before. All relevant published and unpublished existing data will be considered. The newly acquired data are those gathered during the characterization activities described in [Section 6.0](#). The new data will be added to the existing datasets prior to the data assessment activities. The data assessment activities are described in [Sections 5.1.3.2.1](#) and [5.1.3.3.1](#). The results of the data assessment process will be reported in two documentation packages. The first package will document the assessment of geologic data and the second groundwater data.

1.3.1.3 Development of Numerical Groundwater Flow and Transport Model

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

The CAU model will simulate groundwater flow and contaminant transport under transient conditions. The scale of this model will be large, up to 100 kilometers (km) (6.2 miles [mi]). The procedure that will be followed to develop the CAU groundwater flow and contaminant transport model is detailed in [Sections 5.1.2](#) and [5.1.3](#).

Other models to be used in support of the CAU model include:

- Hydrologic models at scales ranging from small (less than 1 km) to intermediate (about 10 km) to investigate specific hydrogeologic features at smaller scales than that of the CAU model
- A near-field model (small-scale) to simulate the hydrologic source term
- The NTS regional groundwater flow model to help estimate boundary conditions for the CAU model
- A random field generator to simulate hydraulic conductivity fields for use in the small- and possibly the intermediate-scale groundwater flow models

Brief descriptions of these models and their use in support of the CAU model are provided throughout [Sections 5.1.2](#) and [5.1.3](#). More detailed descriptions are provided in [Section 5.2](#).

1.3.1.4 Verification of Numerical Groundwater Flow and Contaminant Transport Model

When the CAU model is completed, it will be evaluated by a peer review panel, DOE/NV, and NDEP. If DOE/NV and NDEP do not provide written justification for rejecting the CAU model, a model verification plan will be prepared and submitted to NDEP as an addendum to this CAIP. Once the model verification plan is approved, it will be implemented. In the event that the CAU model is rejected, DOE/NV and NDEP will initiate discussions to identify the appropriate path forward. Activities relating to this step are detailed in [Section 5.1.4](#).

1.3.1.5 Prediction of Contaminant Boundary

The CAU model will be used to simulate a contaminant boundary proposed by DOE/NV and negotiated with NDEP. A postaudit of the CAU model will be performed to verify the validity of the results during the five-year proof-of-concept period. This process is detailed in [Section 5.1.5](#).

1.3.1.6 CAI Documentation

The Yucca Flat/Climax Mine CAI activities will be reported in several data reports: three documentation packages, a CAU-model report, and the Corrective Action Decision Document (CADD) as follows:

- Data reports will describe the results of the characterization activities.
- Volume I of the CAU-model documentation will describe the assessment of geologic data and describe the resulting hydrostratigraphic model.
- Volume II of the CAU-model documentation will describe the assessment of groundwater data including hydrogeologic data, and contaminant transport data.
- Volume III of the CAU-model documentation will describe the results of the modeling activities.
- The CAU model report will summarize the contents of the three documentation packages.
- The CADD is a FFACO document which will discuss the findings of all CAI activities, including the CAU model, its verification, and the contaminant boundary predictions. In addition, the CADD will describe the corrective action alternatives considered and the selected alternative.

1.3.2 Document Organization

As required by the FFACO, this CAIP provides or references all of the specific information used for planning the investigation activities associated with the Yucca Flat/Climax Mine CAU. Specific information required by the FFACO and provided or referenced in this CAIP include managerial and technical aspects, quality assurance, health and safety, public involvement, field sampling, and waste management (FFACO, 1996). The organization and contents of this document are based on an annotated outline agreed to by DOE/NV and NDEP (Liebendorfer, 1998). This document consists of nine sections and one appendix, summarized as follows:

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

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

2.0 Legal/Regulatory Requirements

The State of Nevada, DOE, and DoD have negotiated the *Federal Facility Agreement and Consent Order* to address environmental restoration activities at DOE/NV facilities and sites. The FFACO is the primary regulatory driver for DOE environmental restoration activities in Nevada. Part III of the FFACO (1996) identifies the legal authorities under which the DOE and NDEP entered into the agreement. The FFACO and other regulatory requirements that may be applicable to the Yucca Flat/Climax Mine CAI are discussed in this section.

2.1 Federal Facility Agreement and Consent Order

This section includes a summary of the FFACO requirements and the UGTA corrective action strategy as described in the FFACO (1996). The application of the strategy to the Yucca Flat/Climax Mine CAU is also presented.

2.1.1 FFACO Requirements

The FFACO requirements that are applicable to the Yucca Flat/Climax Mine CAU are discussed in this section.

2.1.1.1 General Requirements

The FFACO sets the framework and contains the requirements for prioritizing and enforcing the environmental restoration activities of contaminated DOE/NV facilities and sites. Technical strategies for these activities are also provided in the FFACO. The DOE, through the UGTA Project, is responsible for completing corrective actions for six CAUs associated with historical underground nuclear testing on the Nevada Test Site. The UGTA CAUs are Frenchman Flat, Western Pahute Mesa, Yucca Flat, Central Pahute Mesa, and Rainier Mesa/Shoshone Mountain. The CAUs were defined based on geography and hydrogeologic characteristics.

Several plans and reports are required to document the corrective action process. These documents provide details about the activities needed to ensure the completion of the corrective action.

Documents that are applicable to UGTA CAUs include the following:

Corrective Action Investigation Plan

This is a FFACO-required document which provides or references all specific information for planning investigation activities associated with corrective action units or sites.

Corrective Action Decision Document

This is a FFACO-required report that documents the corrective action investigation. It describes the results of the CAI, the selected corrective action, and the rationale for its selection.

Corrective Action Plan

This is a FFACO-required planning document that describes the Corrective Action Plan (CAP) and explains the corrective action completion process.

Closure Report

This FFACO-required report documents the corrective action completion process and verifies the corrective action was conducted in accordance with the approved corrective action plan. It also provides all necessary supporting information. The Closure Report also provides information on post closure monitoring.

Notice of Completion

This is a State-issued document marking the completion of the corrective action in accordance with approved plans.

2.1.1.2 Specific Requirements

The Yucca Flat/Climax Mine CAI is planned and will be conducted in accordance with the appropriate investigation purposes of the *Federal Facility Agreement* and *Consent Order* as outlined in Subparts II.1.b.ii, II.1.c as well as the requirements of Subparts IV.14, and IV.15 (FFACO, 1996). Each of these specific subparts of the FFACO are quoted below, followed by a description of how their requirements are being fulfilled during the CAI.

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

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

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

As required by FFACO Subpart II.1.c., a preliminary list of radioactive and hazardous constituents for the Yucca Flat/Climax Mine CAU is provided in [Section 3.5](#) of this report. This list provides all parties with sufficient information to enable adequate evaluation of appropriate remedies and will be updated based on the findings made during the CAI.

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

In accordance with FFACO Subpart IV.14., the Yucca Flat/Climax Mine CAI will be conducted by DOE/NV to gather sufficient data to characterize the nature, extent, and rate of migration or potential rate of migration from releases or potential releases of contaminants from the Yucca Flat/Climax Mine CAU. This CAIP describes the planned investigation activities which include field data gathering ([Section 6.0](#)) and groundwater flow and transport modeling at the CAU scale ([Section 5.0](#)).

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

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

In accordance with FFACO Subpart IV.15, this CAIP provides or references all of the specific information for planning investigation activities associated with the Yucca Flat/Climax Mine Corrective Action Unit. This CAIP includes or references all of the management, technical, quality assurance, health and safety, public involvement, field sampling, and waste management information needed to conduct the investigations in compliance with established procedures and protocols as described in [Section 1.0](#).

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

2.1.2 Corrective Action Strategy

A summary of the UGTA strategy negotiated by DOE/NV and NDEP for UGTA (FFACO, 1996) is presented in the first part of this section. The DOE/NV and NDEP will work together throughout the implementation of the strategy for each of the UGTA CAUs, including the Yucca Flat/Climax Mine CAU. Upon approval of the CAIP and at the beginning of each fiscal year in which the CAI will be conducted, DOE/NV will inform NDEP of the planned activities for the CAI. The DOE/NV will facilitate any visits or meetings requested by NDEP to evaluate the CAI process presented in [Section 5.0](#) of this document. The DOE/NV will also identify when products will be available for transmittal to NDEP. The details of the implementation of the UGTA strategy is described in the following section.

2.1.2.1 Description of Corrective Action Strategy

The objectives of the UGTA strategy are to predict the location of the contaminant boundary for each CAU, develop and implement a corrective action, and close each CAU.

2.1.2.1.1 General Definition of Contaminant Boundary

The contaminant boundary has been defined in Appendix VI of the FFACO (1996) as follows:

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

Also, as explained in the FFACO (1996), uncertainties will be associated with the contaminant boundary predictions using the CAU models (FFACO, 1996). These uncertainties can be expressed as confidence levels as shown on [Figure 2-1](#). As explained in Appendix VI of the FFACO (1996):

“Each contour reflects an increased level of confidence that no contaminants exceeding a given regulatory concentration will ever cross that boundary. As confidence increases, the distance from the CAU increases. The confidence levels could lead to the development of different contaminant boundaries, depending on the degree of certainty decision makers need to select appropriate controls.”

The distance from the source of contamination (the CAU in [Figure 2-1](#)) to the contaminant boundary increases as the confidence level increases.

2.1.2.1.2 Process Description

The process used to achieve the strategy is defined in the flow diagram on page VI-3-6 of FFACO Appendix VI ([Figure 2-2](#)). The shaded portion of the diagram illustrates the portion of the process that will take place during the CAI. This strategy is based on two principal assumptions. The first assumption is that the strategy can be achieved using existing data and wells. The second assumption is that the proposed remedial option is long-term monitoring. However, the strategy does allow for deviations should these assumptions prove to be incorrect.

The first step in the strategy is to collect, assess, and evaluate the existing geologic, hydrologic, geochemical and isotope, and radionuclide information available for each CAU. If DOE/NV determines that sufficient data exist, then a CAU-scale groundwater flow and contaminant transport model is developed utilizing these data. If sufficient data do not exist, then DOE/NV can propose to collect additional data prior to developing the CAU model.

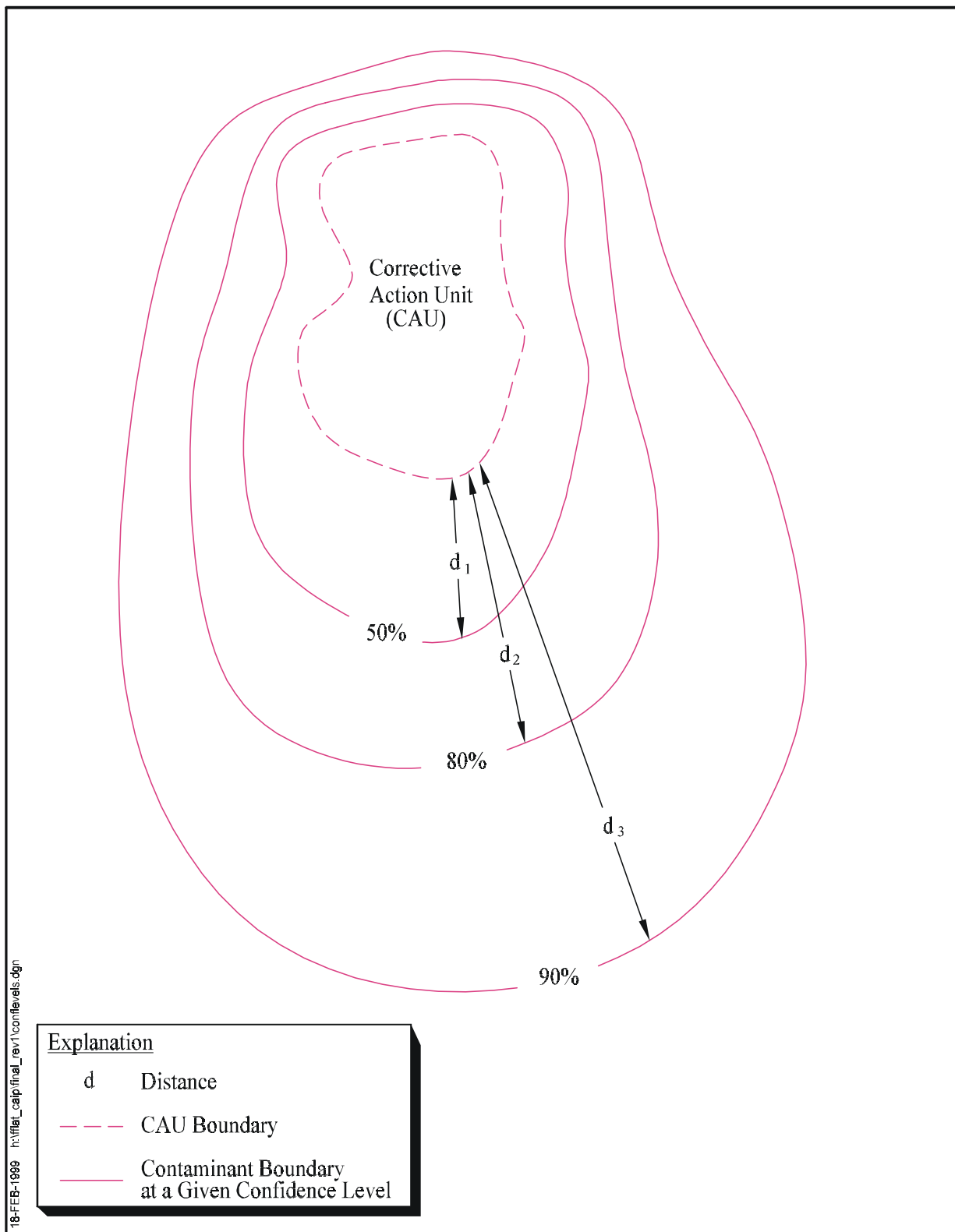


Figure 2-1
Example of Contaminant Boundary Confidence Levels

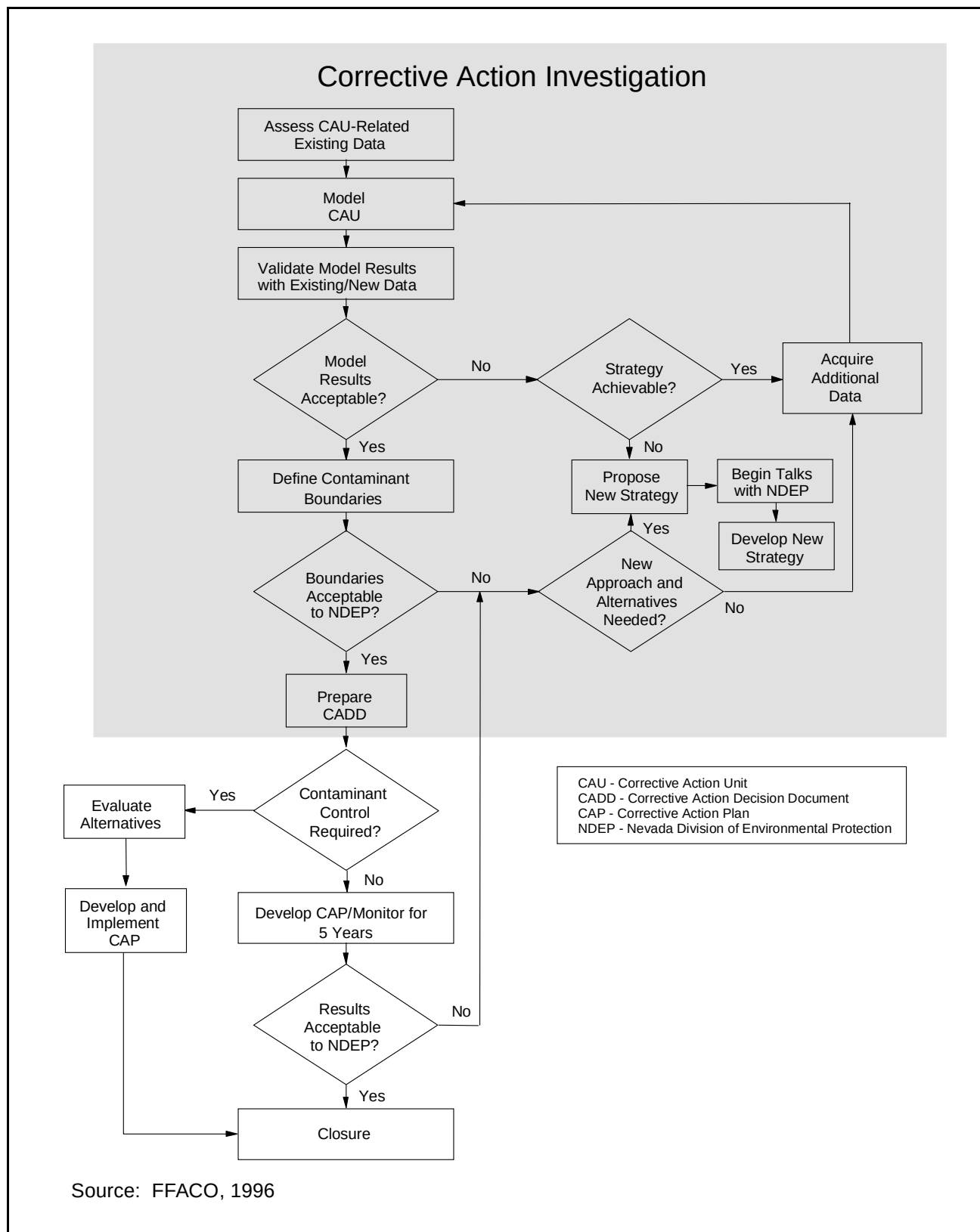


Figure 2-2
Decision Diagram for the Underground Test Area

The second step consists of developing a 3-D groundwater flow and transport model to define the maximum extent of contaminant transport at the CAU scale. Tritium and other radionuclides that are longer-lived will be evaluated to establish the contaminant boundary for each CAU. The boundary will define the maximum extent of contaminant transport in the horizontal direction as well as the lowest aquifer unit affected, as specified in the FFACO (1996). After completion, the CAU model will be presented to NDEP and evaluated by a peer review panel. If DOE/NV and NDEP do not provide written justification for rejecting the CAU model, it will be verified, and the contaminant boundary will be proposed by DOE/NV and negotiated with NDEP.

If the CAU model is rejected or the contaminant boundary cannot be agreed upon between DOE/NV and NDEP, then DOE/NV and NDEP will determine if the strategy, as defined in the FFACO (1996), is achievable. If the strategy can be achieved, DOE/NV will collect additional data. The new data will then be used in the CAU model, and the process will be repeated. If the strategy is not achievable, negotiations will be initiated to develop a new strategy.

After the contaminant boundaries have been defined and accepted, DOE/NV will evaluate various remedial alternatives and propose a corrective action. The CAU modeling results, contaminant boundary, and proposed corrective action will be documented in the CADD and submitted to NDEP for approval. After approval of the CADD, a CAP will be developed to implement the corrective action. If the corrective action is long-term monitoring, a five-year proof-of-concept period will be initiated. This proof-of-concept period will allow DOE/NV and NDEP to determine if the monitoring results support the CAU model. If the monitoring results are acceptable, a Closure Plan will be developed for the CAU. If the results are not acceptable, then DOE/NV and NDEP will need to determine if the strategy is still achievable or not.

2.1.2.2 Implementation of Corrective Action Strategy

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

2.1.2.2.1 Specific Definition of the Contaminant Boundary

The contaminant boundary is specifically defined as the maximum extent of contamination corresponding to a human dose of 4 millirems per year (mrem/yr) for radionuclides, or a concentration equal to drinking water standards (maximum contaminant levels) for other contaminants, at the 50 percent confidence level within a 1,000-year interval. The 4-mrem/yr dose regulatory limit is based on the *Safe Drinking Water Act* (SDWA) (1996), and may include multiple contaminants. The total dose is the sum of the doses of all contributing radionuclides using a drinking water scenario (Adams, 1996a and b). The individual contributions from each contaminant to the dose must be less than the regulatory limit.

2.1.2.2.2 Corrective Action Investigation

The CAI is led by the DOE/NV UGTA Project Manager. A Technical Working Group (TWG) was formed to assist the DOE/NV UGTA Project Manager with technical issues. The TWG consists of representatives from the participating organizations which are Bechtel Nevada (BN); Desert Research Institute (DRI); IT Corporation, Las Vegas (ITLV); Lawrence Livermore National Laboratory (LLNL); Los Alamos National Laboratory (LANL); and the U.S. Geological Survey (USGS). The TWG serves as a technical advisory group to the DOE/NV UGTA Project Manager. Tasks assigned to the TWG committee include providing technical recommendations to DOE/NV, providing expert technical support in specific UGTA tasks via subcommittees, and serving as internal peer reviewers of UGTA products.

The CAI consists of two major phases: planning and implementation. Both the planning and implementation of the CAI rely on the use of the regional groundwater flow and transport model (DOE/NV, 1997c). The two phases of the CAI are described in the following sections. Descriptions of how the regional model is used during the CAI are also provided.

Planning

As stated in the FFACO strategy and in [Section 2.1.2.1](#) of this report, the scope of the CAI consists of developing a CAU model with existing data and predicting the location of the contaminant boundary. However, to evaluate whether additional data are needed, the CAI is planned using the DQO process, which ensures that the type, quantity, and quality of environmental data used in the decision-making

process are appropriate for the intended application (EPA, 1993 and 1994). To support the DQO process, the regional model is used to identify areas of uncertainties associated with the groundwater flow system and transport processes of a given CAU. In addition, a Value of Information Analysis (VOIA) is performed to support the DQO process. The VOIA is a management tool intended to help decision makers evaluate cost-effective, information-collection options to reduce existing uncertainties. A description of the Yucca Flat DQO process including a summary of the VOIA is provided in [Appendix A](#). The detailed Yucca Flat VOIA methodology and results have been described by IT (1999c).

During the VOIA, results of the transport simulations performed using the regional model are used to identify sensitive parameters. An input parameter is said to be sensitive if a given change in its value causes a large change in the model results. Conversely, a parameter is said to be insensitive if a given change in its value causes little change in the model results. Transport simulations used include the tritium transport simulations described in the regional evaluation report (DOE/NV, 1997c) and the results of transport simulations for other radionuclides of concern. The radionuclides of concern for the Yucca Flat/Climax Mine CAU were identified by the VOIA Subcommittee of the UGTA TWG. This subcommittee also proposes various data collection options. This group then estimates how much each of the data collection options will reduce the uncertainty in the model results. This estimated reduction in uncertainty is then combined with the estimated cost of the data collection option, and a cost-benefit analysis is performed on all of the options.

The results of the VOIA are then used to evaluate the benefit of collecting additional data prior to developing the CAU model. However, some data-collection activities can be identified prior to the VOIA, using only the regional model sensitivity analysis. For example, the decision to drill new wells in an uncharacterized area can be made without the benefit of the VOIA if the results of the regional model are highly sensitive to the geology and hydrology of that area. The UGTA Project Manager uses the results of the regional model and those of the VOIA to design a program to collect the appropriate data for the CAU-scale model.

Implementation

If, during the planning process, it is decided that no new data are necessary to develop the CAU model, the CAI is initiated with the modeling activities. The CAU modeling process consists of

model (code) selection, groundwater flow model development, contaminant transport model development, sensitivity and uncertainty analyses, model result verification, contaminant boundary prediction, and postaudit. Other models of varying scales may also be used in support of the CAU model. The modeling process proposed for Yucca Flat is described in [Section 5.0](#).

The process begins with the selection of the groundwater flow and transport code, based on a predefined set of criteria. Several candidate codes have previously been identified for potential use in the UGTA Project (IT, 1998a). For the Yucca Flat/Climax Mine CAI, the FEHM code will first be tested using a problem representative of the area of interest. If the test yields desired results, FEHM will be used; if not, the code selection process described in the UGTA modeling approach document (IT, 1998a) will be applied. The list of candidates will be refined and updated at the time the CAI is initiated and three codes will be selected for further evaluation. These codes will be tested using a sample problem, and the results of this test will lead to the selection of the code to be used. The CAU model must have the ability to represent the important physical and chemical features of the CAU flow system. These features include faulting, stratigraphy, sources and sinks of water, the distribution of contaminants and their rates of introduction into the flow system, and other physical and chemical features characteristic of the CAU. The selected code must also be able to simulate the movement of a variety of contaminants and possess the flexibility to allow grid changes and boundary condition variations.

After a code is selected, the groundwater flow model is developed. This consists of groundwater data assessment, model setup, and model calibration. Existing geologic and hydrologic data are then compiled and evaluated, and a hydrostratigraphic model is constructed using these data including surface and subsurface geologic and geophysical data obtained from boreholes within or near the CAU-model boundary. This hydrostratigraphic model, along with the hydrologic data, is then used to develop the CAU-scale groundwater flow model. The regional groundwater flow model is used to define boundary conditions and initial estimates of areal recharge for the CAU-scale groundwater flow model. Hydraulic conductivity data obtained from aquifer tests conducted in the CAU or the relevant nearby region are used to define an initial distribution. Water level information from boreholes in and near the CAU is used to calibrate and verify the groundwater flow model.

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

After the CAU-scale groundwater flow and contaminant transport model is developed, sensitivity and uncertainty analysis will be performed. The uncertainty analyses will include evaluating the impacts of alternative geologic interpretations and the use of smaller-scale groundwater flow and contaminant transport models to evaluate potential failure scenarios. The CAU model will be presented to a peer review panel, DOE/NV, and NDEP for review. If DOE/NV and NDEP do not provide written justification for rejecting the CAU model, a plan for verifying the CAU model will be presented to NDEP for review. Once the model verification plan is approved, it will be implemented. In the event that the CAU model is rejected, DOE/NV and NDEP will initiate discussions to identify the appropriate path forward.

The CAU model will be used to predict the location of the contaminant boundary. Various remedial alternatives will be evaluated and a recommendation made based on the established boundaries. If the recommendation is long-term monitoring, a monitoring network will be designed.

If, at any time during the process, it is determined that additional data are needed, a plan for collecting the information will be prepared as an addendum to the CAIP. This plan identifies the types of data needs and describes the work proposed to collect this information. Upon approval of the plan by NDEP, the information will be collected and used to develop the CAU model. Any data-collection activities conducted in support of the CAU model will be part of the CAI.

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

2.1.2.2.3 Corrective Action Implementation and CAU Closure

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

3.0 Description of Corrective Action Units

This section includes a description of the Yucca Flat/Climax Mine CAU. The investigative background and operational history of the area are presented first. The corrective action sites are then listed along with their specific attributes. Descriptions of the physical setting, contaminants, and conceptual model of the CAU are then provided based on a preliminary evaluation of the existing information. Finally, the preliminary action levels for the major potential contaminants considered in the CAI are presented.

3.1 Investigative Background

Investigations of the Yucca Flat/Climax Mine area, and the surrounding region have taken place from the late 1950s to the present. These studies have ranged in scope from investigations that encompass all of the NTS, to studies of individual exploratory holes associated with specific nuclear tests in Yucca Flat and Climax Mine. These investigations relate to both the surface and subsurface. Surficial data have been obtained from a network of stations and various land surface investigations. Subsurface data have been obtained from a host of existing boreholes and springs. A selected number of 468 boreholes and 136 springs located within the Yucca Flat/Climax Mine investigation area were utilized during the regional evaluation of the underground test areas of the NTS (DOE/NV, 1997c; IT, 1996c-h; and IT, 1997b and c) ([Figure 3-1](#)). Information on the subsurface is also available from several nonintrusive investigations. A number of investigations conducted in other areas of the NTS or other sites may also be relevant to the Yucca Flat/Climax Mine CAI. Sources of information include: USGS, DRI, LLNL, LANL, BN, ITLV, and related literature.

An overview of the most notable investigations relevant to understanding the subsurface of the Yucca Flat/Climax Mine area and the effects of underground nuclear testing on groundwater is provided in this section. Subject areas of interest to the problem at hand are: precipitation and recharge, topography, geology, groundwater, groundwater chemistry, radiochemistry, and migration processes. Each of these areas are discussed following a description of general information of interest to this CAI. The available information derived from the investigations cited here is summarized in [Section 3.3](#) of this document.

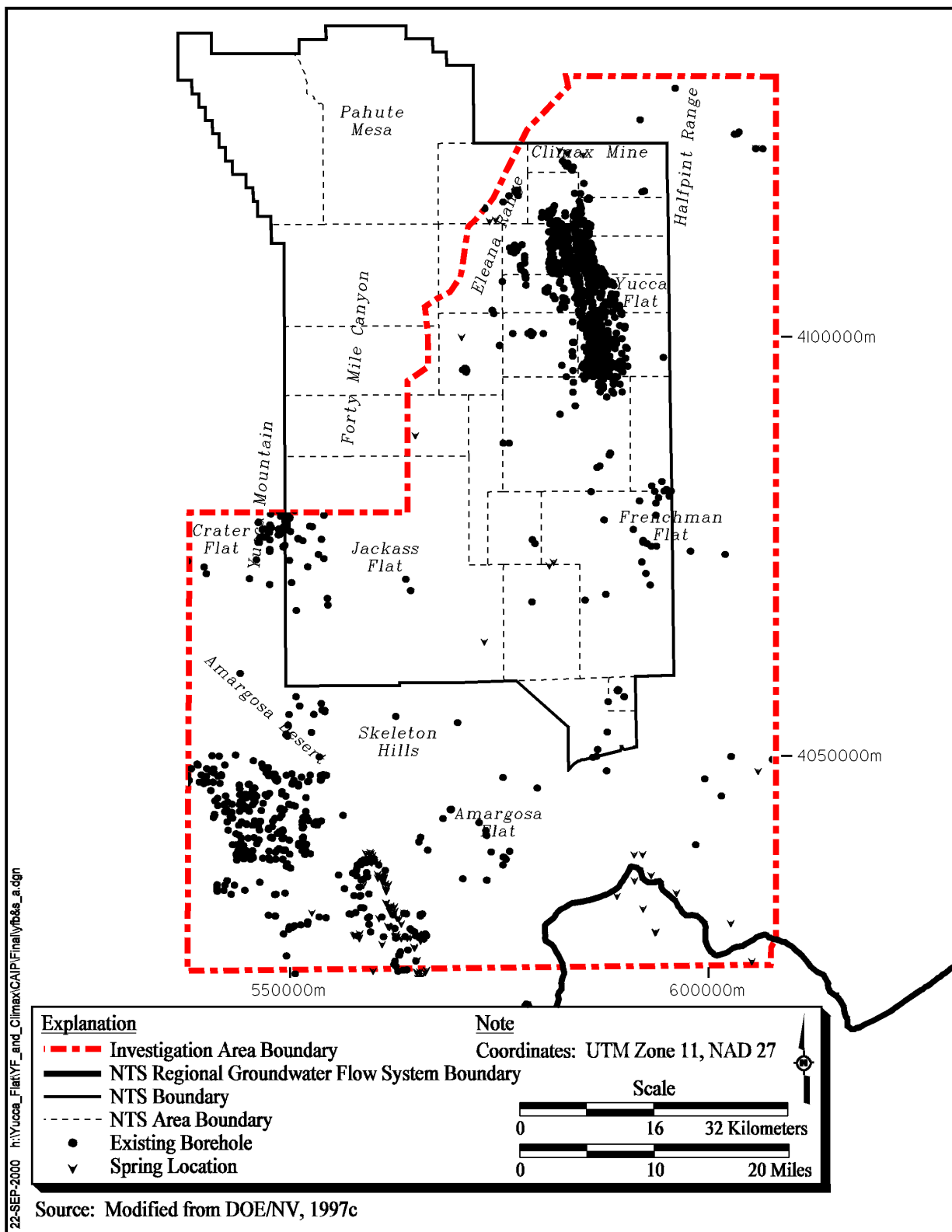


Figure 3-1
Location of Existing Boreholes and Springs Within the
Yucca Flat/Climax Mine Investigation Area

UNCONTROLLED When Printed

General Information

Several documents prepared for the NTS and the UGTA are also relevant to the Yucca Flat/Climax Mine CAI. Two documents which cover the scope of the Yucca Flat/Climax Mine investigation program were developed to satisfy *National Environmental Policy Act* (NEPA) requirements: the NTS site-wide Environmental Impact Statement (DOE/NV, 1996d) and an UGTA project-specific environmental assessment (DOE/NV, 1992). Checklists to ensure compliance with NEPA (1996) will be prepared in support of the planned field activities, as appropriate. No scheduling impacts are expected from the preparation of the NEPA documents. Another report summarizing the results of a focused evaluation of remedial alternatives was also prepared for UGTA (DOE/NV, 1997b).

Although some studies have dealt with migration of various radionuclides, no assessment of human health risk has been completed for the Yucca Flat/Climax Mine area. A regional risk assessment of the UGTA was completed in 1997 (DOE/NV, 1997c).

Precipitation and Recharge

Precipitation is important to groundwater recharge. Researchers at DRI have been investigating precipitation and groundwater recharge at the NTS, and their studies focus on defining precipitation distribution, identifying areas of significant surface runoff, estimating the amount of surface runoff, identifying areas of significant groundwater recharge, and estimating the rates of groundwater recharge (French, 1985).

The DRI researchers developed a digital precipitation database in 1964 (French, 1985) and data for various precipitation stations on the NTS were published in a report by French (1986). In a followup study (French, 1987), researchers investigated the effects of the length of record on estimated annual and seasonal precipitation at the NTS. Ingraham et al. (1990) evaluated the stable isotopic composition of precipitation. Studies relating to infiltration and recharge include those conducted by Doty and Rush (1985), Tyler et al. (1992), McKinnis and Kao (1993), and Hockett and French (1998). Doty and Rush (1985) studied inflow to a crack in playa deposits of Yucca Lake. Tyler et al. (1992) investigated infiltration through the U-3fd crater in Area 3 of the NTS. McKinnis and Kao (1993) studied the potential for infiltration through fractured alluvium in Yucca Flat, while Hockett and French (1998) studied the recharge potential at Crater U5a (WISHBONE).

Researchers at the USGS have also been investigating precipitation and groundwater recharge as a part of the Yucca Mountain Project. An estimate of the NTS regional recharge is also available in the Yucca Mountain regional groundwater flow model report (D'Agnese et al., 1997).

Topography

Topographic information is used to locate sites, delineate the top of the geologic domain of a given area, provide reference points for depth-to-water measurements, and plan field activities. The USGS is the main source for topographic information for the NTS region, including the Yucca Flat/Climax Mine area. Topographic maps for the investigation area may also be available from the U.S. Bureau of Land Management (BLM).

Surface topographic information is available from the USGS in the form of Digital Elevation Models (DEM) and topographic maps at various scales. Digital Elevation Models providing land surface elevation data with 90-meter (m) (295-foot [ft]) resolution (USGS, 1987) have been used to delineate the top of the regional geologic model (IT, 1996f). Various topographic maps are also available from the USGS.

Topographic maps at the 1:24,000 scale are the most accurate available and may be used to obtain critical elevation data, such as elevations of springs, stream channels, evapotranspiration areas, and wells if not surveyed. The following 7.5' topographic quadrangle maps, which provide coverage for the Yucca Flat/Climax mine area and immediate vicinity, were identified from the topographic index map (USGS, 1997):

- Plutonium Valley Quadrangle, Nye County, Nevada
- Yucca Lake Quadrangle, Nye County, Nevada
- Mine Mountain Quadrangle, Nye County, Nevada
- Paiute Ridge Quadrangle, Nye County, Nevada
- Yucca Flat Quadrangle, Nye County, Nevada
- Tippipah Spring Quadrangle, Nye County, Nevada
- Jangle Ridge Quadrangle, Nye County, Nevada
- Oak Spring Quadrangle, Nye County, Nevada
- Rainier Mesa Quadrangle, Nye County, Nevada

Publications describing the effects of nuclear testing on the topography of the Yucca Flat/Climax Mine area include three maps prepared by the U.S. Geological Survey (1990), titled: “*Composite*

Post-shot Surface Effects Map for Yucca Flat.” Allen et al. (1997) also described the surface effects at underground nuclear explosions on the NTS.

Geology

Geologic information is necessary to conceptualize the physical framework of the groundwater flow system. A preliminary interpretation of the geologic framework of the Yucca Flat/Climax Mine subsurface was made as part of the regional evaluation (IT, 1996f; DOE/NV, 1997c). A summary of this interpretation and the supporting information are presented in [Section 3.4.4](#).

Geologic frameworks are usually interpreted from a host of geologic information available in the form of borehole data, surface geophysical surveys, and various maps and reports. The regional geologic framework was constructed using numerous maps and reports which are cited in the *Regional Geologic Model Documentation Package* (IT, 1996f).

For the Yucca Flat/Climax Mine area, borehole data include lithologic logs, geophysical logs, and rock cores that may be obtained from the USGS core library or the literature. Reports containing borehole information that are available include those prepared by DOE/NV under the Weapons Testing Program, and those prepared under the ERP for new or recompleted wells. The USGS, LLNL, and LANL are the main sources of surface geophysical survey data for the Yucca Flat/Climax Mine investigation area.

The USGS and the Nevada Bureau of Mines are the main sources of geologic maps of the NTS region including the Yucca Flat/Climax Mine investigation area. Among the existing surficial geologic maps, the following are the most notable for the Yucca Flat/Climax Mine area and vicinity:

- “Geologic Map of Nevada, Southern Half,” Map 57, scale 1:500,000 (Stewart and Carlson, 1977)
- “Digital Geologic Map of the Nevada Test Site and Vicinity, Nye, Lincoln, and Inyo Counties, Nevada,” Scale 1:100,000 (Slate et al., 1999)
- “Geologic Map of the Paiute Ridge Quadrangle, Nye and Lincoln Counties, Nevada,” U.S. Geological Survey Geologic Quadrangle Map GQ 577, Scale 1:24,000 (Byers and Barnes, 1967)

- “Geologic Map of the Yucca Flat Quadrangle, Nye and Lincoln Counties, Nevada,” U.S. Geological Survey Geologic Quadrangle Map GQ 582, Scale 1:24,000 (Colton and McKay, 1966)
- “Geologic Map of the Plutonium Valley Quadrangle, Nye and Lincoln Counties, Nevada,” U.S. Geological Survey Geologic Quadrangle Map 384, Scale 1:24,000 (Hinrichs and Mckay, 1965)
- “Geologic Map of the Yucca Lake Quadrangle, Nye County, Nevada,” U.S. Geological Survey, GQ-1327, Scale 1:24,000 (McKeown et al., 1976)
- “Geologic Map of the Tippipah Spring Quadrangle, Nye County, Nevada,” U.S. Geological Survey, Quadrangle Map GQ-213, Scale 1:24,000 (Orkild, 1963)
- “Geologic Map of the Mine Mountain Quadrangle, Nye County, Nevada,” U.S. Geological Survey, Quadrangle Map GQ-746, Scale 1:24,000 (Orkild, 1968)

Other notable maps include that of Cole & Cashman (1997): “Geologic Map of the Mine Mountain Area, NTS, So. NV” and that of Cole (1997): “Major Structural Controls on the Distribution of Pre-Tertiary Rocks, NTS Vicinity, So. NV.”

Various reports on the geology of the area are also available. Winograd and Thordarson (1975) and Lacznia et al. (1996) described the regional geology of the NTS, including the Yucca Flat and Climax Mine areas. Caskey and Schweichert (1992) described the Mesozoic deformation in the NTS and Vicinity. Other studies have provided geologic data relating to specific areas of Yucca Flat and Climax Mine. Notable geologic studies include those conducted by Barnes et al. (1963), Hazelwood et al. (1963), and Williams et al. (1963) in support of a long-range USGS program to study the subsurface of the NTS. Barnes et al. (1963) synthesized the geologic data available at the time into a complete picture of the Yucca Flat geology. Hazelwood et al. (1963) reported on a series of geophysical investigations to improve the understanding of the structural geology of Yucca Flat. Williams et al. (1963) reported on the geologic investigations conducted at Yucca Flat. Ander (1984) investigated the rotation of late Cenozoic stresses in the Yucca Flat region. More recently, McCafferty and Grauch (1997) and Ponce (1997) presented surface geophysical survey data for the Yucca Flat/Climax Mine investigation area. Reports specific to the geology of the Climax Mine area include those of by Snyder (1977) and the USGS (1983). Other reports include those by Barnes et al. (1962) and Cole et al. (1989). Barnes et al. (1962) investigated the carbonate rocks east of Yucca Flat. Cole et al. (1989) studied the structural relations within the Paleozoic basement of the Mine

Mountain block in Yucca Flat. Comprehensive lists of geologic references used during the regional evaluation may be found in Appendices C5 through C9, C15, and E2 of Volume I of the regional evaluation documentation (IT, 1996f).

Hydrology

Understanding the hydrology of the groundwater flow system is important to understanding the transport of contaminants from the underground test area in groundwater. A preliminary interpretation of the hydrology of the Yucca Flat/Climax Mine subsurface was made as part of the regional evaluation (DOE/NV, 1997c; IT, 1996c through h; IT, 1997b; and IT, 1997c). The data supporting this interpretation are presented in [Section 3.4.5](#). This interpretation will be refined during the CAI data assessment activities as described in [Section 5.1.3.2.1](#).

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

Several notable studies have been conducted to understand the regional NTS groundwater flow system. Winograd and Thordarson (1975) discussed the regional hydrogeologic and hydrochemical framework of the NTS relative to the regional movement of water. They presented a comprehensive overview of the geologic, hydrologic and geochemical data available at the time in support of their interpretations. Waddell (1982) developed a two-dimensional, steady-state model of groundwater flow beneath the NTS region in support of the investigation of a potential nuclear waste repository at Yucca Mountain. Lacznia et al. (1996) described the hydrologic controls at work within the groundwater flow system of the underground test area and NTS region. The results of the regional evaluation of the underground test area were presented in a report titled *Regional Groundwater Flow and Tritium Transport Modeling, and Risk Assessment of the Underground Test Area of the Nevada Test Site, Nevada* (DOE/NV, 1997c). The purpose of this study was to perform a preliminary evaluation of the risks associated with the underground nuclear testing and to provide a foundation for the models developed for each CAU including the Yucca Flat/Climax Mine CAU. Another notable regional model was developed by D'Agnese et al. (1997) for the Yucca Mountain region. This model

covers almost the same area as the regional model developed for the underground test area (DOE/NV, 1997c).

In addition to the regional studies, there have been various studies on the local groundwater flow system of the Yucca Flat area. Examples of these reports include those by Walker (1962), Hess and Jacobson (1984), and Mihevc (1992). Hess and Jacobson (1984) investigated the hydrogeology of the NTS and southern Amargosa Desert including the Yucca Flat/Climax Mine area. Walker (1962) and Murray (1981) investigated the geohydrology of the Climax Stock area. Hydrologic data may be obtained from the National Water Information System (USGS, 1989) or from reports such as those of Arteaga et al. (1991) and Hale and Trudeau (1993), which contain compilation of hydrogeologic data from wells and test holes located on the NTS and vicinity. Other reports of interest are those of Hoover and Trudeau (1987) and Hawkins et al. (1987). Hoover and Trudeau (1987) discussed the high-fluid levels observed in drill holes located in Yucca Flat. Hawkins et al. (1987) presented geologic and hydrologic information on the Aleman (U3kz) Site and other sites in Yucca Flat.

Hydrologic data are also available for individual borehole locations. Recent such reports include the recompletion reports for Water Well 2 (DOE/NV, 1996c), Well UE-4t (DOE/NV, 1996b), Well UE-10j (DOE/NV, 1997a), and Well ER-6-1 (Gillespie, 1993). Comprehensive lists of publications used during the regional evaluation may be found in the reference lists of Volumes II, III, and IV of the regional evaluation documentation (IT, 1996e, c and d).

Groundwater Chemistry

Site-specific groundwater chemistry data are available from reports by Walker (1962), Schoff and Moore (1964), and Crow (1976). Robinson and Beetem (1965) presented groundwater chemistry data collected by the USGS from five water supply wells in Yucca Flat. Claassen (1973) summarized groundwater chemistry data obtained from 1957 through 1971 by the USGS in Yucca Flat. Perfect et al. (1995) compiled a digital database of groundwater chemistry data for the NTS region. Rose et al. (1997) have recently published chemical and isotopic data for groundwater sampling locations in southern Nevada including the NTS. Schoff and Moore (1964) provide one of the earliest interpretations of NTS groundwater with the purpose of predicting the direction of groundwater flow using chemistry data. Winograd and Thordarson (1975) conducted a detailed, site-wide evaluation of groundwater chemistry in the NTS area in which they used groundwater chemistry to evaluate

regional groundwater flow. Chapman and Lyles (1993) presented groundwater chemistry data collected by the DRI. Preliminary interpretations and supporting data are presented in [Section 3.4.6](#).

Data on stable isotopes at precipitation stations on the NTS and surrounding areas are presented in reports by Ingraham et al. (1990) and Milne et al. (1987). Ingraham and Taylor (1991) evaluated stable isotope systematics for large-scale hydrologic systems of California and Nevada. Benson and Klieforth (1989) present paleoclimatic implications of precipitation and groundwater stable isotope data in the NTS and Yucca Mountain region. Davisson et al. (1999) and Thomas (1999) provide regional-scale interpretations of stable isotopes in southern Nevada groundwater. Thomas (1996) and Thomas et al. (1996) estimated regional flow paths, groundwater age, and travel times based on mass-balance reaction modeling of flow system geochemistry and isotopic data.

Radiochemistry

Beginning in the mid-1970s, radionuclide concentration data in near-field groundwater have been obtained by Hydrologic Resources Management Program (HRMP). The HRMP data have been published in a series of annual progress reports prepared by LANL and LLNL. The individual reports are too numerous to list here, but are referenced as appropriate in [Section 3.4.7](#) where the available data are presented. Nimz and Thompson (1992) provide a summary of HRMP findings as of 1992.

The DOE/NV instituted the Long-Term Hydrological Monitoring Program (LTHMP) in 1972. This program was designed to monitor radionuclide concentrations in groundwater at selected well locations on the NTS and off-site well and spring locations in the vicinity of the NTS. Tritium results from the LTHMP are published in annual site environmental monitoring reports for the NTS. The LTHMP data are presented in [Section 3.4.7](#). The DOE/NV and its contractors have sampled and analyzed groundwater from NTS water-supply wells as part of an on-going annual environmental monitoring program. The results of the monitoring program, which include gross alpha and beta, isotopic plutonium, strontium-90 (^{90}Sr), and tritium, are also published in the annual site environmental monitoring reports for the NTS. The DRI has evaluated the occurrence of tritium in groundwater from wells on the NTS (Lyles, 1990 and Lyles, 1993).

3.2 Operational History

A summary of nuclear testing in general is presented followed by a description of the operational history of testing in Yucca Flat, including Climax Mine.

3.2.1 General

An overview of the purpose and phenomenology of underground nuclear tests is presented in this section.

The purpose of underground nuclear testing was to develop new nuclear weapons, as well as assess and evaluate the effects of nuclear explosions on military systems and other hardware (U.S. Congress, 1989). The primary objectives of underground nuclear testing were twofold: (1) to obtain the desired experimental information, (2) and to contain radioactive material to the subsurface environment rather than releases of contamination to the atmosphere. An average of 12 tests were conducted per year, which were either vertical drill hole tests or horizontal tunnel tests. The majority of vertical drill hole tests were conducted for the purpose of developing new weapon systems (U.S. Congress, 1989).

The testing of an underground nuclear explosion resulted in successive, physical phenomena that occurred within measured time frames. The time frames and corresponding phenomena that occur during the detonation of an underground nuclear explosion are summarized in the following text, based on a report prepared by the U.S. Congress (1989). A detailed description of the phenomenology of underground nuclear tests is presented in [Section 3.6.1.1](#).

- Within microseconds (one-millionth of a second), billions of atoms release their energy, which results in the creation of a powerful shock wave that spreads outward from the point of origin.
- Within tens of milliseconds (thousandths of a second), vaporization occurs that forms high-pressure steam and gas in the shape of a bubble that results in the formation of a cavity.
- Within tenths of a second, an expanded cavity and reduced internal pressure are evident. After a few tenths of a second, the cavity reaches its fullest potential in terms of its growth. The shock wave generated by the explosion, fractures and crushes the rock as it extends outward from the cavity. The shock wave eventually loses its strength and momentum and becomes too weak to continue to crush rock. Thus, the crushed rock is characterized by a compression and relaxation phase that results in seismic waves that move through the earth.

- Within a few seconds, molten rock collects, solidifies, and forms at the bottom of the cavity. Cooling results in a decrease in the cavity's gas pressure.
- Within minutes to days, cavity collapse occurs because of the decreased gas pressure, which causes the overlying rock that supports the cavity to weaken. A process referred to, as "chimneying" is a result of rock debris and loose rubble falling into the cavity causing the void area to move upward. "Chimneying" is continuous until one of the following occurs to the void region: (1) the void becomes completely filled with loose rubble, (2) the void's shape in conjunction with the stability of the rock can sustain the overloaded material, or (3) the chimney approaches ground surface.

3.2.2 Underground Nuclear Testing in the Yucca Flat/Climax Mine Area

The operational history of the Yucca Flat/Climax Mine CAU covers a 35-year time span. Six hundred fifty-nine underground nuclear tests were conducted in Yucca Flat between 1957 and 1992 (DOE/NV, 1994b). Three tests were detonated in Climax Mine in 1962, 1965, and 1966 (DOE/NV, 1994b). Between 1957 to 1992, approximately 659 tests and 747 detonations were conducted underground in Yucca Flat in Area(s) 1, 2, 3, 4, 6, 7, 8, 9, and 10. The yield ranged from zero/200 to 500 kilotons with a depth of burial range of 27 to 1,219 m (89 to 3,999 ft) (Allen et al. 1997). Only four tests conducted in Yucca Flat were considered high-yield detonations (U.S. Congress, 1989). The discussion includes the testing operation, the types of tests, the purpose of the tests, the test yield range, the on-site and off-site radioactivity releases from the tests, and the devices' depths of burial relative to the water table.

Nuclear tests are organized by named testing operations. The operation name refers to a series of underground nuclear tests conducted during a given fiscal year. Prior to 1976, the federal government's fiscal year began on July 1 and ended on June 30. Starting in 1976, the fiscal year was changed to begin on October 1 and end on September 30. As a result of this change, Fiscal Year 1976 was extended to end on September 30, 1976 (DOE/NV, 1994b). Testing in Yucca Flat began with Operation Plumbbob in 1957 and ended with Operation Julin in 1992. Testing in Climax Mine began with Operation Nougat in 1962, continued with Operation Whetstone in 1965, and ended with Operation Flintlock in 1966 (DOE/NV, 1994b).

The term "type of test" refers to the method of deployment of the nuclear device at the time of detonation. Although, nuclear devices were either airdropped or deployed in towers, tunnels, shafts, or craters, only shaft and tunnel detonations are relevant to the Yucca Flat/Climax Mine CAI. Shaft

detonations involved nuclear devices that were exploded at the bottom of a deep, mined or drilled vertical hole (DOE/NV, 1994b). Tunnel detonations involved a nuclear device that was exploded at the end of a horizontal drift mined into a mountain or a mesa (DOE/NV, 1994b).

Only shaft tests were detonated in Yucca Flat, while one test at Climax Mine was detonated in a shaft and the other two tests were detonated in tunnels. A shaft is a vertical drill hole that measures up to 3 m (10 feet) in diameter and from 183 m (600 ft) to more than 1.6 km (1 mile) deep (U.S. Congress, 1989). The purpose of these tests was to develop new weapon systems. One DoD test in particular, the HURON KING, was detonated to study the effects of radiation generated by a nuclear explosion on satellites (U.S. Congress, 1989). However, the yield range was less than 20 kilotons (DOE/NV, 1994b). All vertical emplacement tests were either conducted above or below the static water level (Allen et al., 1997).

Only one test was detonated in a shaft at Climax Mine; the other two tests were detonated in tunnels. The purpose of the horizontal tunnel test was to evaluate the effects, including radiation and ground shock, of various weapons on military hardware and systems (U.S. Congress, 1989). These tests were considered time-consuming and costly and, therefore, only conducted once or twice a year. Between 1962 to 1964, 3 underground tests and 3 detonations were conducted in Area 15 of Climax Mine. These tests are HARD HAT, TINY TOT, and PILE DRIVER (Allen et al., 1997). The yield range was 5.7 to 62 kilotons with a depth of burial range of 229 to 351 m (750 to 1,150 ft). The aforementioned were DoD tests that reported an accidental release of radioactivity only detected on site (DOE/NV, 1994b).

The term “yield range” refers to the total effective energy released in a nuclear explosion and is usually expressed in terms of equivalent tonnage of trinitrotoluene (TNT) required to produce the same energy release in an explosion. A kiloton yield range represents the energy of a nuclear explosion that is equivalent to the explosive power of 1,000 tons of TNT, and a megaton (Mt) is equivalent to one million tons of TNT (DOE/NV, 1994b). Yield ranges for some Yucca Flat tests were termed, low, intermediate, or slight. Between 1945 through 1963 a less-than-20-kt yield was defined as “low,” while a 20 to 200 kt yield range was referred to as “intermediate.” In a few cases, the term slight was used to indicate no yield information had been released. This term was used

without amplification (DOE/NV, 1994b). The maximum upper limit of the reported yield range for Yucca Flat is 500 kt, whereas that of the Climax Mine tests is 62 kt.

Nuclear devices were emplaced in one of four types of geologic medium in Yucca Flat and Climax Mine: alluvial deposits, Tertiary volcanics, carbonate rocks, or intrusives (I). The location of their emplacement is called the working point which could either be above, at, or below the water table. Underground nuclear tests conducted above the water table are further defined as being “near” the water table if their working points are located within 100 m of the water table. As shown in [Table 3-1](#), of the 744 tunnel and shaft nuclear detonations conducted in Yucca Flat, about 23 percent were conducted below or near the water table in Yucca Flat and Climax Mine combined. Specifics about the most notable of these detonations are provided in the following text.

Four hundred twenty-six tests were conducted in the alluvial deposits of Yucca Flat. Only two of these detonations were conducted below the water table: CABRILLO and FARALLONES. CABRILLO was conducted on March 7, 1975, under Operation Bedrock. This test had a yield range of 20 to 200 kt and was conducted at about 34 m (112 ft) below the water table. FARALLONES was conducted on December 14, 1977, under Operation Cresset. This test had a yield range of 20 to 150 kt and was conducted at about 98 m (321 ft) below the water table. Twenty six other detonations were conducted near the water table.

Three hundred fourteen underground nuclear detonations were conducted in the Tertiary volcanics of Yucca Flat. Seventy-four detonations were conducted below the water table, and sixty-four near the water table. The deepest detonations conducted in the volcanics at depths greater than 200 m (656 ft) below the water tables include: BILBY, LANPHER, SCANTLING, SANDREEF, TOPGALLANT, WAGTAIL, and STRAIT. The BILBY test, detonated under Operation Niblick, was unique as it was the first underground nuclear test reported felt in Las Vegas (DOE/NV, 1994b). STRAIT had the largest reported yield range in Yucca Flat (200 to 500 kt). It was conducted on March 17, 1976, under Operation Anvil, at a depth of 780 m below ground surface (bgs) (2,558 ft bgs) or 296 m (971 ft) below the water table.

Four tests were conducted in the carbonate units of Yucca Flat in the 1960s: HANDCAR, KANKAKEE, NASH, and BOURBON. However, all four tests were conducted above the water table. BOURBON is the only one of the four with a burial point located near the water table (41 m

Table 3-1
Summary Information on Underground Nuclear Tunnel and Shaft Detonations
Conducted within the Yucca Flat/Climax Mine CAU

	Yucca Flat	Climax Mine
Operational Period	1957 to 1992	1962 to 1966
Total Number of Detonations	744	3
Number Conducted Below Water Table	76	2
Number Conducted within 100 m of Water Table	91	0
Number Conducted in the Alluvial Aquifer	426	0
Number Conducted in the Volcanic Units	314	0
Number Conducted in the LCA	4	0
Number Conducted in Intrusive Units	0	3
Maximum Yield Range	200 to 500 kt	62 kt

[134 ft]). This test was conducted on January 20, 1967, under Operation Latchkey and had a yield range of 20 to 200 kt. Three tests were conducted in the intrusives of the Climax Stock: HARD HAT, PILE DRIVER, and TINY TOT. PILE DRIVER had the largest yield and was detonated on June 2, 1966. Two of the tests were conducted below the water table, PILE DRIVER was the deepest one, at 277 m (909 ft) below the water table.

Another group of tests are discussed relative to their historical uniqueness and significance. The first test conducted in Yucca Flat was the PASCAL-A test conducted on July 26, 1957, with a reported yield range of “slight.” The AZUL test, detonated on December 14, 1979, under Operation Tinderbox, destroyed the Peninsula device that was damaged during emplacement on October 23, 1975. The Peninsula device was not tested (DOE/NV, 1994b). The ALVA test (Operation Whetstone), FENTON test (Operation Flintlock), and SCUTTLE test (Operation Mandrel) were the only tests in which an accidental release of radioactivity was detected off site by an aircraft. The CYCLAMEN test, conducted under Operation Flintlock, included a heavy element experiment (DOE/NV, 1994b).

Three tests were conducted in which there was no nuclear yield. These tests, which include SAN JUAN (Operation Hardtack II), a safety experiment; COURSER (Operation Whetstone), a Joint US-UK test; and TRANSOM (Operation Cresset), a weapons related test; reported a zero yield. The TRANSOM nuclear device did not detonate, and was subsequently destroyed by the HEARTS (Operation Quicksilver) detonation approximately 16 months later (DOE/NV, 1994b). A total of six safety experiments, conducted under Operation Plumbbob, Operation Project 58, and Operation Hardtack II, reported no radioactive release detected nor any radioactivity detected off site. The DIVIDER test, detonated under Operation Julin, was significant as it was the last test detonated on the NTS prior to the October 2, 1992, unilateral moratorium on nuclear weapons testing (DOE/NV, 1994b). This test was conducted to ensure the safety of U.S. deterrent forces.

3.3 Corrective Action Sites

A total of 747 underground nuclear detonations were conducted shafts and tunnels in the Yucca Flat/Climax Mine CAU. Seven hundred and forty-four such detonations were conducted in Yucca Flat and three tests were detonated in the Climax Mine area. In the FFACO (1996), the underground nuclear tests were identified as corrective action sites either individually or as small groups. The locations of the CASs are shown in [Figure 3-2](#) and [Plate 1](#).

[Table 3-2](#) and [Table 3-3](#) identify each of the CASs of CAU 97 along with their individual features. Each table lists the CAS number, the emplacement hole name, the test name, the detonation date, the yield range, the depth of burial, the depth-to-water, the working point geology, and land surface elevation. Based on the data presented in [Table 3-2](#) and [Table 3-3](#), 78 tests were conducted below the water table, 91 tests within 100 m (328 ft) of the water table, and 578 tests above the water table.

3.4 Physical Setting

Descriptions of the physical features of interest to the Yucca Flat/Climax Mine CAI include climate, topography, geology, and groundwater hydrology. Other topics discussed are geochemistry, radiochemistry and contaminant migration. Summaries of the available data are also provided. The data summaries were mostly obtained from the regional evaluation report (DOE/NV, 1997c) and documentation packages (IT, 1996c through 1996h; IT, 1997b and c). In addition, information was obtained from other reports cited throughout this section. During the CAI, the current understanding

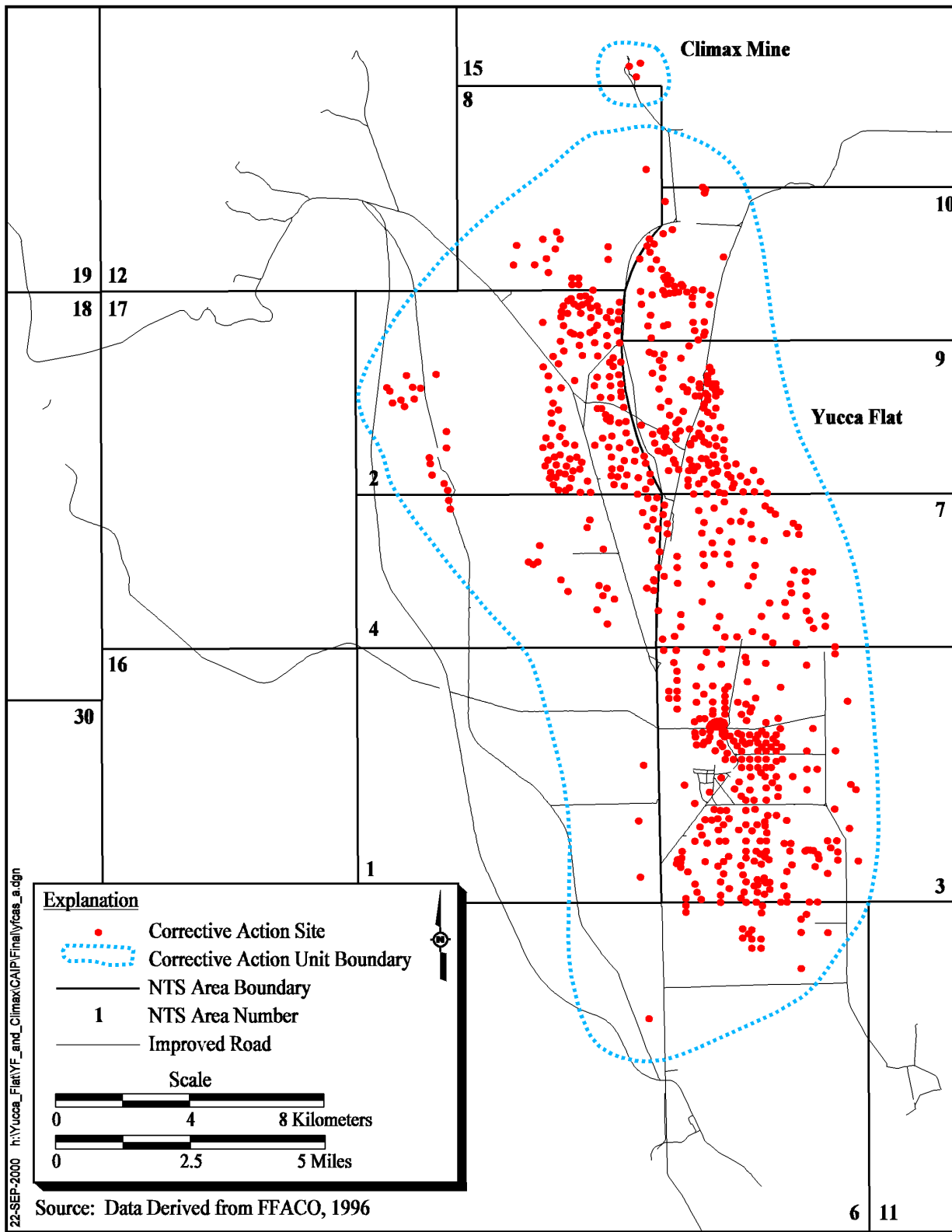


Figure 3-2
Location of Corrective Action Sites in the Yucca Flat/Climax Mine
Corrective Action Unit

Table 3-2
Corrective Action Sites in Yucca Flat
(Page 1 of 22)

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
01-57-001	U 1 A.01	LEDOUX	09/27/1990	<20	291	479.45	QTa	AA	1,217.98
01-57-002	U 1 C	YERBA	12/14/1971	<20	331.99	490.45	QTa	AA	1,228.68
01-57-003	U 1 D	SUNDOWN-A SUNDOWN-B	09/20/1990	<20	270.4	494.69	QTa	AA	1,233.53
02-57-001	U 2 A	ALPACA	02/12/1965	0.33	224.94	603.56	QTa	AA	1,341.79
02-57-002	U 2 AA	CLUB	01/30/1964	<20	180.75	559.34	QTa	AA	1,309.45
02-57-003	U 2 AB	TEE	05/07/1965	7	184.4	564.28	QTa	AA	1,309.82
02-57-004	U 2 AD	CASHMERE	02/04/1965	<20	233.17	549.92	QTa	AA	1,297.29
02-57-005	U 2 AF	KENNEBEC	06/25/1963	Low	226.16	553.88	QTa	AA	1,303.08
02-57-006	U 2 AG	MULLETT	10/17/1963	Low	60.35	552.03	QTa	AA	1,301.53
02-57-007	U 2 AH	PONGEE	07/22/1965	<20	134.72	553.07	QTa	AA	1,301.35
02-57-008	U 2 AI	DRILL-SOURCE (Lower)	12/05/1964	3.4	218.85	557.30	QTa	AA	1,306.5
02-57-008	U 2 AI	DRILL-TARGET (Upper)	12/05/1964	<20	188.37	557.30	QTa	AA	1,306.5
02-57-009	U 2 AK	CENTAUR	08/27/1965	<20	173.74	560.53	QTa	AA	1,310.34
02-57-010	U 2 AL	EMERSON	12/16/1965	<20	260.6	563.67	QTa	AA	1,307.38
02-57-011	U 2 AM	COMMODORE	05/20/1967	250	745.24	548.92	Tn	VCU	1,297.81
02-57-013	U 2 AN	TAPESTRY	05/12/1966	<20	248.72	557.48	QTa	AA	1,307.9
02-57-014	U 2 AO	FLOTOST	08/16/1977	<20	275	568.85	QTa	AA	1,311.04
02-57-015	U 2 AP	EFFENDI	04/27/1967	<20	220.98	559.86	QTa	AA	1,305.71
02-57-016	U 2 AR	ASIAGO	12/21/1976	<20	330.7	545.21	QTa	AA	1,291.97
02-57-017	U 2 AS	CLARKSMOBILE	05/17/1968	20 to 200	472.44	515.21	Tmr	VA	1,285.74
02-57-018	U 2 AT	KNOX	02/21/1968	20 to 200	644.8	503.47	Tbg	VCU	1,279.8
02-57-019	U 2 AU	ILDRIK	07/16/1969	20 to 200	410.26	514.01	Tmr	VA	1,283.02
02-57-020	U 2 AV	CALABASH	10/29/1969	110	624.84	569.38	Tn	VCU	1,310.04
02-57-021	U 2 AW	STANYAN	09/26/1974	20 to 200	572.99	553.70	Tmr	VA	1,301.68
02-57-022	U 2 AX	PORTMANTEAU	08/30/1974	20 to 200	655.29	599.88	Tx	VCU	1,340.24
02-57-023	U 2 AY 1	YANNIGAN-RED	02/26/1970	20 to 200	391.97	507.84	QTa	AA	1,284.47
02-57-024	U 2 AY 2	YANNIGAN-WHITE	02/26/1970	20 to 200	394.72	522.77	QTa	AA	1,288.43
02-57-025	U 2 AY 3	YANNIGAN-BLUE	02/26/1970	20 to 200	363.63	510.37	QTa	AA	1,284.56
02-57-026	U 2 AZ 1	FLASK-GREEN	05/26/1970	105	528.52	496.79	Tmr	VA	1,277.69
02-57-027	U 2 AZ 2	FLASK-YELLOW	05/26/1970	0.09	335.28	516.46	QTa	AA	1,286.38
02-57-028	U 2 AZ 3	FLASK-RED	05/26/1970	0.04	152.4	517.61	QTa	AA	1,286.32
02-57-029	U 2 B	ST LAWRENCE	11/09/1962	Low	166.73	599.14	QTa	AA	1,336.15
02-57-030	U 2 BC	PARASSIA	11/30/1971	<20	330.71	591.59	Tn	VCU	1,328.9
02-57-031	U 2 BD	VULCAN	06/25/1966	25	322.78	588.38	QTa	AA	1,327.22

Table 3-2
Corrective Action Sites in Yucca Flat
(Page 2 of 22)

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
02-57-032	U 2 BE	NOOR	04/10/1968	20 to 200	381	595.98	QTa	AA	1,336.64
02-57-033	U 2 BF	GOURD-AMBER	04/24/1969	<20	181.3	605.86	QTa	AA	1,346.52
02-57-034	U 2 BG	THROW	04/10/1968	<20	228.6	600.61	QTa	AA	1,343.41
02-57-035	U 2 BH	SCUTTLE	11/13/1969	1.7	164.59	601.87	QTa	AA	1,339.18
02-57-036	U 2 BI	OAKLAND	04/04/1967	<20	165.51	600.89	QTa	AA	1,348.26
02-57-037	U 2 BJ	IMP	08/09/1968	<20	182.88	601.60	QTa	AA	1,340.74
02-57-038	U 2 BL	GOURD-BROWN	04/24/1969	<20	226.8	600.19	QTa	AA	1,343.9
02-57-039	U 2 BM	LEXINGTON	08/24/1967	<20	226.47	599.11	QTa	AA	1,336.73
02-57-040	U 2 BN	CHATTY	03/18/1969	<20	195.07	600.67	QTa	AA	1,339.2
02-57-041	U 2 BO 1	BOWL-1	06/26/1969	<20	198.12	603.26	QTa	AA	1,343.31
02-57-041	U 2 BO 2	BOWL-2	06/26/1969	<20	228.6	599.47	QTa	AA	1,341.66
02-57-042	U 2 BP 1	SPIDER-A	08/14/1969	<20	213.36	581.90	QTa	AA	1,318.6
02-57-043	U 2 BP 2	SPIDER-B	08/14/1969	<20	227.69	580.61	QTa	AA	1,318.23
02-57-044	U 2 BQ 1	KYACK-A	09/20/1969	<20	185.93	585.79	QTa	AA	1,323.41
02-57-045	U 2 BQ 2	KYACK-B	09/20/1969	<20	192.02	582.10	QTa	AA	1,320.02
02-57-046	U 2 BR	HAREBELL	06/24/1971	20 to 200	518.77	572.42	Tx	VA	1,314.3
02-57-047	U 2 BS	STARWORT	04/26/1973	90	563.88	525.30	Tx	VA	1,288.21
02-57-048	U 2 BU	MINIATA	07/08/1971	83	528.83	493.84	Tx	VA	1,273.82
02-57-049	U 2 BV	PORTULACA	06/28/1973	20 to 200	466.34	591.04	QTa	AA	1,337.5
02-57-050	U 2 BW	SUTTER	12/21/1976	<20	200	573.03	QTa	AA	1,314.3
02-57-051	U 2 BX	HULSEA	03/14/1974	<20	195.01	577.20	QTa	AA	1,316.34
02-57-052	U 2 BY	POLYGONUM	10/02/1973	<20	213.36	592.11	QTa	AA	1,330.64
02-57-053	U 2 BZ	WALLER	10/02/1973	<20	310.9	581.53	QTa	AA	1,320.67
02-57-054	U 2 C	KERMET	11/23/1965	<20	196.29	594.39	QTa	AA	1,331.4
02-57-055	U 2 CA	STUTZ	04/06/1966	<20	226.16	466.23	Tn	VA	1,484.87
02-57-056	U 2 CC	SAXON	07/28/1966	1.2	153.62	536.27	Tx	VA	1,438.48
02-57-057	U 2 CD	TRAVELER	05/04/1966	<20	197.51	497.26	QTa	AA	1,457.38
02-57-058	U 2 CE	NASH	01/19/1967	39	365.15	527.06	Cbk	LCA	1,452.13
02-57-059	U 2 CG	HEILMAN	04/06/1967	<20	152.71	531.21	QTa	AA	1,432.2
02-57-060	U 2 CI	POD-B	10/29/1969	16.7 (total) ^f	248.72	443.94	Tn	VA	1,491.54
02-57-061	U 2 CJ	POD-C	10/29/1969	16.7 (total) ^f	170.69	465.98	QTa	AA	1,474.56
02-57-062	U 2 CK	POD-D	10/29/1969	16.7 (total) ^f	312.42	512.38	Tu	VA	1,451.16
02-57-063	U 2 CH	POD-A	10/29/1969	16.7 (total) ^f	266.7	540.01	Tn	VA	1,423.63
02-57-064	U 2 CM	STODDARD	09/17/1968	81	467.87	522.09	Tn	VA	1,396.87
02-57-065	U 2 CN	CRUET	10/29/1969	11	263.65	523.02	Tx	VA	1,398.71

Table 3-2
Corrective Action Sites in Yucca Flat
(Page 3 of 22)

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
02-57-066	U 2 CO	KRYDDOST	05/06/1982	<20	335	515.75	Tx	VA	1,390.53
02-57-067	U 2 CP	CABOC	12/16/1981	<20	335	521.45	Tx	VA	1,374.59
02-57-068	U 2 CQ	GORBEA	01/31/1984	20 to 150	388	520.93	Tx	VA	1,371.32
02-57-069	U 2 CR	WEXFORD	08/30/1984	<20	314	558.39	Tn	VA	1,403.3
02-57-070	U 2 CS	MARIBO	06/26/1985	<20	381	546.97	Tn	VA	1,379.38
02-57-071	U 2 CT	CHEEDAM	02/17/1983	<20	343	584.79	Tn	VCU	1,320.27
02-57-072	U 2 CU	KAWICH-BLACK	02/24/1989	<20	431	551.30	Tn	VA	1,379.44
02-57-072	U 2 CU	KAWICH-RED	02/24/1989	<20	370	551.30	Tn	VA	1,379.44
02-57-073	U 2 DB	CREW	11/04/1968	20 to 200	358.84	561.52	QTa	AA	1,314.38
02-57-073	U 2 DB	CREW-2ND	11/04/1968	<20	359.66	561.52	QTa	AA	1,314.38
02-57-073	U 2 DB	CREW-3RD	11/04/1968	<20	603.5	561.52	Tma	VA	1,314.38
02-57-074	U 2 DC 5b	TYG-E	12/12/1968	<20	197.82	551.09	QTa	AA	1,296.63
02-57-075	U 2 DC 4a	TYG-D	12/12/1968	<20	206.96	552.51	QTa	AA	1,298.66
02-57-076	U 2 DC 3c	TYG-C	12/12/1968	<20	228.3	550.92	QTa	AA	1,294.94
02-57-077	U 2 DC 1e	TYG-A	12/12/1968	<20	228.3	555.99	QTa	AA	1,300.01
02-57-078	U 2 DC 2d	TYG-B	12/12/1968	<20	251.16	555.42	QTa	AA	1,296.69
02-57-079	U 2 DC 6f	TYG-F	12/12/1968	<20	264.87	558.64	QTa	AA	1,299.61
02-57-080	U 2 DD 2	ARNICA-YELLOW	06/26/1970	<20	309.37	553.83	QTa	AA	1,296.93
02-57-081	U 2 DD 3	ARNICA-VIOLET	06/26/1970	<20	263.65	558.00	QTa	AA	1,298.66
02-57-082	U 2 DE	COFFER	03/21/1969	<100	464.82	569.25	QTa	AA	1,317.53
02-57-083	U 2 DF	HUTCH	07/16/1969	20 to 200	548.64	580.89	QTa	AA	1,327.04
02-57-084	U 2 DG	CARPETBAG	12/17/1970	220	661.7	552.23	Tma	VA	1,311.18
02-57-085	U 2 DH 2	SAPPHO	03/23/1972	<20	197.82	552.30	QTa	AA	1,292.66
02-57-086	U 2 DH 3	KARA	05/11/1972	<20	259.08	553.50	QTa	AA	1,294.47
02-57-087	U 2 DI	CHANTILLY	09/29/1971	<20	330.71	561.90	QTa	AA	1,306.83
02-57-088	U 2 DJ	FLAX-BACKUP	12/21/1972	<20	445.12	577.44	QTa	AA	1,323.08
02-57-088	U 2 DJ	FLAX-SOURCE	12/21/1972	<20	435.86	577.23	QTa	AA	1,323.08
02-57-088	U 2 DJ	FLAX-TEST	12/21/1972	20 to 200	688.3	577.23	Tmr	VA	1,323.08
02-57-089	U 2 DK	ZINNIA	05/17/1972	<20	322.78	563.18	QTa	AA	1,304.15
02-57-090	U 2 DL	CHAENACTIS	12/14/1971	20 to 200	330.71	565.10	QTa	AA	1,307.9
02-57-091	U 2 DM	LONGCHAMPS	04/19/1972	<20	326.44	559.52	QTa	AA	1,302.93
02-57-092	U 2 DN	MERIDA	06/07/1972	<20	204.22	556.29	QTa	AA	1,297.87
02-57-093	U 2 DO	GAZOOK	03/23/1973	<20	326.14	558.34	QTa	AA	1,300.83
02-57-094	U 2 DP	DELPHINIUM	09/26/1972	15	295.66	562.25	QTa	AA	1,303.22
02-57-095	U 2 DQ	SATZ	07/07/1978	<20	315	536.15	Tmr	VA	1,289.92

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
02-57-096	U 2 DR	CABRILLO	03/07/1975	20 to 200	600.5	566.08	QTa	AA	1,314.67
02-57-097	U 2 DS	GROVE	05/22/1974	<20	313.94	537.21	Tmr	VA	1,290.98
02-57-098	U 2 DT	TANYA	07/30/1968	20 to 200	381	557.53	QTa	AA	1,297.58
02-57-099	U 2 DU	ALVISO	06/11/1975	<20	183	522.52	QTa	AA	1,287.87
02-57-100	U 2 DV	FALLON	05/23/1974	20 to 200	466.34	547.58	QTa	AA	1,302.57
02-57-101	U 2 DW	CRESTLAKE-BRIAR	07/18/1974	<20	373.7	559.53	QTa	AA	1,301.11
02-57-101	U 2 DW	CRESTLAKE-TANS	07/18/1974	<20	271.61	559.53	QTa	AA	1,301.11
02-57-102	U 2 DY	EDAM	04/24/1975	20 to 200	411.5	555.83	Tbg	VA	1,299.24
02-57-103	U 2 DZ	BANON	08/26/1976	20 to 150	536.4	543.67	QTa	AA	1,302.32
02-57-104	U 2 E	CUMBERLAND	04/11/1963	Low	226.47	587.56	QTa	AA	1,326.4
02-57-105	U 2 EA	SEAFOAM	12/13/1973	<20	198.12	595.22	QTa	AA	1,333.14
02-57-106	U 2 EB	PORTRERO	04/23/1974	<20	210.31	597.26	QTa	AA	1,337.01
02-57-107	U 2 EF	GOUDA	10/06/1976	<20	200	551.72	QTa	AA	1,298.48
02-57-108	U 2 EG	RIVOLI	05/20/1976	<20	200	559.04	QTa	AA	1,305.8
02-57-109	U 2 EH	LIPTAUER	04/03/1980	20 to 150	417	585.13	QTa	AA	1,331.28
02-57-110	U 2 EI	COULOMMIERS	09/27/1977	20 to 150	530.3	578.64	Tbg	VCU	1,319
02-57-111	U 2 EK	CHIBERTA	12/20/1975	20 to 200	716	540.11	Tn	VCU	1,291.44
02-57-112	U 2 EL	MARSILLY	04/05/1977	20 to 150	690	519.93	Tx	VCU	1,286.2
02-57-113	U 2 EM	AZUL	12/14/1979	<20	205	555.65	QTa	AA	1,302.41
02-57-114	U 2 EN	REBLOCHON	02/23/1978	20 to 150	658.4	534.17	Tx	VA	1,287.94
02-57-115	U 2 EO	KLOSTER	02/15/1979	20 to 150	536.4	584.18	Tx	VA	1,323.93
02-57-116	U 2 EP	NESSEL	08/29/1979	20 to 150	464	531.51	QTa	AA	1,286.5
02-57-117	U 2 EQ	RIOLA	09/25/1980	1.07	424	508.53	QTa	AA	1,281.2
02-57-118	U 2 ER	ISLAY	08/27/1981	<20	294	587.18	Tn	VCU	1,323.58
02-57-119	U 2 ES	AKAVI	12/03/1981	20 to 150	494	575.80	Tx	VA	1,320.43
02-57-120	U 2 ET	CHEEDAM	02/17/1983	<20	343	584.79	Tn	VCU	1,320.27
02-57-121	U 2 EU	DANABLU	06/09/1983	<20	320	607.01	QTa	AA	1,353.47
02-57-122	U 2 EV	AGRINI	03/31/1984	<20	320	583.91	QTa	AA	1,330.67
02-57-123	U 2 EW	BRANCO	09/21/1983	<20	293	519.69	QTa	AA	1,282.91
02-57-123	U 2 EW	BRANCO-HERKIME	09/21/1983	<20	427	519.69	Tmr	VA	1,282.91
02-57-124	U 2 EX	ROMANO	12/16/1983	20 to 150	515	561.54	Tma	VA	1,314.09
02-57-125	U 2 EY	NIGHTINGALE	06/22/1988	<150	237.7	599.88	QTa	AA	1,336.28
02-57-126	U 2 EY	RHYOLITE	06/22/1988	<150	207.3	599.88	QTa	AA	1,336.28
02-57-127	U 2 F	NARRAGUAGUS	09/27/1963	Low	150.27	588.97	QTa	AA	1,329.02
02-57-128	U 2 FA	FARALLONES	12/14/1977	20 to 150	668	570.23	QTa	AA	1,317.29

Table 3-2
Corrective Action Sites in Yucca Flat
(Page 5 of 22)

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
02-57-129	U 2 FB	QUARGEL	11/18/1978	20 to 150	542	538.68	Tmr	VA	1,301.9
02-57-130	U 2 FC	FAJY	06/28/1979	20 to 150	536	583.75	QTa	AA	1,330.21
02-57-131	U 2 FD	TARKO	02/28/1980	<20	369	561.26	QTa	AA	1,306.8
02-57-132	U 2 FE	CROWDIE	05/05/1983	<20	390	589.88	QTa	AA	1,336.03
02-57-133	U 2 FF	LABAN	08/03/1983	<20	326	561.27	QTa	AA	1,303.15
02-57-134	U 2 G	SATSOP	08/15/1963	Low	226.16	589.89	QTa	AA	1,332.99
02-57-135	U 2 GA S	CORNUCOPIA	07/24/1986	<20	381	565.59	QTa	AA	1,314.18
02-57-136	U 2 GB	PANAMINT	05/21/1986	<20	480	528.39	Tmr	VA	1,285.82
02-57-137	U 2 GE	BORATE	10/23/1987	20 to 150	542.5	572.72	QTa	AA	1,321.31
02-57-138	U 2 GF	SHELLBOURNE	05/13/1988	<150	463	540.72	QTa	AA	1,295.1
02-57-139	U 2 GG	INGOT	03/09/1989	20 to 150	500	563.71	Tmr	VA	1,307.42
02-57-140	U 2 GH	METROPOLIS	03/10/1990	20 to 150	469.4	479.21	Tmr	VA	1,273.21
02-57-141	U 2 H	CARMEL	02/21/1963	Low	164.29	598.76	QTa	AA	1,338.2
02-57-142	U 2 J	ALVA	08/19/1964	4.4	166.12	601.59	QTa	AA	1,347.13
02-57-143	U 2 L	AHTANUM	09/13/1963	Low	226.16	603.47	QTa	AA	1,346.88
02-57-144	U 2 M 1	FENTON	04/23/1966	1.4	167.34	601.04	QTa	AA	1,348.1
02-57-145	U 2 N	ACE	06/11/1964	3	263.35	579.19	QTa	AA	1,326.86
02-57-146	U 2 P	PAR	10/09/1964	38	405.69	585.89	QTa	AA	1,331.43
02-57-147	U 2 Q	CREPE	12/05/1964	20 to 200	403.86	497.99	Tmr	VA	1,278.58
02-57-148	U 2 R	PLAID II	02/03/1966	<20	268.53	545.68	QTa	AA	1,298.54
02-57-149	U 2 T	DUMONT	05/19/1966	20 to 200	670.87	486.16	Tx	VCU	1,278.64
02-57-150	U 2 U	PACKARD	01/15/1969	10	246.89	574.56	QTa	AA	1,315.22
02-57-151	U 2 V	AGILE	02/23/1967	20 to 200	733.35	543.58	Tx	VCU	1,297.35
02-57-152	U 2 X	LANPHER	10/18/1967	20 to 200	715.06	498.29	Tc	VCU	1,281.93
02-57-153	U 2 Y	HUPMOBILE	01/18/1968	7.4	246.89	572.72	QTa	AA	1,313.69
03-57-001	U 3 AA	BOOMER	10/01/1961	Low	100.58	494.54	QTa	AA	1,227.58
03-57-002	U 3 AB	ERMINE	03/06/1962	Low	73.15	494.61	QTa	AA	1,227.65
03-57-003	U 3 AC	SHREW	09/16/1961	Low	98.15	494.24	QTa	AA	1,227.28
03-57-004	U 3 AD	PLATYPUS	02/24/1962	Low	57.91	494.06	QTa	AA	1,227.1
03-57-005	U 3 AE	MINK	10/29/1961	Low	192.02	494.70	QTa	AA	1,227.74
03-57-006	U 3 AF	COYPU	04/10/1963	Low	74.68	494.54	QTa	AA	1,227.58
03-57-007	U 3 AG	CHINCHILLA	02/19/1962	1.9	150.08	495.25	QTa	AA	1,228.29
03-57-008	U 3 AH	FISHER	12/03/1961	13.4	363.72	491.95	QTa	AA	1,225.3
03-57-009	U 3 AI	HOGNOSE	03/15/1962	Low	240.34	491.89	QTa	AA	1,224.93
03-57-010	U 3 AJ S	RACCOON	06/01/1962	Low	164.29	492.69	QTa	AA	1,225.73

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-011	U 3 AK	RINGTAIL	12/17/1961	Low	363.02	490.21	QTa	AA	1,223.56
03-57-012	U 3 AL	PAMPAS	03/01/1962	9.5	363.02	489.76	QTa	AA	1,222.8
03-57-013	U 3 AM S	AARDVARK	05/12/1962	40	434.04	503.32	Tx	VA	1,240.94
03-57-014	U 3 AN	WAGTAIL	03/03/1965	20 to 200	749.6	491.83	Tu	VCU	1,237.37
03-57-015	U 3 AO	AGOUTI	01/18/1962	6.4	260.91	494.42	QTa	AA	1,227.46
03-57-016	U 3 AP	STOAT	01/09/1962	5.1	302.36	492.53	QTa	AA	1,225.57
03-57-017	U 3 AQ	DORMOUSE	01/30/1962	Low	363.02	493.29	QTa	AA	1,227.25
03-57-018	U 3 AR	ARMADILLO	02/09/1962	7.1	239.57	491.77	QTa	AA	1,225.12
03-57-019	U 3 AS	CHINCHILLA II	03/31/1962	Low	136.55	493.81	QTa	AA	1,227.16
03-57-020	U 3 AT	JERBOA	03/01/1963	Low	301.14	490.58	QTa	AA	1,223.93
03-57-021	U 3 AU S	HAYMAKER	06/27/1962	67	408.43	490.58	QTa	AA	1,223.32
03-57-022	U 3 AV	WOLVERINE	10/12/1962	Low	73.46	494.39	QTa	AA	1,227.43
03-57-023	U 3 AW	PACKRAT	06/06/1962	Low	261.98	492.38	QTa	AA	1,226.03
03-57-024	U 3 AX	PACA	05/07/1962	Low	258.32	492.05	QTa	AA	1,225.7
03-57-025	U 3 AY	CHIPMUNK	02/15/1963	Low	59.44	494.73	QTa	AA	1,227.77
03-57-026	U 3 AZ	DORMOUSE PRIME	04/05/1962	10.6	260.91	490.43	QTa	AA	1,224.08
03-57-027	U 3 BA	TENDRAC	12/07/1962	Low	302.67	496.34	QTa	AA	1,229.38
03-57-028	U 3 BB	PEBA	09/20/1962	Low	241.4	499.27	QTa	AA	1,232.31
03-57-029	U 3 BC	HUTIA	06/06/1963	Low	134.57	491.86	QTa	AA	1,224.9
03-57-030	U 3 BD	MERRIMAC	07/13/1962	Intermediate	413.31	497.65	QTa	AA	1,231.61
03-57-031	U 3 BE	DAMAN 1	06/21/1962	Low	260.3	491.04	QTa	AA	1,224.08
03-57-032	U 3 BF	FERRET	02/08/1963	Low	325.83	501.64	QTa	AA	1,234.99
03-57-033	U 3 BG	ACUSHI	02/08/1963	Low	260.91	492.23	QTa	AA	1,225.88
03-57-034	U 3 BH	HYRAX	09/14/1962	Low	216.71	490.70	QTa	AA	1,224.35
03-57-035	U 3 BJ	BANDICOOT	10/19/1962	12.5	241.4	488.63	QTa	AA	1,221.67
03-57-036	U 3 BK	MATACO	06/14/1963	Low	195.68	493.26	QTa	AA	1,227.22
03-57-037	U 3 BL	BOBAC	08/24/1962	Low	206.05	491.95	QTa	AA	1,225.6
03-57-038	U 3 BM	GUNDI	11/15/1962	Low	241.4	489.21	QTa	AA	1,222.25
03-57-039	U 3 BN	CASSOWARY	12/16/1964	<20	150.14	487.81	QTa	AA	1,220.85
03-57-040	U 3 BO	STURGEON	04/15/1964	<20	149.77	491.19	QTa	AA	1,224.84
03-57-041	U 3 BP	GERBIL	03/29/1963	Low	279.5	489.21	QTa	AA	1,222.86
03-57-042	U 3 BQ	ANCHOVY	11/14/1963	Low	260.25	488.02	QTa	AA	1,221.37
03-57-043	U 3 BR	BELEN	02/04/1970	20 to 200	420.8	496.49	QTa	AA	1,232.89
03-57-044	U 3 BS	PUCE	06/10/1966	<20	485.55	492.65	QTa	AA	1,235.45
03-57-045	U 3 BT	BONEFISH	02/18/1964	<20	300.76	497.89	QTa	AA	1,234.29

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-046	U 3 BU	NUMBAT	12/12/1962	Low	231.95	494.42	QTa	AA	1,228.38
03-57-047	U 3 BV	HARKEE	05/17/1963	Low	241.4	491.80	QTa	AA	1,225.76
03-57-048	U 3 BW	PEKAN	08/12/1963	Low	302.27	490.12	QTa	AA	1,223.77
03-57-049	U 3 BX	BARBEL	10/16/1964	<20	258.9	487.63	QTa	AA	1,221.28
03-57-050	U 3 BY	FERRET PRIME	04/05/1963	Low	241.55	486.77	QTa	AA	1,219.81
03-57-051	U 3 BZ	GRUNION	10/11/1963	Low	261.31	486.71	QTa	AA	1,219.75
03-57-052	U 3 CB	CARP	09/27/1963	Low	329.55	486.28	QTa	AA	1,219.93
03-57-053	U 3 CD	DOVEKIE	01/21/1966	<20	333.05	482.87	QTa	AA	1,216.52
03-57-054	U 3 CF	HOOPOE	12/16/1964	<20	70.35	493.90	QTa	AA	1,226.94
03-57-055	U 3 CG	TEJON	05/17/1963	Low	74.68	493.97	QTa	AA	1,227.01
03-57-056	U 3 CH	SARDINE	12/04/1963	Low	262.01	488.60	QTa	AA	1,221.34
03-57-057	U 3 CJ	SIENNA	01/18/1966	<20	275.01	486.77	QTa	AA	1,220.12
03-57-058	U 3 CN	BILBY	09/13/1963	249	714.3	509.02	Tot	VCU	1,241.76
03-57-059	U 3 CO	PIPEFISH	04/29/1964	<20	261.92	488.26	QTa	AA	1,221
03-57-060	U 3 CP	CANVASBACK	08/22/1964	<20	447.66	514.35	Tx	VCU	1,253.49
03-57-061	U 3 CR	BARRACUDA	12/04/1963	Low	263.34	494.69	QTa	AA	1,228.65
03-57-062	U 3 CT	MERLIN	02/16/1965	10.1	296.14	496.83	QTa	AA	1,230.48
03-57-063	U 3 CU	BITTERLING	06/12/1964	<20	192.6	489.14	QTa	AA	1,223.1
03-57-064	U 3 CV	MINNOW	05/15/1964	<20	241.34	491.80	QTa	AA	1,225.76
03-57-065	U 3 CX	CYCLAMEN	05/05/1966	12	304.97	496.22	QTa	AA	1,230.18
03-57-066	U 3 CY	PIKE	03/13/1964	<20	114.5	501.46	QTa	AA	1,237.55
03-57-067	U 3 CZ	SOLENDON	02/12/1964	<20	150.18	500.31	QTa	AA	1,233.35
03-57-068	U 3 D	PASCAL-B	08/27/1957	Slight	152.4	494.64	QTa	AA	1,227.68
03-57-069	U 3 DA S	SCAUP	05/14/1965	<20	427.03	506.57	Tx	VCU	1,249.06
03-57-070	U 3 DB	GUNDI PRIME	05/09/1963	Low	271.73	498.05	QTa	AA	1,232.31
03-57-071	U 3 DD	KESTREL	04/05/1965	<20	446.87	481.19	QTa	AA	1,214.54
03-57-072	U 2 DD 1	CAN-GREEN	04/21/1970	<20	274.32	553.34	QTa	AA	1,293.14
03-57-073	U 2 DD 4	CAN-RED	04/21/1970	20 to 200	399.29	554.13	Tn	VCU	1,295.1
03-57-074	U 3 DE	TUNA	12/20/1963	Low	414.35	496.51	QTa	AA	1,229.86
03-57-075	U 3 DF	CORMORANT	07/17/1964	<20	271.64	477.93	QTa	AA	1,211.58
03-57-076	U 3 DG	SCREAMER	09/01/1965	<20	301.75	478.29	QTa	AA	1,211.64
03-57-077	U 3 DH	BUFF	12/16/1965	20 to 200	500.41	514.82	Tn	VCU	1,250.3
03-57-078	U 3 DI	GUANAY	09/04/1964	<20	260.97	477.62	QTa	AA	1,211.58
03-57-079	U 3 DJ	TROGON	07/24/1964	<20	193.03	496.83	QTa	AA	1,231.09
03-57-080	U 3 DK	PARROT	12/16/1964	1.3	180.32	485.49	QTa	AA	1,219.45

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-081	U 3 DL	HADDOCK	08/28/1964	<20	363.66	515.21	Tx	VCU	1,248.86
03-57-082	U 3 DM	CINNAMON	03/07/1966	<20	119.85	486.77	QTa	AA	1,219.2
03-57-083	U 3 DN	PERSIMMON	02/23/1967	<20	299.11	476.47	QTa	AA	1,210.73
03-57-084	U 3 DO	COURSER	09/25/1964	Zero	358.99	522.76	Tx	VCU	1,264.34
03-57-085	U 3 DP	MAUVE	08/06/1965	<20	320.95	479.43	QTa	AA	1,212.47
03-57-086	U 3 DR	BORDEAUX	08/18/1967	<20	332.03	476.62	QTa	AA	1,209.97
03-57-087	U 3 DS	PURPLE	03/18/1966	<20	332.79	469.43	Tmr	VA	1,206.74
03-57-088	U 3 DT	TURNSTONE	10/16/1964	<20	125.55	485.00	QTa	AA	1,218.04
03-57-089	U 3 DU	FINFOOT	03/07/1966	<20	195.54	487.84	QTa	AA	1,220.27
03-57-090	U 3 DW	TERN	01/29/1965	<20	210.65	494.91	QTa	AA	1,228.87
03-57-091	U 3 DX	MUSCOVY	04/23/1965	<20	180.29	482.32	Tmr	VA	1,216.58
03-57-092	U 3 DY	PETREL	06/11/1965	1.3	180.75	490.40	QTa	AA	1,224.05
03-57-093	U 3 DZ	KNIFE B	11/15/1968	<20	362.93	481.89	QTa	AA	1,215.24
03-57-094	U 3 E	PASCAL-C	12/06/1957	Slight	76.2	495.58	QTa	AA	1,228.62
03-57-095	U 3 EB	TANGERINE	08/12/1966	<20	87.88	492.28	QTa	AA	1,225.63
03-57-096	U 3 EC	OCHRE	04/29/1966	<20	126.14	489.45	QTa	AA	1,223.1
03-57-097	U 3 ED	MOA	09/01/1965	<20	193.55	487.14	QTa	AA	1,220.79
03-57-098	U 3 EE	POMMARD	03/14/1968	1.5	209.1	500.79	QTa	AA	1,235.36
03-57-099	U 3 HP	JARA	06/06/1974	<20	377.95	470.86	QTa	AA	1,206.95
03-57-100	U 3 EF	MUSHROOM	03/03/1967	<20	179.55	491.10	QTa	AA	1,225.06
03-57-102	U 3 EH	FUTTOCK	06/18/1975	<20	185.9	514.06	QTa	AA	1,247.71
03-57-103	U 3 EI	MORRONES	05/21/1970	20 to 200	482.72	517.85	Tx	VCU	1,264.31
03-57-104	U 3 EJ	WISE	01/30/1969	20 to 200	454.06	497.59	Tmr	VA	1,230.63
03-57-105	U 3 EK	TOMATO	04/07/1966	<20	226.31	488.69	Tx	VA	1,222.34
03-57-106	U 3 EL	PLANER	11/21/1969	<20	377.84	475.95	QTa	AA	1,210.21
03-57-107	U 3 EM	UMBER	06/29/1967	10	310.24	482.24	QTa	AA	1,215.59
03-57-108	U 3 EN	SEPIA	11/12/1965	<20	241.19	495.52	QTa	AA	1,229.17
03-57-109	U 3 EO	FAWN	04/07/1967	<20	271.06	499.88	QTa	AA	1,233.53
03-57-110	U 3 EP	ABSINTHE	05/26/1967	<20	118.65	491.83	QTa	AA	1,225.79
03-57-111	U 3 EQ	BRUSH	01/24/1968	<20	118.3	491.67	QTa	AA	1,225.63
03-57-112	U 3 ER	KNIFE C	10/03/1968	<20	301.44	495.06	Tmr	VA	1,228.41
03-57-113	U 3 ES	CHOCOLATE	04/21/1967	<20	240.45	479.76	QTa	AA	1,212.8
03-57-114	U 3 ET	KHAKI	10/15/1966	<20	232.55	494.63	QTa	AA	1,228.59
03-57-115	U 3 EU	CERISE	11/18/1966	<20	211.09	494.39	QTa	AA	1,228.65
03-57-116	U 3 EV2S	SNUBBER	04/21/1970	12.7	343.5	550.66	Tu	VCU	1,279.74

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Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-117	U 3 EW	GIBSON	08/04/1967	<20	240.76	478.85	QTa	AA	1,213.11
03-57-118	U 3 EX	GILROY	09/15/1967	<20	240.63	485.27	QTa	AA	1,218.62
03-57-119	U 3 EY	WEMBLEY	06/05/1968	<20	238.09	484.94	QTa	AA	1,218.59
03-57-120	U 3 EZ	SIDECAR	12/13/1966	<20	240.27	489.21	QTa	AA	1,222.25
03-57-121	U 3 FA	SAZERAC	10/25/1967	<20	301.34	484.64	QTa	AA	1,217.68
03-57-122	U 3 FB	KNIFE A	09/12/1968	<20	331.81	483.26	Tmr	VA	1,217.22
03-57-123	U 3 FC	PICCALILLI	11/21/1969	20 to 200	393.81	488.92	Tu	VCU	1,222.27
03-57-124	U 3 FD	LAGUNA	06/23/1971	20 to 200	454.92	479.71	Tmr	VA	1,213.36
03-57-125	U 3 FE	LOVAGE	12/17/1969	<20	378.05	472.48	QTa	AA	1,207.96
03-57-126	U 3 FF	PLOMO	05/01/1974	<20	149.41	522.45	Tx	VA	1,253.97
03-57-127	U 3 FH	STILT	12/15/1967	<20	332.43	496.83	Tw	VCU	1,230.79
03-57-128	U 3 FJ	TORCH	02/21/1968	<20	240.58	501.10	Tmr	VA	1,237.19
03-57-129	U 3 FK	SEVILLA	06/25/1968	<20	358.65	516.09	Tx	VCU	1,253.1
03-57-130	U 3 FM	COGNAC	10/25/1967	<20	240.39	495.31	QTa	AA	1,229.57
03-57-131	U 3 FN	BEEBALM	05/01/1970	<20	390.21	502.59	Tmr	VA	1,235.63
03-57-132	U 3 FQ	CANJILON	12/16/1970	<20	302.19	521.38	Tx	VA	1,254.42
03-57-133	U 3 FR	FIZZ	03/10/1967	<20	117.73	492.41	QTa	AA	1,225.76
03-57-134	U 3 FS	WELDER	10/03/1968	<20	117.65	492.56	QTa	AA	1,225.91
03-57-135	U 3 FU	BEVEL	04/04/1968	<20	240.75	498.35	QTa	AA	1,232.31
03-57-136	U 3 FV	MALLET	01/31/1968	<20	240.27	465.01	QTa	AA	1,204.15
03-57-137	U 3 FW	ADZE	05/28/1968	<20	240.03	475.37	Tpt	VA	1,215.12
03-57-138	U 3 FX	AUGER	11/15/1968	<20	240.62	506.57	Tx	VA	1,248.76
03-57-139	U 3 FY	SPUD	07/17/1968	<20	240.29	463.45	Tmr	VA	1,205.64
03-57-140	U 3 FZ	HATCHET	05/03/1968	<20	240.53	481.84	QTa	AA	1,215.19
03-57-141	U 3 GA	FUNNEL	06/25/1968	<20	118.7	493.05	QTa	AA	1,226.09
03-57-142	U 3 GB	FILE	10/31/1968	<20	228.95	478.81	QTa	AA	1,212.16
03-57-143	U 3 GC	BARSAC	03/20/1969	<20	304.13	480.08	QTa	AA	1,213.73
03-57-144	U 3 GD	AJO	01/30/1970	<20	304.11	485.70	QTa	AA	1,218.44
03-57-145	U 3 GE	SAPELLO	04/12/1974	<20	180.69	482.41	QTa	AA	1,215.76
03-57-146	U 3 GF	WINCH	02/04/1969	<20	240.63	479.15	QTa	AA	1,212.19
03-57-147	U 3 GG	TORTUGAS	03/01/1984	20 to 150	640.1	473.63	Tc	VCU	1,243.25
03-57-148	U 3 GH	SCISSORS	12/12/1968	<20	240.58	475.26	QTa	AA	1,208.61
03-57-149	U 3 GI	TULOSO	12/12/1972	<20	271.09	483.18	QTa	AA	1,216.53
03-57-150	U 3 GJ	ALIMENT	05/15/1969	<20	240.51	502.74	Tc	VCU	1,234.26
03-57-151	U 3 GK	SHAVE	01/22/1969	<20	240.75	483.08	Tx	VA	1,217.95

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-152	U 3 GL	NIPPER	02/04/1969	<20	240.73	465.60	QTa	AA	1,204.74
03-57-153	U 3 GM	HOREHOUND	08/27/1969	<20	331.83	460.27	Tc	VCU	1,201.54
03-57-154	U 3 GN	PLIERS	08/27/1969	<20	238.87	481.16	QTa	AA	1,214.2
03-57-155	U 3 GO	TAPPER	06/12/1969	<20	303.01	474.61	QTa	AA	1,208.57
03-57-156	U 3 GQ	BAY LEAF	12/12/1968	<20	130.16	493.17	QTa	AA	1,226.21
03-57-157	U 3 GR	MANZANAS	05/21/1970	<20	240.65	484.79	Tx	VA	1,221.49
03-57-158	U 3 GS	APODACA	07/21/1971	<20	241.4	487.43	Tw	VA	1,222
03-57-159	U 3 GT	BIT A	10/31/1968	<20	148.31	492.67	QTa	AA	1,226.02
03-57-159	U 3 GT	BIT B	10/31/1968	<20	117.83	492.67	QTa	AA	1,226.02
03-57-160	U 3 GU	MESCALERO	01/05/1972	<20	120.24	491.93	QTa	AA	1,225.28
03-57-161	U 3 GV	BONARDA	09/25/1980	20 to 150	381	490.46	Tmr	WTA	1,236.61
03-57-162	U 3 GX	ABEYAS	11/05/1970	20 to 200	393.46	481.11	Tx	VA	1,215.37
03-57-163	U 3 GZ	CUMARIN	02/25/1970	20 to 200	408.51	498.27	Tu	VCU	1,232.84
03-57-164	U 3 HA	CORAZON	12/03/1970	<20	241.12	473.67	QTa	AA	1,207.32
03-57-165	U 3 HB	JIB	05/08/1974	<20	179.8	462.94	Tmr	VA	1,204.21
03-57-166	U 3 HC	SPRIT	11/10/1976	<20	182.9	485.45	QTa	AA	1,219.1
03-57-167	U 3 HD	EMBUDO	06/16/1971	<20	303.06	483.92	QTa	AA	1,217.88
03-57-168	U 3 HE	BARRANCA	08/04/1971	<20	270.74	480.54	QTa	AA	1,214.19
03-57-169	U 3 HF	FRIJOLAS-GUAJE	09/22/1971	<20	257.03	479.07	QTa	AA	1,213.03
03-57-170	U 3 HG	PEDERNAL	09/29/1971	<20	378.68	469.95	Tpt	VA	1,207.26
03-57-171	U 3 HH	JAL	03/19/1970	<20	301.39	468.77	QTa	AA	1,205.47
03-57-172	U 3 HI A	CULANTRO-A	12/10/1969	<20	134.13	472.15	QTa	AA	1,208.24
03-57-173	U 3 HI B	CULANTRO-B	12/10/1969	<20	149.44	473.03	QTa	AA	1,209.12
03-57-174	U 3 HJ	SCUPPER	08/19/1977	<20	449.6	478.30	QTa	AA	1,211.95
03-57-175	U 3 HK A	IPECAC-A	05/27/1969	<20	124.18	472.30	QTa	AA	1,208.39
03-57-176	U 3 HK B	IPECAC-B	05/27/1969	<20	124.22	473.47	QTa	AA	1,209.56
03-57-177	U 3 HK D	SEAWEEED-B	10/16/1969	<20	118.55	474.27	QTa	AA	1,211.89
03-57-178	U 3 HK C	SEAWEEED-E	10/01/1969	<20	124.48	474.30	QTa	AA	1,211.31
03-57-179	U 3 HK E	SEAWEEED-C	10/01/1969	<20	118.55	473.88	QTa	AA	1,211.61
03-57-180	U 3 HK F	SEAWEEED-D	10/01/1969	<20	118.43	471.10	QTa	AA	1,210.23
03-57-181	U 3 HL	PENASCO	11/19/1970	<20	270.92	475.29	QTa	AA	1,209.86
03-57-182	U 3 HO	TRUCHAS-CHAMISAL	10/28/1970	<20	118.38	474.87	QTa	AA	1,209.44
03-57-183	U 3 HM	TRUCHAS-RODARTE	10/28/1970	<20	266.4	475.68	QTa	AA	1,209.94
03-57-184	U 3 HN	TRUCHAS-CHACON	10/28/1970	<20	118.45	474.87	QTa	AA	1,209.44
03-57-185	U 3 HQ	PRATT	09/25/1974	<20	313.3	476.08	QTa	AA	1,210.04

Table 3-2
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-186	U 3 HR	CARRIZOZO	12/03/1970	<20	279.26	476.71	QTa	AA	1,210.06
03-57-187	U 3 HS	DEXTER	06/23/1971	<20	119.94	474.48	QTa	AA	1,209.35
03-57-188	U 3 HT	ATARQUE	07/25/1972	<20	294.44	473.72	QTa	AA	1,209.2
03-57-189	U 3 HU	KEEL	12/16/1974	<20	305.01	473.25	QTa	AA	1,208.73
03-57-190	U 3 HV	COLMOR	04/26/1973	<20	245.8	474.57	QTa	AA	1,209.44
03-57-191	U 3 HX	COWLES	02/03/1972	<20	301.78	468.09	QTa	AA	1,205.4
03-57-192	U 3 HY	ELIDA	12/19/1973	<20	381	471.05	QTa	AA	1,205.62
03-57-193	U 3 HZ	FRIJOLES-PETACA	09/22/1971	<20	229.17	479.45	QTa	AA	1,213.1
03-57-194	U 3 J	PASCAL-A	07/26/1957	Slight	152.4	495.85	QTa	AA	1,229.2
03-57-195	U 3 JA	ESTACA	10/17/1974	<20	320.31	469.72	Tma	VA	1,206.73
03-57-196	U 3 JB	BOBSTAY	10/26/1977	<20	381	471.01	Tmr	VA	1,207.41
03-57-197	U 3 JC	CEBOLLA	08/09/1972	<20	286.7	471.43	QTa	AA	1,207.52
03-57-198	U 3 JD	MESITA	05/09/1973	<20	149.35	470.19	QTa	AA	1,206.89
03-57-199	U 3 JE	HOSPAH	12/14/1971	<20	302.03	481.80	QTa	AA	1,215.15
03-57-200	U 3 JF	SHALLOWS	02/26/1976	<20	243.8	481.19	QTa	AA	1,215.15
03-57-201	U 3 JG	ANGUS	04/25/1973	<20	452.93	472.29	QTa	AA	1,207.47
03-57-202	U 3 JH	BACKGAMMON	11/29/1979	<20	228.6	465.26	QTa	AA	1,202.57
03-57-203	U 3 JI	PAJARA	12/12/1973	<20	277.98	464.82	QTa	AA	1,202.44
03-57-204	U 3 JJ	CAPITAN	06/28/1972	<20	134.48	464.46	QTa	AA	1,202.69
03-57-205	U 3 JK	VELARDE	04/25/1973	<20	276.76	464.96	QTa	AA	1,203.19
03-57-206	U 3 JL	PUYE	08/14/1974	<20	430.01	482.17	QTa	AA	1,215.21
03-57-207	U 3 JM	JICARILLA	04/19/1972	<20	148.11	470.18	QTa	AA	1,206.88
03-57-208	U 3 JN	ALGODONES	08/18/1971	20 to 200	527.61	496.47	Tma	VA	1,233.17
03-57-209	U 3 JP	OCATE	03/30/1972	<20	210.1	468.66	QTa	AA	1,206.28
03-57-210	U 3 JQ	MONERO	05/19/1972	<20	537.35	522.10	Tc	VCU	1,272.52
03-57-211	U 3 JR	SPAR	12/19/1973	<20	149.35	470.73	QTa	AA	1,207.13
03-57-212	U 3 JS	ONAJA	03/30/1972	<20	279.04	470.47	QTa	AA	1,206.87
03-57-213	U 3 JT	CUCHILLO	08/09/1972	<20	198.43	469.46	QTa	AA	1,206.16
03-57-214	U 3 JU	FRIJOLES-ESPUELA	09/22/1971	<20	149.28	478.81	QTa	AA	1,212.77
03-57-215	U 3 JV	RIB	12/14/1977	<20	213.4	476.65	QTa	AA	1,210.91
03-57-216	U 3 JW	FRIJOLES-DEMING	09/22/1971	<20	149.86	478.38	QTa	AA	1,212.34
03-57-217	U 3 JX	SOLANO	08/09/1972	<20	133.81	468.37	QTa	AA	1,205.99
03-57-218	U 3 JY	BERNAL	11/28/1973	<20	283.46	475.49	QTa	AA	1,209.75
03-57-219	U 3 K	COLFAX	10/05/1958	0.0055	106.7	494.89	QTa	AA	1,227.93
03-57-220	U 3 KB	MARSH	09/06/1975	<20	426.7	480.43	QTa	AA	1,214.08

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-221	U 3 KC	BILGE	02/19/1975	<20	319	469.84	QTa	AA	1,205.93
03-57-222	U 3 KD	DECK	11/18/1975	<20	326.1	478.57	QTa	AA	1,212.53
03-57-223	U 3 KF	FOREFOOT	06/02/1977	<20	193.5	500.24	QTa	AA	1,233.59
03-57-224	U 3 KG	PUDDLE	11/26/1974	<20	183	457.23	QTa	AA	1,196.37
03-57-225	U 3 KI	COVE	02/16/1977	<20	335.3	473.69	QTa	AA	1,207.95
03-57-226	U 3 KJ	JACKPOTS	06/01/1978	<20	304.8	479.27	QTa	AA	1,212.92
03-57-227	U 3 KK	CERNADA	09/24/1981	<20	213	473.43	QTa	AA	1,208.3
03-57-228	U 3 KM	OARLOCK	02/16/1977	<20	320	476.12	QTa	AA	1,210.08
03-57-229	U 3 KN	CONCENTRATION	12/01/1978	<20	243.8	483.27	QTa	AA	1,216.31
03-57-230	U 3 KP	SEAMOUNT	11/17/1977	<20	371.9	478.87	QTa	AA	1,212.83
03-57-231	U 3 KQ	MEMORY	03/14/1979	<20	365.8	484.55	QTa	AA	1,217.59
03-57-232	U 3 KR	CLAIRETTE	02/05/1981	<20	353.6	475.55	QTa	AA	1,209.51
03-57-233	U 3 KS	OFFSHORE	08/08/1979	20 to 150	396.2	472.29	Tx	VCU	1,208.69
03-57-234	U 3 KT	EBBTIDE	09/15/1977	<20	381	487.02	QTa	AA	1,220.67
03-57-235	U 3 KU	VERDELLO	07/31/1980	<20	365.8	475.65	QTa	AA	1,209.91
03-57-236	U 3 KV	VICTORIA	06/19/1992	<20	243.9	467.65	QTa	AA	1,205.88
03-57-237	U 3 KW	FREEZEOUT	05/11/1979	<20	335.3	466.13	QTa	AA	1,204.36
03-57-238	U 3 KX	CANFIELD	05/02/1980	<20	350.5	503.59	Tma	VA	1,237.55
03-57-239	U 3 KY	HURON KING	06/24/1980	<20	320	481.29	QTa	AA	1,214.64
03-57-240	U 3 KZ	ALEMAN	09/11/1986	<20	502.9	474.58	Tmr	VA	1,245.11
03-57-241	U 3 LA	BOUSCHET	05/07/1982	20 to 150	563.9	479.15	Tc	VCU	1,244.5
03-57-242	U 3 LB	NAVATA	09/29/1983	<20	183	499.84	QTa	AA	1,233.8
03-57-243	U 3 LC	SABADO	08/11/1983	<20	320	460.74	Tmr	VA	1,202.62
03-57-244	U 3 LD	VILLITA	11/10/1984	<20	373.4	466.71	QTa	AA	1,204.63
03-57-245	U 3 LF	CERRO	09/02/1982	<20	228.6	477.47	QTa	AA	1,211.43
03-57-246	U 3 LG	FLORA	05/22/1980	<20	335.3	472.09	QTa	AA	1,206.35
03-57-247	U 3 LH	TENAJA	04/17/1982	<20	357	470.00	Tx	VA	1,204.57
03-57-248	U 3 LI	MOGOLLON	04/20/1986	<20	259.1	480.67	Tma	VA	1,214.63
03-57-249	U 3 LJ	TREBBIANO	09/04/1981	<20	304.8	485.95	Tma	VA	1,237.89
03-57-250	U 3 LK	MONAHANS A	11/09/1988	<20	289.6	463.45	QTa	AA	1,202.29
03-57-251	U 3 LL	TORNERO	02/11/1987	<20	298.4	480.06	Tmr	VA	1,213.41
03-57-252	U 3 LM	SEYVAL	11/12/1982	<20	365.8	481.01	QTa	AA	1,214.36
03-57-253	U 3 LO	COALORA	02/11/1983	<20	274	491.78	Tma	VA	1,237.02
03-57-254	U 3 LP	WHITEFACE A	12/20/1989	<20	197.1	481.35	QTa	AA	1,214.7
03-57-254	U 3 LP	WHITEFACE B	12/20/1989	<20	182.9	481.35	QTa	AA	1,214.7

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Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
03-57-255	U 3 LR	VAUGHN	03/15/1985	20 to 150	426.7	488.57	Tmr	VA	1,238.07
03-57-256	U 3 LS	MUGGINS	12/09/1983	<20	244	481.57	Tma	VA	1,215.22
03-57-257	U 3 LT	MINERO	12/20/1984	<20	243.8	481.27	Tma	VA	1,214.62
03-57-258	U 3 LU	WACO	12/01/1987	<20	182.9	460.59	QTa	AA	1,202.78
03-57-259	U 3 LV	DUORO	06/20/1984	20 to 150	381	474.26	Tma	VA	1,207.3
03-57-260	U 3 LW	CORREO	08/02/1984	<20	335.3	474.41	Tmr	VA	1,208.98
03-57-261	U 3 LZ	CHAMITA	08/17/1985	<20	335.3	475.17	Tma	VA	1,208.21
03-57-262	U 3 M	LUNA	09/21/1958	0.0015	147.5	494.65	QTa	AA	1,227.69
03-57-263	U 3 MC	ABO	10/30/1985	<20	198.1	495.30	QTa	AA	1,228.95
03-57-264	U 3 ME	KINIBITO	12/05/1985	20 to 150	579.1	495.53	Tac	VCU	1,234.97
03-57-265	U 3 MF	TAHOKA	08/13/1987	20 to 150	640.1	486.95	Tn	VCU	1,239.5
03-57-266	U 3 MG	PANCHUELA	06/30/1987	<20	320	473.05	QTa	AA	1,206.09
03-57-267	U 3 MH	LAREDO	05/21/1988	<150	350.5	514.69	Tn	VCU	1,247.12
03-57-268	U 3 MK	BOWIE	04/06/1990	<20	213.4	567.63	Tc	VTa	1,297.63
03-57-269	U 3 ML	DIVIDER	09/23/1992	<20	339.9	502.63	Tc	VCU	1,234.76
03-57-270	U 3 MN	ABILENE	04/07/1988	<20	243.8	481.28	Tmr	VA	1,214.63
03-57-271	U 3 MT	LUBBOCK	10/18/1991	20 to 150	457.2	468.57	Tp	VCU	1,239.71
03-57-272	U 3 N	BERNALILLO	09/17/1958	0.015	140	494.74	QTa	AA	1,227.78
03-57-273	U 3 P	SAN JUAN	10/20/1958	Zero	71.3	494.93	QTa	AA	1,227.97
03-57-274	U 3 Q	OTERO	09/12/1958	0.038	146.3	495.75	QTa	AA	1,228.79
03-57-275	U 3 R	VALENCIA	09/26/1958	0.002	147.52	495.05	QTa	AA	1,228.09
04-57-001	U 4 A	STRAIT	03/17/1976	200 to 500	780.3	484.17	Tn	VCU	1,270.55
04-57-002	U 4 AA	TRUMBULL	09/26/1974	<20	262.71	399.78	QTa	AA	1,295.59
04-57-003	U 4 AB	TEMESCAL	11/02/1974	<20	262.71	445.19	QTa	AA	1,290.4
04-57-004	U 4 AC	BELLOW	05/16/1984	<20	207.3	418.28	QTa	AA	1,292.75
04-57-005	U 4 AF	CARNELIAN	07/28/1977	<20	208	492.19	QTa	AA	1,291.68
04-57-006	U 4 AH	KARAB	03/16/1978	<20	331	524.71	Tn	VCU	1,274.52
04-57-007	U 4 AI	BURZET	08/03/1979	20 to 150	450	501.03	QTa	AA	1,262.42
04-57-008	U 4 AJ	MONTEREY	07/29/1982	20 to 150	400	494.69	Tx	VA	1,280.16
04-57-009	U 4 AK	TILCI	11/11/1981	20 to 150	445	492.10	QTa	AA	1,258.98
04-57-010	U 4 AL	MANTECA	12/10/1982	20 to 150	413	505.24	QTa	AA	1,262.97
04-57-011	U 4 AM	VILLE	06/12/1985	<20	293.2	520.33	Tx	VA	1,276.84
04-57-012	U 4 AN	COSO-BRONZE	03/08/1991	<20	333	499.42	Tmr	VA	1,281.23
04-57-012	U 4 AN	COSO-GRAY	03/08/1991	<20	442	499.42	Tc	VCU	1,281.23
04-57-012	U 4 AN	COSO-SILVER	03/08/1991	<20	475	499.42	Tbg	VCU	1,281.23

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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
04-57-013	U 4 AR	BRETON	09/13/1984	20 to 150	483	502.89	Tma	VA	1,264.59
04-57-014	U 4 AS	ROQUEFORT	10/16/1985	20 to 150	415	507.67	Tn	VCU	1,367.82
04-57-015	U 4 AT	PALISADE 1	05/15/1989	<20	335.3	490.05	Tc	VA	1,365.13
04-57-015	U 4 AT	PALISADE 2	05/15/1989	<20	390	490.05	Tc	VA	1,365.13
04-57-015	U 4 AT	PALISADE 3	05/15/1989	<20	404	490.05	Tc	VA	1,365.13
04-57-016	U 4 AU	BULLFROG	08/30/1988	<150	489.2	500.49	Tmr	VA	1,263.4
04-57-017	U 4 AV	BRISTOL	11/26/1991	<20	457.2	482.26	Tc	VCU	1,273.22
04-57-018	U 4 B	MACKEREL	02/18/1964	<20	333.71	484.00	Tx	VA	1,263.37
04-57-019	U 4 C	ZAZA	09/27/1967	20 to 200	667	488.04	Tn	VCU	1,267.41
04-57-020	U 4 D	LATIR	02/27/1974	20 to 200	640.99	486.08	Tn	VCU	1,270.03
04-57-021	U 4 E	TOPGALLANT	02/28/1975	20 to 200	713.2	483.55	Tn	VCU	1,272.07
04-57-022	U 4 F	TRANSOM	05/10/1978	Zero	640	472.41	Tc	VCU	1,258.49
04-57-023	U 4 G	ICEBERG	03/23/1978	20 to 150	640	485.38	Tn	VCU	1,265.67
04-57-024	U 4 H	SCANTLING	08/19/1977	20 to 150	701	481.52	Tn	VCU	1,272.48
04-57-025	U 4 I	GLENCOE	03/22/1986	29	609.6	492.74	Tc	VCU	1,260.53
04-57-026	U 4 J	JORNADA	01/28/1982	139	640	477.38	Tn	VCU	1,260.11
04-57-027	U 4 L	QUINELLA	02/08/1979	20 to 150	579.1	483.69	Tc	VCU	1,267.64
04-57-028	U 4 N	HEARTS	09/06/1979	140	640	472.81	Tc	VCU	1,258.89
04-57-029	U 4 O	TECHADO	09/22/1983	<150	533.4	492.48	Tn	VCU	1,267.59
04-57-030	U 4 P	ROUSANNE	11/12/1981	20 to 150	518.2	498.66	Tbg	VCU	1,269.8
04-57-031	U 4 Q	CAPROCK	05/31/1984	20 to 150	600	492.57	Tn	VCU	1,263.71
04-57-032	U 4 R	VERMEJO	10/02/1984	<20	350.5	467.08	Tma	VA	1,255.6
04-57-033	U 4 S	TULIA	05/26/1989	<20	396.24	470.61	Tma	VA	1,257.3
04-57-034	U 4 T	GASCON	11/14/1986	20 to 150	593.14	490.12	Tn	VCU	1,263.09
04-57-035	U 4 U	DALHART	10/13/1988	<150	640.1	477.16	Tn	VCU	1,255.62
06-57-001	U 6 A	RUSSET	03/05/1968	<20	119.79	458.88	QTa	AA	1,197.41
06-57-002	U 6 D	PRESIDIO	04/22/1987	<20	320	457.85	Tp	VA	1,198.51
06-57-003	U 6 E	AUSTIN	06/21/1990	<20	350.5	458.42	Tmr	VA	1,201.52
06-57-004	U 6 G	HARLINGEN A	08/23/1988	<20	289.6	462.88	QTa	AA	1,202.32
06-57-005	U 6 H	HARLINGEN B	08/23/1988	<20	289.6	462.12	QTa	AA	1,201.87
06-57-006	U 6 I	MONAHANS B	11/09/1988	<20	289.6	462.32	QTa	AA	1,201.46
07-57-001	U 7 A	FOREST	10/31/1964	<20	386.79	561.59	Tc	TC	1,296.77
07-57-002	U 7 AA	TAJIQUE	06/28/1972	<20	332.31	571.03	Tn	VCU	1,300.72
07-57-003	U 7 AB	REDMUD	12/08/1976	<20	426.7	533.36	Tn	VCU	1,295.66
07-57-004	U 7 AC	ESCABOSA	07/10/1974	20 to 200	639.99	513.39	Tn	VCU	1,250.4

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Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
07-57-005	U 7 AD	MIERA	03/08/1973	20 to 200	568.76	572.86	Tn	VCU	1,306.21
07-57-006	U 7 AE	STRAKE	08/04/1977	20 to 150	518.2	546.10	Tn	VCU	1,300.18
07-57-007	U 7 AF	POTRILLO	06/21/1973	20 to 200	568.45	547.74	Tc	VCU	1,282.31
07-57-008	U 7 AG	OBAR	04/30/1975	20 to 200	569	572.70	To	VCU	1,306.35
07-57-009	U 7 AH	MIZZEN	06/03/1975	20 to 200	637	536.08	Tn	VCU	1,274
07-57-010	U 7 AI	KEELSON	02/04/1976	20 to 200	640	508.38	Tn	VCU	1,244.78
07-57-011	U 7 AJ S	RUDDER	12/28/1976	20 to 150	640	544.11	Tn	VCU	1,281.73
07-57-012	U 7 AK	ESROM	02/04/1976	20 to 200	655.3	547.73	Tn	VCU	1,285.04
07-57-013	U 7 AL	DRAUGHTS	09/27/1978	20 to 150	442	525.95	To	VCU	1,261.43
07-57-014	U 7 AM	BULKHEAD	04/27/1977	20 to 150	594.3	551.45	Tn	VCU	1,286.02
07-57-015	U 7 AN	BILLET	07/27/1976	20 to 150	635.5	486.61	Tn	VCU	1,249.52
07-57-016	U 7 AO	PINEAU	07/16/1981	<20	204.2	552.12	Tma	VA	1,286.38
07-57-017	U 7 AP	CREWLINE	05/25/1977	20 to 150	563.9	497.71	Tn	VCU	1,264.28
07-57-018	U 7 AQ	SANDREEF	11/09/1977	20 to 150	701	478.66	Tbg	VCU	1,247.98
07-57-019	U 7 AT	CHESS	06/20/1979	<20	335.3	604.10	Tn	VCU	1,336.23
07-57-020	U 7 AU	RUMMY	09/27/1978	20 to 150	640	488.47	Tc	VCU	1,252.91
07-57-021	U 7 AV	LOWBALL	07/12/1978	20 to 150	563.9	490.13	Tn	VCU	1,252.43
07-57-022	U 7 AX	BACCARAT	01/24/1979	<20	326	606.01	Tn	VCU	1,337.83
07-57-023	U 7 AY	TOPMAST	03/23/1978	<20	457.2	575.68	Tn	VCU	1,309.33
07-57-024	U 7 B	AUK	10/02/1964	<20	452.38	528.39	Tn	VCU	1,280.94
07-57-025	U 7 BA	BASEBALL	01/15/1981	20 to 150	563.9	458.51	Tn	VCU	1,258.61
07-57-026	U 7 BD	PALIZA	10/01/1981	20 to 150	472.4	533.24	Tn	VCU	1,287.32
07-57-027	U 7 BE	PYRAMID	04/16/1980	20 to 150	579.1	557.27	Tn	VCU	1,292.75
07-57-028	U 7 BG	ALIGOTE	05/29/1981	<20	320	605.65	Tub	VCU	1,337.47
07-57-029	U 7 BH	FAHADA	05/26/1983	<20	384	606.39	Tn	VCU	1,338.82
07-57-030	U 7 BI	DOLCETTO	08/30/1984	<20	365.8	568.38	Tn	VCU	1,317.88
07-57-031	U 7 BK	MULESHOE	11/15/1989	<20	243.8	606.11	Tn	VCU	1,338.24
07-57-032	U 7 BL	TAJO	06/05/1986	20 to 150	518.2	581.50	Tn	VCU	1,315.76
07-57-033	U 7 BM	DUTCHESS	10/24/1980	<20	427	533.71	Tn	VCU	1,291.75
07-57-034	U 7 BO	MUNDO	05/01/1984	20 to 150	567	586.32	Tn	VCU	1,319.06
07-57-035	U 7 BP	ATRISCO	08/05/1982	138	640.1	537.95	Toy	VCU	1,294.77
07-57-036	U 7 BR	BORREGO	09/29/1982	<150	563.9	493.30	Tn	VCU	1,261.09
07-57-037	U 7 BS	HERMOSA	04/02/1985	20 to 150	640.1	541.38	Tn	VCU	1,277.78
07-57-038	U 7 BU	TURQUOISE	04/14/1983	<150	533	480.19	Tc	VCU	1,246.15
07-57-039	U 7 BV	PONIL	09/27/1985	<20	365.8	556.26	Tn	VCU	1,310.64

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
07-57-040	U 7 BY	MIDLAND	07/16/1987	20 to 150	487.7	577.23	Tn	VCU	1,310.58
07-57-041	U 7 CA	TEXARKANA	02/10/1989	20 to 150	502.9	519.08	Tn	VCU	1,293.58
07-57-042	U 7 CB	FLOYDADA	08/15/1991	<20	502.9	544.52	Tn	VCU	1,306.52
07-57-043	U 7 E	PIRANHA	05/13/1966	20 to 200	548.72	526.40	Tbg	VCU	1,263.71
07-57-044	U 7 F	BRONZE	07/23/1965	20 to 200	530.81	547.83	Tx	VCU	1,284.23
07-57-045	U 7 G	CHARCOAL	09/10/1965	20 to 200	455.37	532.77	Tx	VCU	1,271.61
07-57-046	U 7 H	CABRESTO	05/24/1973	<20	197.82	518.75	QTa	AA	1,255.15
07-57-047	U 7 J	LIME	04/01/1966	<20	561.44	584.75	Tn	VCU	1,318.4
07-57-048	U 7 K	TAN	06/03/1966	20 to 200	560.68	498.53	Tx	VCU	1,240.41
07-57-049	U 7 I	LAMPBLACK	01/18/1966	20 to 200	561.48	559.81	Tn	VCU	1,294.07
07-57-050	U 7 M	MICKEY	05/10/1967	20 to 200	499.65	573.46	Tn	VCU	1,304.68
07-57-051	U 7 N	BOURBON	01/20/1967	20 to 200	559.72	600.84	Op	LCA	1,333.27
07-57-052	U 7 O	DAIQUIRI	09/23/1966	<20	561.15	550.29	Tn	VCU	1,287.3
07-57-053	U 7 P	BLENTON	04/30/1969	20 to 200	557.73	535.84	Tn	VCU	1,281.69
07-57-054	U 7 R	SHAPER	03/23/1970	20 to 200	560.44	544.71	Tn	VCU	1,278.67
07-57-055	U 7 S	GRAPE A	12/17/1969	20 to 200	550.67	538.90	Tn	VCU	1,300.9
07-57-056	U 7 T	THISTLE	04/30/1969	20 to 200	560.47	555.76	Tn	VCU	1,308.01
07-57-057	U 7 U	COBBLER	11/08/1967	<20	667.12	531.52	Tn	VCU	1,269.44
07-57-058	U 7 V	GRAPE B	02/04/1970	20 to 200	554.03	562.66	To	VCU	1,296.31
07-57-059	U 7 W	TORRIDO	05/27/1969	20 to 200	514.72	566.40	Tn	VCU	1,297.31
07-57-060	U 7 X	ARTESIA	12/16/1970	20 to 200	484.83	595.03	Tn	VCU	1,328.99
07-57-061	U 7 Y	TIJERAS	10/14/1970	20 to 200	560.62	523.28	To	VCU	1,276.14
07-57-062	U 7 Z	OSCURO	09/21/1972	20 to 200	560.22	513.15	Tc	VCU	1,251.99
08-57-001	U 8 A	DISCUS THROWER	05/27/1966	22	337.06	660.65	Tx	VA	1,406.5
08-57-002	U 8 B	CYATHUS	03/06/1970	8.7	293.88	610.36	Tx	VA	1,379.68
08-57-003	U 8 C	NORBO	03/08/1980	<20	271	638.75	To	VCU	1,376.06
08-57-004	U 8 E	CREMINO	09/27/1978	<20	210	587.57	QTa	AA	1,367.86
08-57-004	U 8 E	CREMINO-CAERPHILLY	09/27/1978	<20	420	587.57	Tn	VCU	1,367.86
08-57-005	U 8 J	COTTAGE	03/23/1985	20 to 150	515	626.76	Tot	VCU	1,388.76
08-57-006	U 8 K	VIDE	04/30/1981	<20	323	634.53	To	VCU	1,373.37
08-57-007	U 8 L	SECO	02/25/1981	<20	200	645.73	Tn	VCU	1,383.04
08-57-008	U 8 M	FRISCO	09/23/1982	20 to 150	451	582.90	Tot	VCU	1,373.86
08-57-009	U 8 N	KAWICH A -WHITE	12/09/1988	<20	369	540.12	Tn	VCU	1,384.42
08-57-009	U 8 N	KAWICH A-BLUE	12/09/1988	<20	384	540.12	Tn	VCU	1,384.42
08-57-010	U 8 D	BANEBERRY	12/18/1970	10	277.98	648.47	Tma	VA	1,394.01

Table 3-2
Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
09-57-001	U 9ITST28	AVENS-ANDORRE	12/16/1970	<20	379.48	555.35	Tn	VCU	1,291.14
09-57-002	U 9ITSU 24	AVENS-ALKERMES	12/16/1970	<20	306.02	554.19	Tn	VCU	1,288.45
09-57-003	U 9ITSV 24	ARABIS-RED	03/06/1970	<20	249.91	558.52	Tn	VCU	1,291.87
09-57-004	U 9ITSV 26	FOB-RED	01/23/1970	<20	265.79	556.21	Tn	VA	1,289.86
09-57-005	U 9IV 27	FOB-GREEN	01/23/1970	<20	244.45	559.58	Tn	VA	1,292.93
09-57-006	U 9ITSW 21	AVENS-ASAMITE	12/16/1970	<20	306.32	556.97	Tn	VCU	1,290.62
09-57-007	U 9ITSX 20	HOD B-RED	05/01/1970	<20	265.18	559.89	Tn	VCU	1,292.93
09-57-008	U 9ITSX 23	HOD A-GREEN	05/01/1970	<20	240.79	562.02	Tn	VCU	1,294.76
09-57-009	U 9ITSX 24	SCREE-ACAJOU	10/13/1970	<20	249.94	563.24	Tn	VCU	1,295.98
09-57-010	U 9ITSX 27	PITON-B	05/28/1970	<20	228.6	564.45	Tn	VCU	1,296.88
09-57-011	U 9ITSX 28	ARABIS-GREEN	03/06/1970	<20	258.71	564.84	Tn	VCU	1,297.27
09-57-012	U 9ITSX 29	AVENS-CREAM	12/16/1970	<20	294.13	565.97	Tn	VCU	1,298.4
09-57-013	U 9IY 27	FOB-BLUE	01/23/1970	<20	100.58	567.22	Tn	VA	1,299.65
09-57-014	U 9ITSY 30	PITON-A	05/28/1970	<20	236.22	568.03	Tn	VCU	1,300.77
09-57-015	U 9TISZ 21	SCREE-ALHAMBRA	10/13/1970	<20	192.02	567.61	Tn	VA	1,300.04
09-57-016	U 9ITSZ 24	SCREE-CHAMOIS	10/13/1970	<20	100.58	569.33	Tn	VA	1,301.76
09-57-017	U 9IZ 25	HOD C-BLUE	05/01/1970	<20	100.58	570.11	Tn	VA	1,302.54
09-57-018	U 9ITSZ 26	ARABIS-BLUE	03/06/1970	<20	100.58	570.52	Tn	VCU	1,302.95
09-57-019	U 9ITSZ 27	NAMA-MEPHISTO	08/05/1971	<20	243.84	570.56	Tn	VCU	1,302.99
09-57-020	U 9ITSXY31	NAMA-AMARYLIS	08/05/1971	<20	272.8	567.91	Tn	VCU	1,300.34
09-57-021	U 9ITSW 22	HAPLOPAPPUS	06/28/1972	<20	184.4	557.94	Tx	VA	1,291.29
09-57-022	U 9ITSW 24.5	SOLANUM	12/14/1972	<20	201.17	561.57	Tn	VCU	1,294.31
09-57-023	U 9 A	MAD	12/13/1961	0.5	181.66	537.36	QTa	AA	1,281.38
09-57-024	U 9 AA	TAUNTON	12/04/1962	Low	227.08	538.46	QTa	AA	1,282.78
09-57-025	U 9 AB	KAWEAH	02/21/1963	3	227.08	534.01	QTa	AA	1,276.2
09-57-026	U 9 AC	TOYAH	03/15/1963	Low	130.45	538.13	QTa	AA	1,279.1
09-57-027	U 9 AD	MISSISSIPPI	10/05/1962	115	493.78	545.72	Tmr	VA	1,290.65
09-57-028	U 9 AE	STONES	05/22/1963	Intermediate	393.19	546.78	Tx	VA	1,284.09
09-57-029	U 9 AF	MANATEE	12/14/1962	Low	59.74	543.37	QTa	AA	1,280.68
09-57-030	U 9 AH	PLEASANT	05/29/1963	Low	210.92	539.74	QTa	AA	1,279.49
09-57-031	U 9 AI	APSHAPA	06/06/1963	Low	89	543.92	QTa	AA	1,281.23
09-57-032	U 9 AJ	GARDEN	10/23/1964	<20	149.66	567.84	Tmr	VA	1,301.19
09-57-033	U 9 AK 1	NATCHES	08/23/1963	Low	59.13	554.10	QTa	AA	1,288.36
09-57-034	U 9 AK	KOHOCTON	08/23/1963	Low	254.81	566.26	Tmr	VA	1,300.52
09-57-035	U 9 AL	AJAX	11/11/1966	<20	239.88	537.36	QTa	AA	1,280.77

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Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
09-57-036	U 9 AO	FORE	01/16/1964	20 to 200	491.03	544.92	Tx	VA	1,289.55
09-57-037	U 9 AP	RACK	08/15/1968	<20	199.64	536.21	QTa	AA	1,280.53
09-57-038	U 9 AQ	TORNILLO	10/11/1963	0.38	149.66	558.94	QTa	AA	1,293.51
09-57-039	U 9 AR	DRIVER	05/07/1964	<20	149.96	542.94	QTa	AA	1,280.25
09-57-040	U 9 AT	MUSTANG	11/15/1963	Low	165.81	541.85	QTa	AA	1,283.73
09-57-041	U 9 AU	BOGEY	04/17/1964	<20	119.18	557.52	QTa	AA	1,291.78
09-57-042	U 9 AV	EAGLE	12/12/1963	5.3	164.9	540.84	QTa	AA	1,281.2
09-57-043	U 9 AW	BACKSWING	05/14/1964	<20	160.63	547.49	QTa	AA	1,284.19
09-57-044	U 9 AX	GREYS	11/22/1963	Intermediate	301.14	533.47	QTa	AA	1,274.74
09-57-045	U 9 AY	OCONTO	01/23/1964	10.5	264.87	551.72	Tx	VA	1,286.59
09-57-046	U 9 AZ	TINDERBOX	11/22/1968	<20	441.96	546.97	Tx	VA	1,287.63
09-57-048	U 9 B	WHITE	05/25/1962	Low	192.63	533.85	QTa	AA	1,280.31
09-57-049	U 9 BA	HANDICAP	03/12/1964	<20	143.56	553.49	QTa	AA	1,287.75
09-57-050	U 9 BB	BUNKER	02/13/1964	<20	227.08	564.04	Tn	VCU	1,296.47
09-57-051	U 9 BC	HOOK	04/14/1964	<20	204.22	570.59	Tn	VCU	1,302.72
09-57-052	U 9 BD	SPOON	09/11/1964	<20	179.83	582.87	Tmr	VA	1,315.61
09-57-053	U 9 BE	FADE	06/25/1964	<20	205.13	573.47	Tmr	VA	1,306.82
09-57-054	U 9 BF	LINKS	07/23/1964	<20	120.4	565.84	QTa	AA	1,300.1
09-57-055	U 9 BG	CHENILLE	04/22/1965	<20	140.82	569.34	QTa	AA	1,303.3
09-57-056	U 9 BH	WOOL	01/14/1965	<20	216.1	581.78	Tn	VA	1,313.6
09-57-057	U 9 BI 1	TERRINE-WHITE	12/18/1969	20 to 200	457.2	556.13	Tn	VCU	1,290.7
09-57-058	U 9 BI 2	TERRINE-YELLOW	12/18/1969	20 to 200	417.58	571.93	Tn	VCU	1,304.06
09-57-059	U 9 BJ	TICKING	08/21/1965	<20	208.48	582.08	Tmr	VA	1,314.82
09-57-060	U 9 BK	SUEDE	03/20/1965	<20	143.26	580.52	Tmr	VA	1,312.65
09-57-061	U 9 BM	SEERSUCKER	02/19/1965	<20	144.17	567.81	Tmr	VA	1,301.16
09-57-062	U 9 BN	TWEED	05/21/1965	<20	284.38	576.01	Tn	VA	1,308.14
09-57-063	U 9 BO	ORGANDY	06/11/1965	<20	168.86	587.75	Tx	VA	1,320.49
09-57-064	U 9 BP	IZZER	07/16/1965	<20	163.68	565.26	QTa	AA	1,299.52
09-57-065	U 9 BR	MAXWELL	01/13/1966	<20	182.88	577.51	Tx	VA	1,309.94
09-57-066	U 9 BS	ELKHART	09/17/1965	<20	220.37	558.43	Tmr	VA	1,293.91
09-57-067	U 9 BT	TEMPLAR	03/24/1966	0.37	149.96	567.42	Tmr	VA	1,301.68
09-57-068	U 9 BU	HULA	10/29/1968	<20	200.56	543.00	QTa	AA	1,280.62
09-57-069	U 9 BV	SWITCH	06/22/1967	3.1	302.06	571.66	Tn	VCU	1,303.48
09-57-070	U 9 BX	NOGGIN	09/06/1968	20 to 200	582.17	543.54	Tx	VCU	1,286.34
09-57-071	U 9 BY	VALISE	03/18/1969	<20	91.44	547.82	QTa	AA	1,287.87

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Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
09-57-072	U 9 BZ	BIGGIN	01/30/1969	<20	243.84	544.92	Tmr	VA	1,283.76
09-57-073	U 9 C	STILLWATER	02/08/1962	3.07	181.36	540.41	QTa	AA	1,286.26
09-57-074	U 9 CB	CUP	03/26/1965	20 to 200	538.89	554.53	Tn	VCU	1,293.97
09-57-075	U 9 CC	PLAYER	08/27/1964	<20	90.22	543.16	QTa	AA	1,280.47
09-57-076	U 9 CE	CLYMER	03/12/1966	<20	398.07	545.87	QTa	AA	1,292.93
09-57-077	U 9 CF	VAT	10/10/1968	<20	192.02	542.88	QTa	AA	1,282.63
09-57-078	U 9 CG	GRUYERE	08/16/1977	<20	207	544.69	QTa	AA	1,289.93
09-57-078	U 9 CG	GRUYERE-GRADINO	08/16/1977	<20	320	544.69	QTa	AA	1,289.93
09-57-079	U 9 CH	CATHAY	10/08/1971	<20	377.95	551.81	Tx	VA	1,288.21
09-57-080	U 9 CI	ARSENATE	11/09/1972	<20	250.24	561.97	Tx	VA	1,295.01
09-57-081	U 9 CJ	ALUMROOT	02/14/1973	<20	182.88	545.84	QTa	AA	1,291.38
09-57-082	U 9 CK	SILENE	06/28/1973	<20	198.12	543.03	QTa	AA	1,280.65
09-57-083	U 9 CL	TELEME	02/06/1975	<20	304.8	594.36	Tn	VCU	1,327.1
09-57-084	U 9 CM	LEYDEN	11/26/1975	<20	326.1	596.98	Tn	VCU	1,329.72
09-57-085	U 9 CN	KESTI	06/16/1982	<20	289	606.07	Tn	VCU	1,338.5
09-57-086	U 9 CP	CAMPOS	02/13/1978	<20	320	563.92	Tn	VCU	1,296.35
09-57-087	U 9 CQ	DAUPHIN	11/14/1980	<20	320	600.25	Tn	VCU	1,332.68
09-57-088	U 9 CR	NIZA	07/10/1981	<20	341	559.99	Tn	VCU	1,293.03
09-57-089	U 9 CS	ARMADA	04/22/1983	<20	265	590.10	Tx	VCU	1,322.53
09-57-090	U 9 CV	GALENA-GREEN	06/23/1992	<20	401	563.19	Tn	VCU	1,295.62
09-57-090	U 9 CV	GALENA-ORANGE	06/23/1992	<20	381	563.19	Tn	VCU	1,295.62
09-57-090	U 9 CV	GALENA-YELLOW	06/23/1992	<20	290	563.19	Tn	VCU	1,295.62
09-57-091	U 9 CW	CEBRERO	08/14/1985	<20	183	610.51	Tc	VCU	1,342.64
09-57-092	U 9 D	BRAZOS	03/08/1962	8.4	256.34	535.02	QTa	AA	1,280.56
09-57-093	U 9 E	HATCHIE	02/08/1963	Low	60.96	546.32	QTa	AA	1,282.72
09-57-094	U 9 F	TIOGA	10/18/1962	Low	59.44	543.04	QTa	AA	1,280.96
09-57-095	U 9 G	CODSAW	02/19/1962	Low	212.14	549.96	Tmr	VA	1,285.44
09-57-096	U 9 H	CIMARRON	02/23/1962	11.9	304.8	539.47	QTa	AA	1,282.57
09-57-098	U 9 I	ANACOSTIA	11/27/1962	5.2	226.77	568.88	Tu	VCU	1,301.01
09-57-099	U 9 ITSS 25	BALTIC	08/06/1971	<20	411.48	546.82	Tn	VCU	1,286.87
09-57-100	U 9 ITSZ26	CANNA-LIMOGES	11/17/1972	<20	213.42	567.55	Tn	VCU	1,299.98
09-57-100	U 9 ITSZ26	CANNA-UMBRINUS	11/17/1972	<20	182.88	567.55	Tn	VCU	1,299.98
09-57-101	U 9 J	HOOSIC	03/28/1962	3.4	186.84	557.30	Tu	VA	1,290.95
09-57-102	U 9 K	DEAD	04/21/1962	Low	193.55	565.69	QTa	AA	1,298.73
09-57-103	U 9 L	PASSAIC	04/06/1962	Low	233.48	536.05	QTa	AA	1,274.89

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Corrective Action Sites in Yucca Flat
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CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
09-57-104	U 9 M	EEL	05/19/1962	4.5	217.63	536.36	QTa	AA	1,280.07
09-57-105	U 9 N	HUDSON	04/12/1962	Low	150.88	538.92	QTa	AA	1,280.19
09-57-106	U 9 P	BLACK	04/27/1962	Low	217.63	549.38	QTa	AA	1,285.47
09-57-107	U 9 Q	ROANOKE	10/12/1962	Low	176.78	530.20	QTa	AA	1,279.4
09-57-108	U 9 R	ARIKAREE	05/10/1962	Low	166.42	537.94	QTa	AA	1,281.35
09-57-109	U 9 U	RARITAN	09/06/1962	Low	157.28	540.44	QTa	AA	1,281.41
09-57-110	U 9 V	SACRAMENTO	06/30/1962	Low	149.05	527.09	QTa	AA	1,273.24
09-57-111	U 9 W	KOOTANAI	04/24/1963	Low	181.97	552.27	QTa	AA	1,287.75
09-57-112	U 9 W 1	PAISANO	04/24/1963	Low	57	552.63	QTa	AA	1,287.81
09-57-113	U 9 X	ALLEGHENY	09/29/1962	Low	210.92	563.46	QTa	AA	1,297.72
09-57-114	U 9 Y	WICHITA	07/27/1962	Low	150.27	546.69	QTa	AA	1,291.93
09-57-115	U 9 Z	YORK	08/24/1962	Low	226.47	545.71	QTa	AA	1,282.72
09-57-116	U 2 A	ALPACA	02/12/1965	0.33	224.94	603.56	QTa	AA	1,341.79
10-57-001	U10 A	DUB	06/30/1964	11.7	259.08	574.52	QTa	AA	1,308.48
10-57-002	U10 AA	RIVET 1	01/18/1967	<20	151.79	566.59	QTa	AA	1,302.38
10-57-003	U10 AB	VITO	07/14/1967	<20	96.62	571.29	QTa	AA	1,304.64
10-57-004	U10 AD	VIGIL	11/22/1966	<20	91.44	571.75	QTa	AA	1,304.79
10-57-005	U10 AF	YARD	09/07/1967	20 to 200	521.21	554.89	Tx	VCU	1,297.38
10-57-006	U10 AG	WORTH	10/25/1967	<20	187.45	547.93	QTa	AA	1,295.6
10-57-007	U10 AH	STACCATO	01/19/1968	20 to 200	443.48	559.13	QTa	AA	1,298.88
10-57-008	U10 AI	POLKA	12/06/1967	<20	190.5	558.13	QTa	AA	1,299.4
10-57-009	U10 AJ A	TUB-F	06/06/1968	<20	188.98	575.46	QTa	AA	1,308.81
10-57-010	U10 AJ B	TUB-B	06/06/1968	<20	188.98	573.45	QTa	AA	1,306.19
10-57-011	U10 AJ C	TUB-A	06/06/1968	<20	188.98	575.46	QTa	AA	1,308.81
10-57-012	U10 AJ D	TUB-D	06/06/1968	<20	273.1	571.99	QTa	AA	1,305.03
10-57-013	U10 AJ F	TUB-C	06/06/1968	<20	188.98	576.78	QTa	AA	1,310.13
10-57-014	U10 AK	CROCK	05/08/1968	<20	181.66	583.07	QTa	AA	1,315.81
10-57-015	U10 AM 1	TUN-A	12/10/1969	<20	199.64	611.45	QTa	AA	1,349.98
10-57-016	U10 AM 2	TUN-B	12/10/1969	<20	193.85	613.15	Tn	VCU	1,351.38
10-57-017	U10 AM 3	TUN-C	12/10/1969	<20	193.7	608.02	Tbg	VCU	1,345.64
10-57-018	U10 AM 4	TUN-D	12/10/1969	<20	256.34	609.72	Tn	VCU	1,347.34
10-57-019	U10 AN	LABIS	02/05/1970	25	441.96	579.65	Tn	VCU	1,313
10-57-020	U10 AP 1	CORNICE-YELLOW	05/15/1970	20 to 200	390.14	583.88	Tn	VCU	1,319.36
10-57-021	U10 AP 3	CORNICE-GREEN	05/15/1970	20 to 200	443.48	579.67	Tn	VCU	1,312.41
10-57-022	U10 AQ	BRACKEN	07/09/1971	<20	304.8	585.25	Tn	VCU	1,323.48

Table 3-2
Corrective Action Sites in Yucca Flat
(Page 21 of 22)

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
10-57-023	U10 AR	LAGOON	10/14/1971	<20	304.8	575.00	QTa	AA	1,312.62
10-57-024	U10 AS	PINEDROPS-BAYOU	01/10/1974	<20	342.9	575.62	Tn	VCU	1,309.88
10-57-024	U10 AS	PINEDROPS-SLOAT	01/10/1974	<20	213.36	575.62	QTa	AA	1,309.88
10-57-024	U10 AS	PINEDROPS-TAWNY	01/10/1974	<20	281.94	575.62	QTa	AA	1,309.88
10-57-025	U10 AT	DIANTHUS	02/17/1972	<20	304.8	571.99	QTa	AA	1,305.95
10-57-026	U10 AV	KASHAN	05/24/1973	<20	265.18	566.48	QTa	AA	1,303.79
10-57-027	U10 AW	NATOMA	04/05/1973	<20	243.84	573.76	QTa	AA	1,309.85
10-57-028	U10 AX	AKBAR	11/09/1972	<20	266.7	587.72	Tn	VCU	1,321.98
10-57-029	U10 AY	CHEVRE	11/23/1976	<20	317	571.93	QTa	AA	1,304.97
10-57-030	U10 B	HANDCAR	11/05/1964	12	403.25	598.23	Cbk	LCA	1,333.41
10-57-031	U10 BA	DOFINO	03/08/1977	<20	183	574.68	QTa	AA	1,309.55
10-57-031	U10 BA	DOFINO-LAWTON	03/08/1977	<20	282	574.68	QTa	AA	1,309.55
10-57-032	U10 BB	PORTOLA	02/06/1975	<20	198.1	575.28	QTa	AA	1,312.29
10-57-032	U10 BB	PORTOLA-LARKIN	02/06/1975	<20	274.3	575.28	QTa	AA	1,312.29
10-57-033	U10 BC	ASCO	04/25/1978	<20	183	579.45	Tn	VCU	1,312.19
10-57-034	U10 BD	PERA	09/08/1979	<20	200	574.49	Tx	VA	1,307.23
10-57-035	U10 BE	ORKNEY	05/02/1984	<20	210	605.67	QTa	AA	1,378.34
10-57-036	U10 BF	QUESO	08/11/1982	<20	216	570.89	QTa	AA	1,337.16
10-57-037	U10 BG	HAVARTI	08/05/1981	<20	200	577.48	Tn	VCU	1,309.91
10-57-038	U10 BH	HAZEBROOK-APRICOT	02/03/1987	<20	262	570.62	QTa	AA	1,317.38
10-57-038	U10 BH	HAZEBROOK-CHECKERBERRY	02/03/1987	<20	226	570.62	QTa	AA	1,317.38
10-57-038	U10 BH	HAZEBROOK-EMERALD	02/03/1987	<20	186	570.62	QTa	AA	1,317.38
10-57-039	U10 C	TURF	04/24/1964	20 to 200	506.27	553.21	Tmr	VA	1,298.45
10-57-040	U10 CA	JARLSBERG	08/27/1983	<20	200	325.17	Tub	VCU	1,344.42
10-57-041	U10 CB	NORMANNA	07/12/1984	<20	200	349.61	Tub	VCU	1,342.34
10-57-042	U10 CC	BRIE	06/18/1987	<20	203	326.55	Tub	VCU	1,345.19
10-57-043	U10 D S	DUFFER	06/18/1964	<20	446.84	580.43	Tn	VCU	1,314.39
10-57-044	U10 D S1	MARVEL	09/21/1967	2.2	175.87	580.43	QTa	AA	1,314.39
10-57-045	U10 E	KLICKITAT	02/20/1964	70	492.56	567.60	Tn	VCU	1,300.34
10-57-046	U10 F	SANTEE	10/27/1962	Low	318.52	550.93	QTa	AA	1,296.47
10-57-047	U10 G	CASSELMAN	02/08/1963	Low	302.97	548.76	QTa	AA	1,294.61

Table 3-2
Corrective Action Sites in Yucca Flat
(Page 22 of 22)

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation (m amsl) ^e
							Stratigraphy ^c	HSU ^d	
10-57-048	U10 I	BYE	07/16/1964	20 to 200	390.75	565.80	Tn	VCU	1,321.4
10-57-049	U10 K	CORDUROY	12/03/1965	20 to 200	678.79	568.03	Tn	VCU	1,302.29
10-57-050	U10 M	REO	01/22/1966	<20	208.18	576.71	QTa	AA	1,309.45
10-57-051	U10 N	MUDPACK	12/16/1964	2.7	152.1	602.26	Tn	VA	1,336.83
10-57-052	U10 P	KANKAKEE	06/15/1966	20 to 200	454.76	574.44	Cbk	LCA	1,308.09
10-57-053	U10 Q	STANLEY	07/27/1967	20 to 200	483.72	547.50	Tx	VA	1,291.52
10-57-054	U10 R	WASHER	08/10/1967	<20	466.34	552.72	Tu	VCU	1,297.65
10-57-055	U10 S	ROVENA	08/10/1966	<20	195.07	571.96	QTa	AA	1,304.7
10-57-056	U10 T	SHUFFLE	04/18/1968	20 to 200	493.17	574.05	Tot	VCU	1,306.18
10-57-057	U10 U	NEWARK	09/29/1966	<20	229.21	572.96	QTa	AA	1,306
10-57-058	U10 W	SIMMS	11/05/1966	2.3	198.73	572.96	QTa	AA	1,306.31
10-57-059	U10 X	WARD	02/08/1967	<20	259.99	571.05	QTa	AA	1,303.79
10-57-060	U10 Y	RIVET III	03/02/1967	<20	273.71	571.05	QTa	AA	1,301.56
10-57-061	U10 Z	RIVET II	01/26/1967	<20	197.51	571.05	QTa	AA	1,300.65

Source: FFACO (1996); DOE/NV, 1994b; and DOE/NV, 1997d

^akt = Kiloton

^bm bgs = Meters below ground surface

^cStratigraphy - see list of stratigraphic unit symbols

^dHydrostratigraphy

AA = Alluvial Aquifer

VA = Volcanic Aquifer

VCU = Volcanic Confining Unit

LCA = Lower Carbonate Aquifer

^em amsl = Meters above mean sea level

^fTotal includes all four detonations

Table 3-3
Corrective Action Sites in Climax Mine

CAS No.	Hole Name	Detonation Name	Date	Yield Range (kt) ^a	Depth of Burial (m bgs) ^b	Depth to Water (m bgs)	Working Point		Land Surface Elevation
							Stratigraphy ^c	HSU ^d	(m amsl) ^e
15-57-001	U-15a	HARD HAT	02/15/62	5.7	287.12	221.9	Kg	I	1,558.75
15-57-002	U-15.01	PILE DRIVER	06/02/66	62	462.69	185.33	Kg	I	1,551.44
15-57-003	U-15e	TINY TOT	06/17/65	<20	110.95	227.99	Kg	I	1,530.71

Source: FFACO, 1996; DOE/NV, 1994b; and DOE/NV, 1997d

^akt = Kiloton

^bm bgs = Meters below ground surface

^cStratigraphic Unit - see list of stratigraphic unit symbols

^dHSU

I = Intrusives

^em amsl = Meters above mean sea level

of the Yucca Flat/Climax Mine CAU conceptual model will be updated following a thorough data assessment process as discussed in [Sections 5.1.1](#), [5.1.3.2.1](#), and [5.1.3.3.1](#).

3.4.1 Climate

The Yucca Flat/Climax Mine CAU lies approximately 40 miles northeast of the most arid part of Nevada, the Amargosa Desert, and 85 miles northeast of Death Valley, California ([Figure 1-2](#)) where average annual rainfall is approximately 7 centimeters (cm) (2.7 inches [in.]).

Information on precipitation was gathered during the regional evaluation (DOE/NV, 1997c).

Information on both precipitation and recharge has been provided in Sections 3.0 through 11.0 (pages 3-1 through 11-6) of Volume III of the documentation package (IT, 1996c). Information specific to precipitation has also been provided in Section 7.3.1 of Volume III (Pages 7-5 to 7-12) (IT, 1996c) and Section 5.7.1.2.1 (pages 5-24 to 5-25) of the regional evaluation report (DOE/NV, 1997c).

[Table 3-4](#) includes average annual precipitation totals for stations located within the Yucca Flat/Climax Mine investigation area. Their locations are shown in [Figure 3-3](#). Average annual precipitation within the Yucca Flat/Climax Mine investigation area ranges from over 21.3 centimeters per year (cm/yr) (8.39 inches per year [in./yr]) at the Stockade Pass station located on the Eleana

Table 3-4
Average Precipitation Rates within the Investigation Area

Station Number	Station Name	UTM Zone 11, NAD 27		Land Surface Elevation	Average Annual Precipitation		
		Easting	Northing	(meters)	Depth		Years
		(meters)	(meters)		(cm/year)	(inches/year)	Record
27	Lathrop Wells	558,275.00	4,030,159.00	664.00	8.5	3.35	21
35	4JA	563,445.00	4,071,032.00	1,043.00	13.3	5.24	34
36	Shoshone Basin	566,464.00	4,087,547.00	1,725.00	21.6	8.50	13
40	Skull Mountain Pass	568,500.00	4,065,887.00	1,186.00	16.1	6.32	8
43	Stockade Pass	570,759.00	4,113,178.00	2,053.00	21.3	8.39	9
46	Tippipah Spring	571,887.00	4,100,851.00	1,518.00	24.3	9.57	28
47	RV-1	572,151.00	4,060,050.00	1,036.00	15.9	6.26	28
49	Mid Valley	573,701.00	4,091,914.00	1,420.00	23.6	9.29	29
53	RV-Wash	576,721.00	4,053,568.00	866.00	10	3.92	8
54	Cane Springs	579,583.00	4,074,185.00	1,219.00	20.6	8.11	29
56	BJY	584,209.00	4,102,022.00	1,241.00	16.1	6.34	33
57	Yucca	584,791.00	4,090,231.00	1,195.00	17	6.69	34
58	PHS Farm	585,301.00	4,118,280.00	1,391.00	19.4	7.64	24
59	Desert	587,122.00	4,053,108.00	1,005.00	15.2	5.98	30
62	Mercury	589,740.00	4,057,169.00	1,149.00	15.7	6.18	23
63	Well 5B	592,263.00	4,073,193.00	939.00	12.7	5.00	30

Source: Jacobson, 1996 and French, 1996

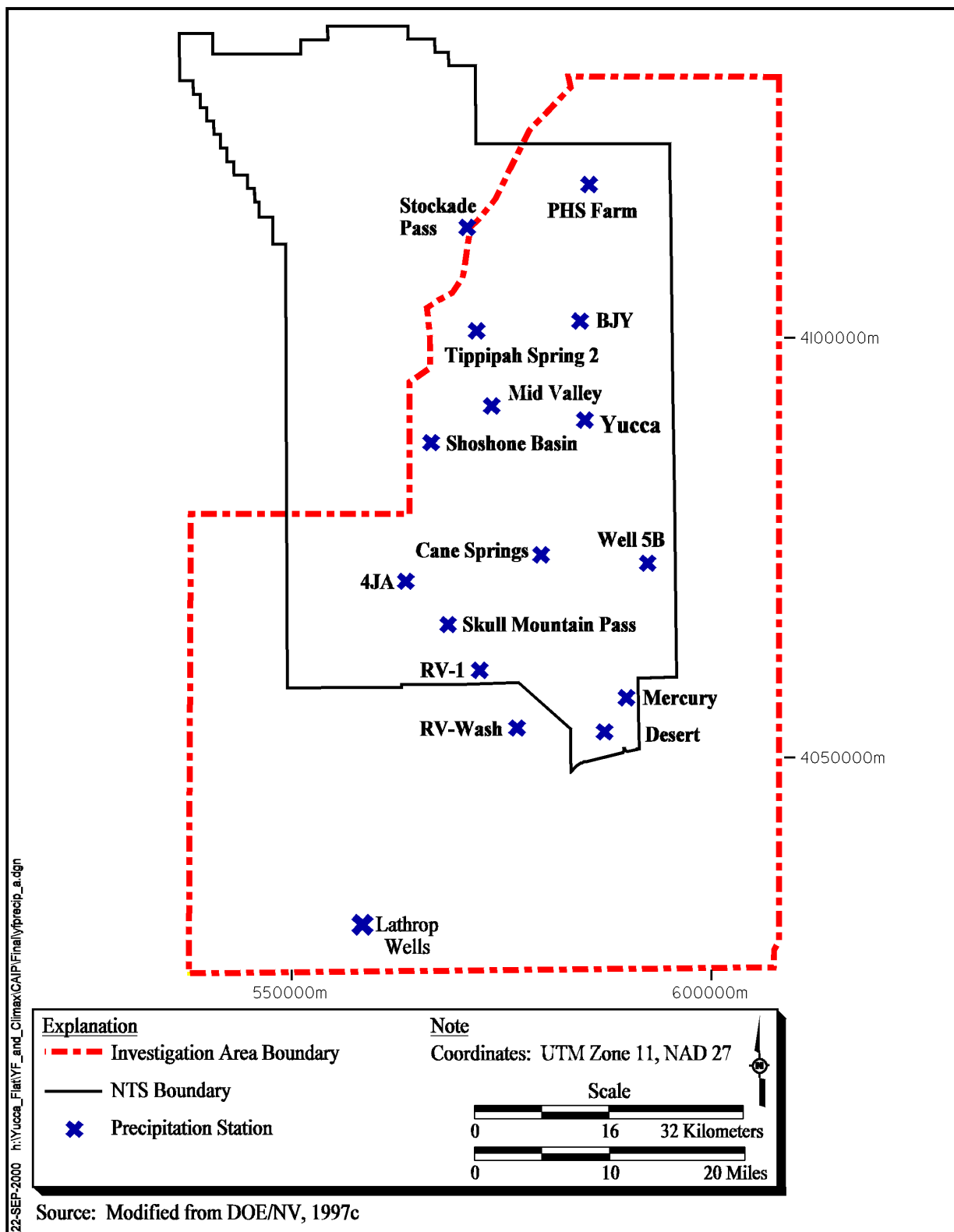


Figure 3-3
Location of Precipitation Stations in the Yucca Flat/Climax Mine Investigation Area

Range to 16.10 cm/yr (6.34 in./yr) at the BJY station in Yucca Flat (Jacobson, 1996 and French, 1996).

Precipitation is highly seasonal, falling predominantly in the winter and summer months. Winter precipitation usually results from relatively large low-pressure systems moving in from the west. In the summer, precipitation is typically from small convective storms that originate south of the study area.

The potential annual evaporation from reservoirs and lakes in the region is estimated to range from 152 to 208 cm/yr (60 to 82 in./yr) (Meyers and Nordenson, 1962), which is 4 to 14 times greater than annual precipitation within the Yucca Flat drainage basin. However, no permanent reservoirs or lakes exist within Yucca Flat, and no groundwater evapotranspiration (ET) is known to occur from the regional groundwater flow system within Yucca Flat. As in most arid regions, the relative humidity is low, ranging from 10 to 30 percent in summer, and 20 to 60 percent in the winter.

At Area 6, in southern Yucca Flat, at an elevation of 1,200 m above mean sea level (amsl) (3,936 ft amsl), the mean daily maximum and minimum temperatures are 10.6 and -6.1 degrees Celsius (°C) (51.1 and 21.0 degrees Fahrenheit [°F]) in January, and 35.6 and 13.9 °C (96.1 and 57.0 °F) in July, respectively (REECo, 1995).

The movements of large-scale pressure systems control the seasonal changes in wind-direction frequencies. Predominating winds are southerly during summer, and northerly during winter. The general downward slope of the terrain in the region from north to south results in an intermediate regime that is reflected in the characteristic diurnal wind reversal from southerly winds during the day to northerly winds at night. This reversal is strongest in the summer and, on occasion, becomes intense enough to override the seasonal prevailing wind (DOE/NV, 1992). At Area 6 in Yucca Flat, the average annual wind speed is 11 kilometers per hour (7 miles per hour) (REECo, 1995).

3.4.2 Topography

Information on the topography of the NTS region including Yucca Flat has previously been provided in Volume I of the regional evaluation documentation package (Map F20 in Appendix F) (IT, 1996f); and in Section 2.2 (pages 2-1 to 2-4) of regional evaluation report (DOE/NV, 1997c). The following

description of topography of the area of interest is based mainly on the 15-minute USGS quadrangle maps: Tippipah Spring, Papoose Lake, Cane Spring, and Frenchman Lake. The regional terrain is dominated by Basin and Range topography, produced by crustal extension and normal block faulting. Yucca Flat is a typical example of an intermontane basin. The axes of the alternating basins and ranges are generally north-south; but to the southeast of Yucca Flat, the orientation of the axes is rotated to northeast-southwest.

The floor of Yucca Flat slopes from a maximum elevation of approximately 1,342 m amsl (4,400 ft amsl) at the north end to a minimum elevation of approximately 1,189 m amsl (3,900 ft amsl) on a playa lake bed at the south end. Numerous anthropogenic craters, created by underground weapons tests, are present on the floor of Yucca Flat (Allen et al., 1997). The largest of these, the Sedan Crater, located at the northern end of the basin is over 90 m (300 ft) deep. Yucca Flat is enclosed by topographic highs formed by the Halfpint Range to the east, by Mine Mountain and the Eleana Range to the west, and by the Massachusetts Mountains and CP Hills to the south. The northeastern end of the Eleana Range, where the Climax Mine is located, borders Yucca Flat to the north. An unnamed ridge divides the southern third of the basin longitudinally into Yucca Flat and the smaller Plutonium Valley. The maximum elevations of the east and west margins of the basin are above 1,900 m amsl (6,300 ft amsl) in the Halfpint Range, and 2,346 m amsl (7,694 ft amsl) on Rainier Mesa. The maximum elevations of the north and south margins of the basin are above 2,165 m amsl (7,100 ft amsl) on Quartzite Ridge, and 1,628 m amsl (5,341 ft amsl) in the CP Hills. All drainage systems within the Yucca Flat hydrographic area terminate at the Yucca Lake playa.

3.4.3 Surface Water

Surface water for the NTS region, including Yucca Flat, has previously been discussed in Section 5.0 (pages 5-1 to 5-2), Section 8.0 (Pages 8-1 to 8-7), and Appendix A (pages A-1 to A-26) of Volume III of the regional documentation package (IT, 1996c). A summary was also provided in Section 5.7.2.1 (pages 5-30 to 5-37) of regional evaluation report (DOE/NV, 1997c). A description of the surface water features specific to Yucca Flat is provided in this section.

No natural permanent streams or bodies of water are present within the Yucca Flat hydrographic area. The predominant geomorphological feature of Yucca Flat is Yucca “Lake,” a dry playa. The nearest significant source of surface water is located at Ash Meadows, approximately 31 km (50 mi)

southwest of the Yucca Flat/Climax Mine CAU. Within the Yucca Flat hydrographic area, surface water occurs perennially only at a few locations in the form of perched springs or seeps ([Figure 3-4](#)), which have been described in detail by Hansen et al. (1997). Tippihah Spring occurs at the southern end of the Eleana Range in Area 16 at an elevation of 1,583 meters amsl (5,194 ft amsl). Captain Jack Spring and White Rock Springs occur in the Eleana Range in Area 12 at approximate elevations of 1,768 and 1,555 m amsl (5,800 and 5,100 ft amsl), respectively. Oak Spring and Tub Spring occur in the northeastern end of the Eleana Range in Area 15 at approximate elevations of 1,768 and 1,616 m amsl (5,800 and 5,300 ft amsl), respectively. Reitmann Seep occurs in the Halfpint Range in Area 7 at an approximate elevation of 1,402 m amsl (4,600 ft amsl).

More typically, surface water in the region occurs only during and after storm events, or as meltwater from snow. This component of precipitation is hydrologically significant and provides some recharge to the regional groundwater flow system via direct infiltration or by being conducted from higher areas down washes or canyons to be redistributed into alluvium on the valley floors.

3.4.4 Geology

An overview of the geology of the NTS region is presented, followed by a detailed description of the geology of the Yucca Flat/Climax Mine area. The description is based on the regional geologic model (IT, 1996f; DOE/NV,1997c), which was interpreted using the information available at the time. The location of the existing boreholes from which information was available at that time are shown in [Figure 3-1](#). Sources of data included the Weapons Program and other public and private sources.

3.4.4.1 Regional Geology

The geology of the NTS and the surrounding area is the product of a complex history, marked by major structural events (ERDA, 1977). The historical events that shaped the stratigraphy and structure of the region during the Precambrian, Paleozoic, Mesozoic, and Tertiary geologic times are described in this section. The stratigraphic nomenclature and correlation of the pre-Tertiary and Mesozoic sediments in the region are shown in [Table 3-5](#). Stratigraphic nomenclature of the Tertiary rocks (Ferguson et al., 1994) is shown in [Table 3-6](#). For a view of the surficial geology of the region, the reader is referred to the state of Nevada geologic map (Stewart and Carlson, 1977); and to the geologic map of the NTS and vicinity (Slate et al., 1999).

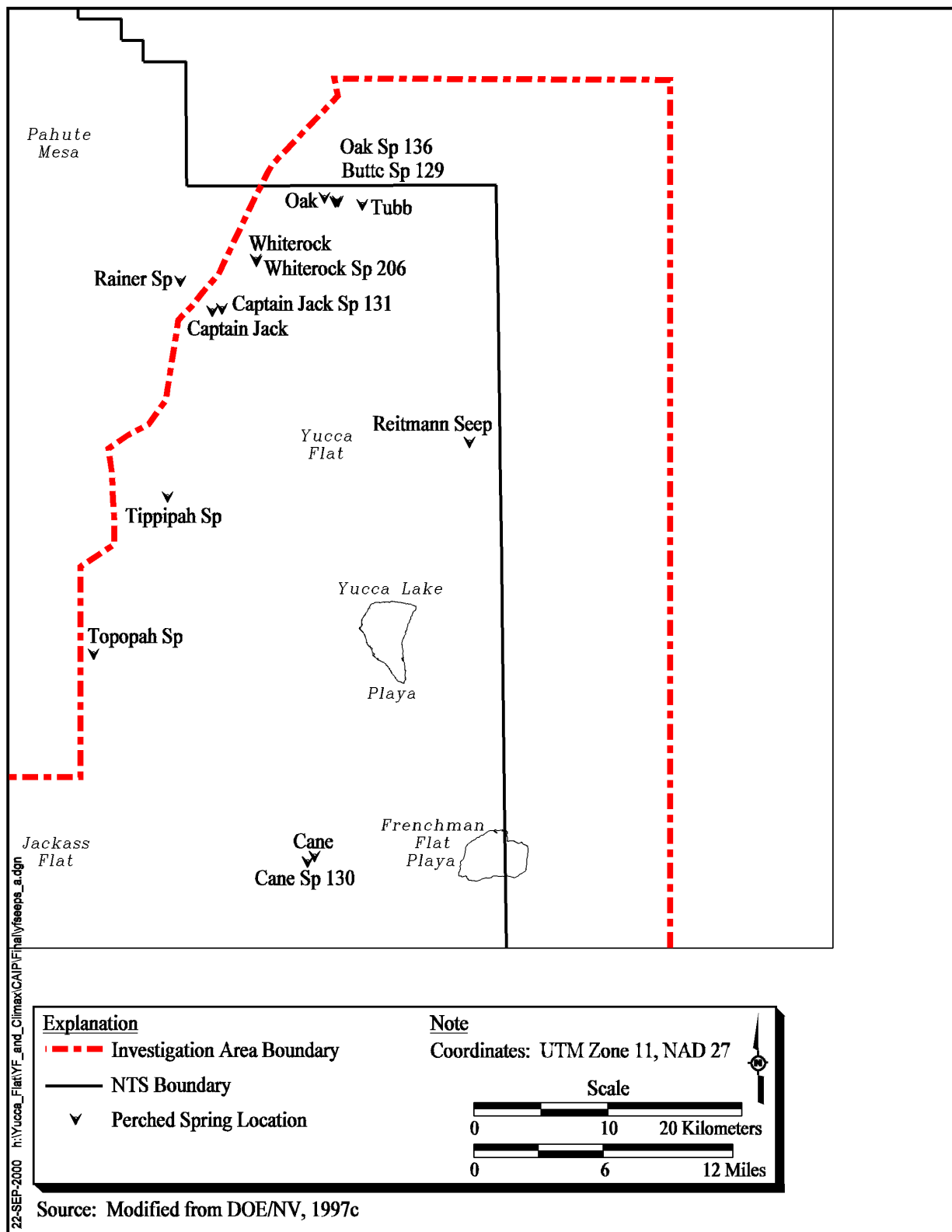


Figure 3-4
Location of Perched Springs or Seeps within the Yucca Flat/Climax Mine Area

Table 3-5
Pre-Tertiary Stratigraphic and Hydrostratigraphic Correlation
for the Investigation Area

		NEVADA TEST SITE	BARE MOUNTAIN	CACTUS RANGE TRAPPMAN HILLS	BELTED RANGE	MONTGOMERY MOUNTAINS/ NOPAH RANGE	FUNERAL MOUNTAINS	H ^a S U
PENNSYLVANIAN		Tippipah Ls. ^b				Bird Spring Ls.		U ^e C A
MISSISSIPPIAN		Eleana Fm. ^{c,d} and Chainman Shale	Eleana Fm.	Eleana Fm.	Eleana Fm.	Monte Cristo Ls.	Perdido Fm. Tin Mountain Ls.	U ^f C C U
SILURIAN/ DEVONIAN	U. DEVON.	Guilmette Ls.	Rocks of	Simonson Fm.	Simonson Fm.	Guilmette Ls.	Lost Burro Fm.	L C A 3 / L ^h C A
	M. DEVON.	Simonson Fm.	Tarantula Canyon	Simonson Fm.	Simonson Fm.	Simonson Fm.		
	L. DEVON.	Sevy Ds. ^g	Lone Mountain Ds.	Sevy Ds.	Sevy Ds.	Hidden Valley Fm.	Hidden Valley Fm.	
	SILURIAN	Laketown Ds.	Roberts Mountain Fm.	Roberts Mountain Fm.	Laketown Ds.			
ORDOVICIAN	UPPER	Ely Springs Dolostone						
	MIDDLE	Antelope Valley Ls.	Eureka Quartzite					
	LOWER	Ninemile Fm. Goodwin Ls.	Pogonip Group					
CAMBRIAN	UPPER	Nopah Formation						
	MIDDLE	Bonanza King Formation						
	LOWER	Carrara Formation						
PRECAMBRIAN (PROTEROZOIC)		Wood Canyon Formation						L ⁱ C C U
		Stirling Quartzite						
		Johnnie Formation						
		Older Precambrian Metamorphic Rocks						

Source: DOE/NV, 1997c

^a HSU - Hydrostratigraphic Unit

^b Ls. - Limestone

^c Fm. - Formation

^d In the southeastern portion of the NTS, the Mississippian section is represented by the Mercury Limestone, which is correlative to the Monte Cristo Limestone.

^e The Upper Carbonate Aquifer consists of all Pennsylvanian strata, plus Mississippian sections that do not include Eleana Formation.

^f The Upper Clastic Aquitard includes the Eleana Formation and the Chainman Shale.

^g Ds. - Dolostone

^h The Lower Carbonate Aquifer consists of all Devonian, Silurian, and Ordovician strata, plus the Nopah Formation, the Bonanza King Formation, and the upper half of the Carrara Formation.

ⁱ The Lower Clastic Aquitard consists of the lower half of the Carrara Formation, the Wood Canyon Formation, and all Precambrian units. The predominantly clastic facies of Esmeralda County is also included in the Lower Clastic Aquitard.

Table 3-6
Tertiary Stratigraphy of the NTS Region

Stratigraphic Unit	Stratigraphy Symbol
Volcanics of Fortymile Canyon	Tf
Timber Mountain Group	Tm
Ammonia Tanks Tuff	Tma
Rainier Mesa Tuff	Tmr
Tuff of Holmes Road	Tmrh
Paintbrush Group	Tp
Rhyolite of Scrugham Peak	Tps
Tiva Canyon Tuff	Tpc
Topopah Spring Tuff	Tpt
Volcanics of Area 20	Ta
Calico Hills Formation	Tac
Volcanics of Area 20	Ta
Wahmonie Formation	Tw
Tuff of Mara Wash	Tww
Crater Flat Group	Tc
Prow Pass Tuff	Tcp
Bullfrog Tuff	Tcb

Stratigraphic Unit	Stratigraphy Symbol
Tram Tuff	Tcb
Belted Range Group	Tb
Dead Horse Flat Formation	Tbd
Grouse Canyon Tuff	Tbg
Thirsty Canyon Group	Tt
Tram Ridge Group	Tr
Tunnel Formation	Tn
Volcanics of Quartz Mountain	Tq
Volcanics of Big Dome	Tu
Tub Spring Tuff	Tub
Older Volcanics	To
Tunnel Bed 2	Ton2
Yucca Flat Tuff	Toy
Tunnel Bed 1	Ton1
Redrock Valley Tuff	Tor
Tuff of Twin Peaks	Tot
Paleocolluvium	TI

Source: Ferguson et al., 1994

Precambrian and Paleozoic

The lowermost, oldest rocks in the NTS region are Precambrian in age. This region of the western United States was a stable, continental margin from Late Precambrian time until Late Devonian time (middle Paleozoic). During the period of Late Precambrian to early Cambrian, a thick section of sandstone, limestone, and siltstone was deposited over the entire NTS region. A thick section of predominately carbonate sediments was deposited on top of this sequence during Middle Cambrian to Late Devonian time. During the Late Devonian-Mississippian Antler orogeny, uplift north and west of the investigation area resulted in erosion of these early Paleozoic sediments and deposition of thick Mississippian and early Pennsylvanian sandstone and conglomerate interfingering with marine shelf shales in a foreland basin. During the Pennsylvanian Period, the basin was filled, and shallow marine

carbonates were deposited on the Mississippian sandstones and shales. More than 10,600 m (34,700 ft) of Paleozoic and late Precambrian sediments were deposited over the NTS region.

Mesozoic

In the Mesozoic Era, regional crustal shortening during the Nevadan and Sevier orogenies (mountain-forming phases of the Cordilleran orogeny) produced large-scale, complex contractional features such as thrust fault systems, folds, and wrench faults. The entire NTS region was affected by the contraction, with regional detachments and generally north-south-trending predominant thrust systems (Armstrong, 1968; Cole and Cashman, 1997). Locally, the stratigraphic sections were repeated vertically because of thrusting. Intrusion of granitic plutons occurred during late Mesozoic time.

Tertiary and Quaternary

Following the Nevadan and Sevier orogenies, the highlands were severely eroded and late Precambrian marine sedimentary rocks were exposed at the surface locally. Following erosion throughout most of the early Tertiary Period, the area in and around the Nevada Test Site began to be pulled apart in the late Oligocene Epoch along normal and strike-slip faults associated with the formative stages of the modern Basin-and-Range structural province (Guth, 1981; Wernicke et al., 1988; Cole et al., 1989). Eruptions of the Southwestern Nevada Volcanic Field (SWNVF) occurred in the middle Tertiary Period (Sawyer et al., 1990; Warren et al., 1989). Successive eruptions produced at least six large and partially overlapping calderas that were filled with lava flows, and blanketed surrounding Paleozoic and Precambrian rocks with vast deposits of tuff. Volcanic rocks now cover large parts of the NTS region. Basins formed by continued extension of the region were filled with thick accumulations of alluvial debris derived from rocks that form the nearby highlands.

3.4.4.2 Geology of Yucca Flat and Vicinity

The geology of Yucca Flat has previously been described in Volume I of the regional evaluation documentation package (IT, 1996f). Specific descriptions may be found in Appendices C5 through C9 (pages C5-1 to C9-15), C15 (pages C15-1 to C15-10) (IT, 1996f). Stratigraphy information for boreholes located on the NTS may be found in Appendix B of Volume II (Pages B-1 to B-73) (IT, 1996e). The information was also summarized in Section 4.0 (pages 4-1 to 4-15) of the regional

evaluation report (DOE/NV, 1997c). A summary of the geology of Yucca Flat and vicinity is presented in this section. This interpretation will be refined during the CAI as described in [Section 5.1.2.3](#).

Geologic data used include borehole data, geophysical data, gravity data, and published geologic maps and cross-sections. Stratigraphic information for selected boreholes located on the Nevada Test Site are provided in Appendix B of the *Potentiometric Data Documentation Package* (IT, 1996e). The geology of the underground nuclear tests' working points is provided in [Table 3-2](#) and [Table 3-3](#). Other data used in the development of the regional geologic model that are relevant to the Yucca Flat/Climax Mine area are included in Appendices C5 through C9 (pages C5-1 to C9-15), C15 (pages C15-1 to C15-10), and E2 (pages E2-1 to E2-15) of Volume I of the regional evaluation documentation package (IT, 1996f). The locations of boreholes for which geologic information is available in Yucca Flat are shown in [Figure 3-5](#), [Figure 3-6](#), and [Figure 3-7](#). Any geologic information not used before, will be used during the CAI.

The geology of the Yucca Flat area includes most of the rock units found in the NTS region. As described in [Section 3.4.4.1](#), these rocks units consist of Precambrian and Paleozoic sedimentary rock units, Mesozoic granitic intrusives, Tertiary volcanic and sedimentary rocks, and Quaternary alluvial fill. The stratigraphic nomenclature and correlation of the geologic units found in the area are shown in [Table 3-7](#). Stratigraphic nomenclature is also provided in [Table 3-7](#). A map of Yucca Flat and vicinity showing the locations of the areas discussed in [Table 3-7](#) is shown in [Figure 3-8](#). A surficial geologic map of the Yucca Flat/Climax Mine potential model area is presented in [Plate 2](#). Major faults present in the area are depicted in [Plate 2](#).

Mesozoic rocks in the investigation and nearby areas consist solely of Cretaceous monzogranite and granodiorite of the Climax Mine stock and Gold Meadows stock (USGS, 1983; Snyder, 1977). Lying on the Precambrian and Paleozoic units is the SWNVF extrusive sequence, produced during the Tertiary volcanic episodes, and reaching at least 4,000 m (13,000 ft) in thickness. The volcanic units in [Table 3-7](#) are listed in relative depositional order with the oldest at the bottom of the table. Volcanic units vary widely in distribution, thickness, lithology, and degree of welding. At most localities, only a partial section is present. North of the NTS, volcanic units other than those listed in [Table 3-7](#) are present; however, these units were not differentiated during the regional evaluation

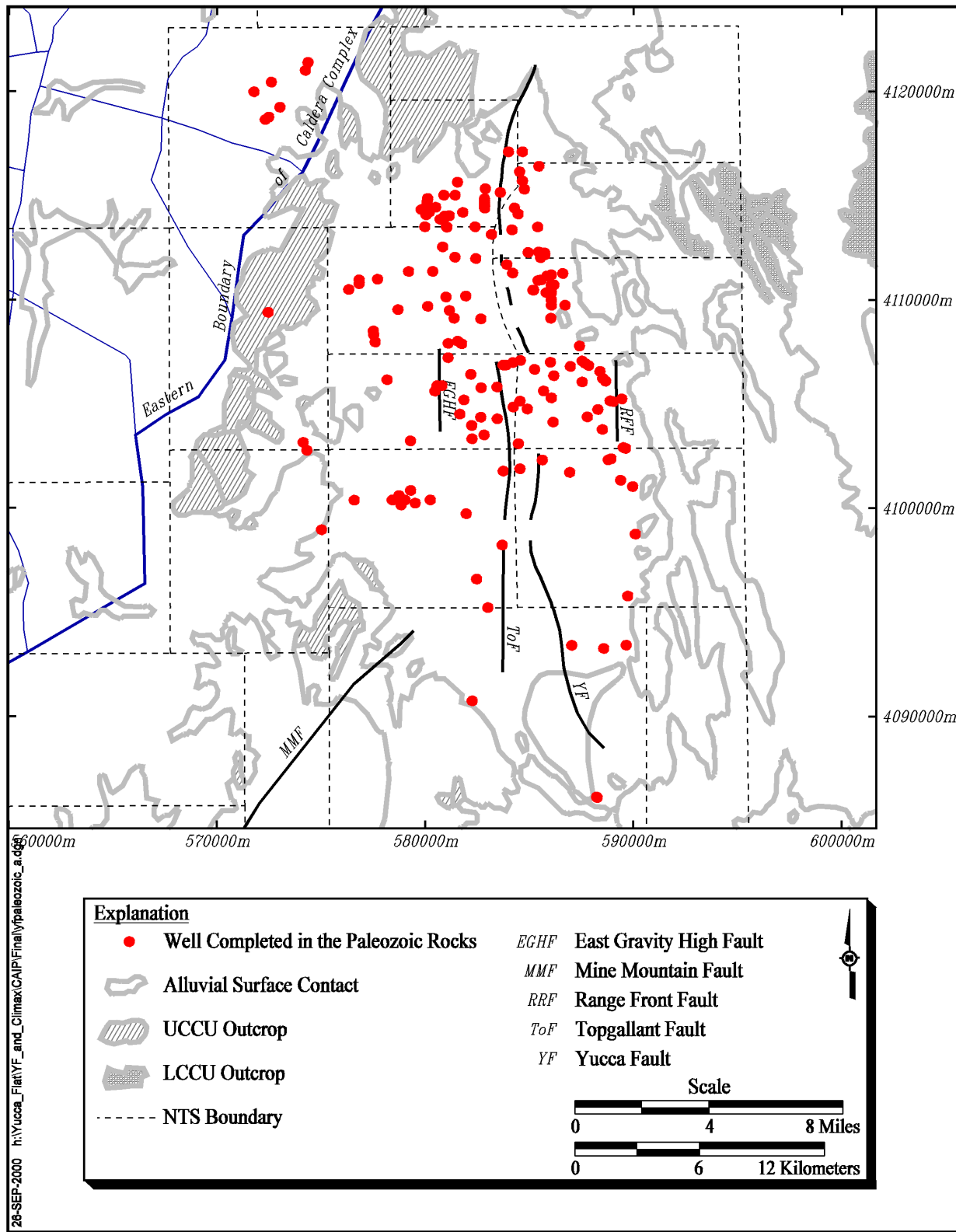


Figure 3-5
Location of Boreholes Tagging Paleozoic Rocks in Yucca Flat

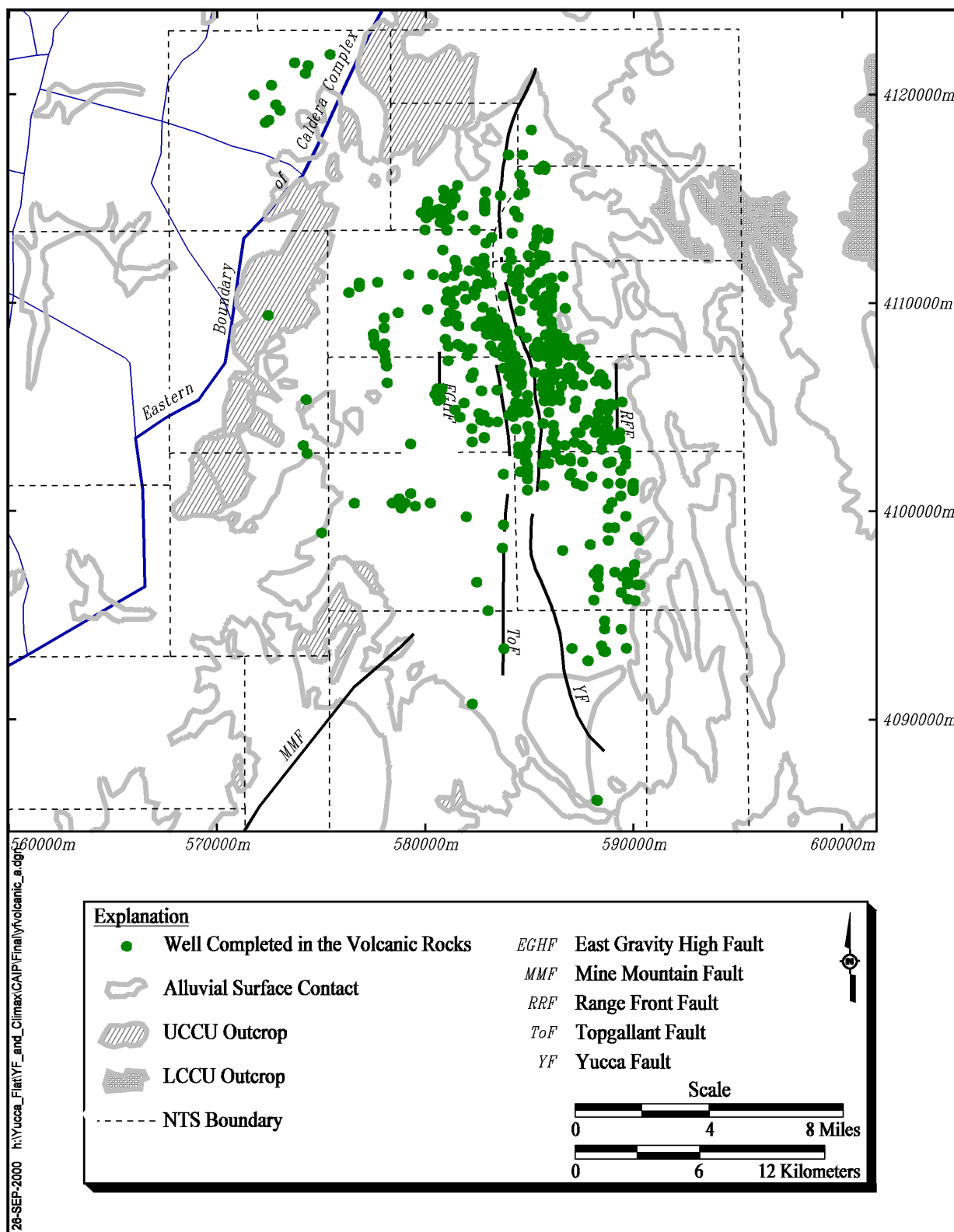


Figure 3-6
Locations of Boreholes Tagging Volcanic Rocks in Yucca Flat

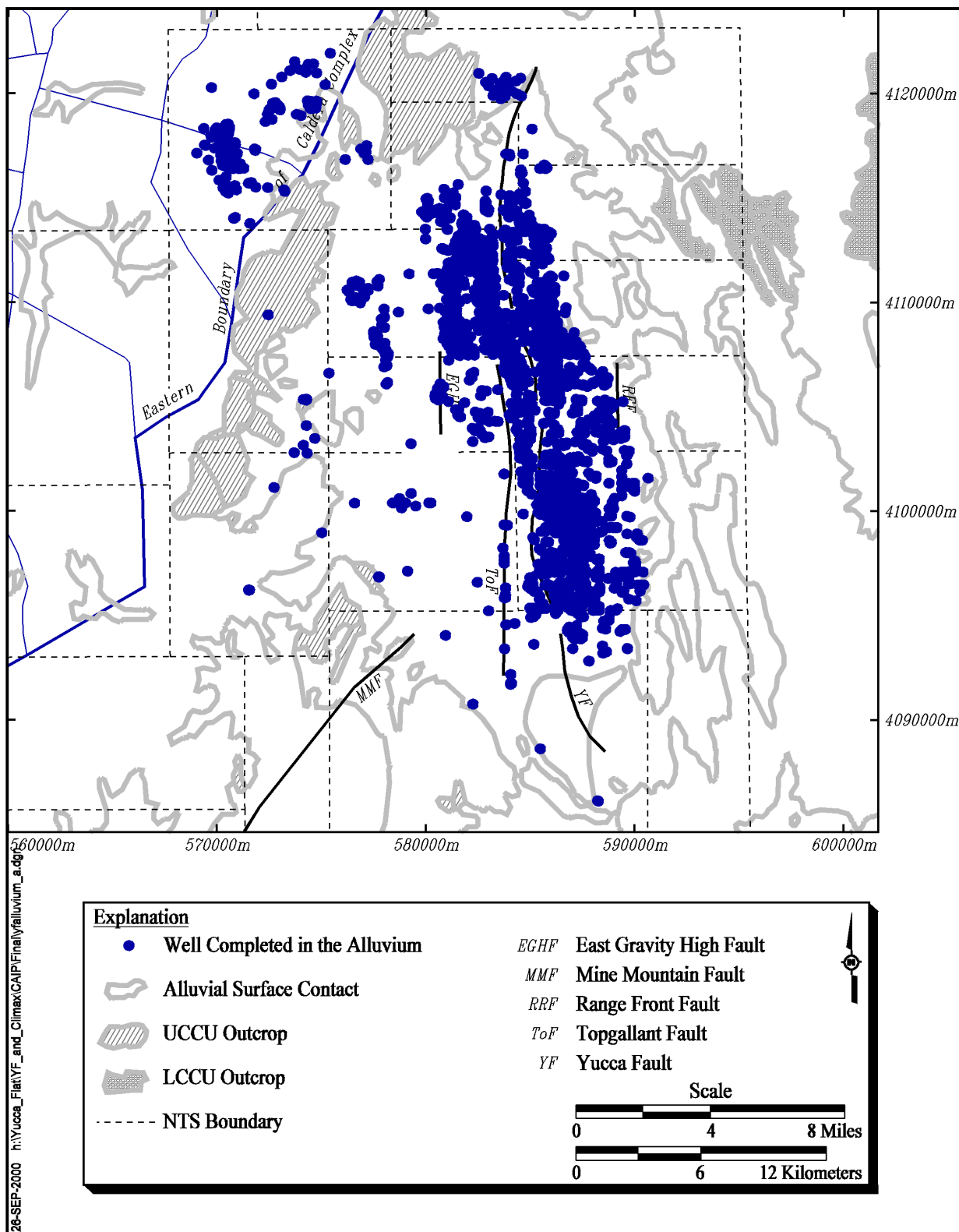


Figure 3-7
Locations of Boreholes Tagging Alluvium in Yucca Flat

(DOE/NV, 1997c; IT, 1996f). Tertiary crustal extension and consequent normal faulting was greatest after eruption of the SWNVF. The extension caused severe tilting, large vertical displacements, and lateral translation of upper crustal fault blocks. Tertiary and Quaternary sediments have filled modern-day alluvial basins with as much as 1,200 m (3,900 ft) of coarse gravels, sands, and localized deposits of playa silt and clay such as that found at Yucca Lake.

The Yucca Flat area is underlain by Precambrian and lower Cambrian siliciclastic sediments, and older Precambrian metamorphic rocks. In geochronological order, the siliciclastic sediments are represented as the Johnnie Formation, the Stirling Quartzite, the Wood Canyon Formation, and the lower unit of the Carrara Formation. Overlying the Precambrian and lower Cambrian siliciclastic sediments is a sequence of middle Cambrian to Ordovician strata that are mostly carbonates. These deposits are represented as the upper unit of the Carrara Formation, the Bonanza King Formation, the Nopah Formation, the Pogonip Group, the Eureka Quartzite, and the Ely Springs Dolostone.

The base of the carbonates is exposed, along with the siliciclastic sediments, on a structural uplift on the eastern side of the valley, the Halfpint Range anticline ([Plate 2](#)). These Precambrian and Paleozoic siliciclastics and carbonates dip generally southwestward beneath Yucca Flat, forming the southwest flank of the Halfpint Range anticline. In the interior of the valley, the Paleozoic carbonates are irregularly down-thrown along north-south trending faults to depths of 457 to 1,220 m bgs (1,500 to 4,000 feet bgs). Silurian and Devonian carbonates occur in stratigraphic sequence above the Cambrian and Ordovician carbonates, but may not be present beneath the central valley where middle Tertiary volcanics cover late Mesozoic and early Tertiary erosional surfaces on the carbonates. The Silurian and Devonian carbonates are represented as Laketown Dolostone, Sevy Dolostone, Simonson Dolostone, and Guilmette Limestone.

Upper Devonian to Mississippian age siliciclastic sediments, the Eleana Formation and Chainman Shale, overlie the older Paleozoic carbonates in the subsurface and in outcrops in the western part of Yucca Flat in the Eleana Range ([Plate 2](#)). The Eleana Formation and Chainman Shale are contracted into several north-south trending folds. Winograd and Thordarson (1975) interpreted that they had been thrust eastward over the stratigraphically lower carbonates along a fault named the Tippinip Thrust. The easternmost extent of the Chainman Shale is defined by the Topgallant Fault, which is a normal fault that truncates it. The transition from the southwestward-dipping Paleozoic strata on the

Table 3-7
Generalized Stratigraphic Units in Yucca Flat and Vicinity
(Page 1 of 2)

Age	Group	Formation, Member, or Unit	Symbol	NE Yucca Flat	Central Yucca Flat	SE Yucca Flat	SW Yucca Flat	Sycline Ridge Yucca Flat	NW Yucca Flat	Climax Area	North of Climax
Quaternary ⁱ	Surficial deposits	Alluvium: Playa deposit	Qp								
		Eolian sand	QTe								
		Basalt	Tybf								
		Undivided	QTa								
Tertiary	Timber Mountain Group	Ammonia Tanks Tuff	Tma, Tmab								
		Rainier Mesa Tuff	Tmr								
		Pre-Rainier Mesa, post-Wahmonie bedded tuff, undivided	Tmrh/Th								
	Paintbrush Group	Tiva Canyon	Tpc								
		Topopah Spring Tuff	Tpt								
	Calico Hills Formation		Th								
	Wahmonie Formation	Tuff of Wahmonie Flat	Twlb								
	Crater Flat Group	Crater Flat Tuff, undivided	Tc								
	Belted Range Group	Grouse Canyon Member	Tbg								
		Comendite of Quartet Dome	Tbq								
	Tunnel Formation	4 and 3 Members, undivided	Tn4 Tn3								
	Volcanics of Big Dome	Comendite of Ochre Ridge	Tuo								
		Tub Spring Tuff	Tub								
		Comendite of Emigrant Valley	Tue								
	Volcanics of Oak Spring Butte	Tunnel bed 2	Ton2								
		Yucca Flat Tuff	Toy								
		Tunnel bed 1	Ton1								
		Redrock Valley Tuff	Tor								
		Tuff of Twin Peaks	Tot								
		Older volcanics, undivided	To								
	Paleocolluvium	Paleocolluvium, undivided	Tl								

Table 3-7
Generalized Stratigraphic Units in Yucca Flat and Vicinity
(Page 2 of 2)

Age	Group	Formation, Member, or Unit	Symbol	NE Yucca Flat	Central Yucca Flat	SE Yucca Flat	SW Yucca Flat	Sycline Ridge Yucca Flat	NW Yucca Flat	Climax Area	North of Climax
Cretaceous	Plutonic rocks	Climax Stock	Kgc								
		Gold Meadows Stock	Kgg								
Pennsylvanian		Tippipah Limestone (correlative with the Bird Spring Formation)	P Pt								
Mississippian		Eleana Formation and Chainman Shale	Me/Mc								
Devonian		Guilmette Formation Simonson Dolomite	Dg Ds								
Siluvian		Sevy Dolomite Laketown Dolomite	DSs Sl								
Ordovician		Ely Spring Dolomite Eureka Quartzite Antelope Valley Limestone Ninemile Formation Goodwin Limestone	Oes Oe Oa On Og								
Cambrian		Nopah Formation Bonanza King Formation Carrara Formation (upper)	Cn Cb Cc								
Pre-Cambrian		Carrara Formation (lower) Zabriskie Quartzite Wood Canyon Formation Stirling Quartzite Johnnie Formation	Cc Cz CZw Zs Zj								
Possible LCA3 present (Cb through Dg in thrust plate[s])							Yes		Yes	Yes	Yes

 = Unit generally not present

Notes:

1. Lithologies for volcanic units may vary (e.g., Tub is an ash flow tuff in NW and N of Climax areas, but only a thin air fall tuff in SE Yucca Flat).
2. Unit extents vary even within the above areas (this table is generalized!).
3. Structural complexities not represented here (e.g., normal faults, thrust faults, intrusions, uplift and erosion).

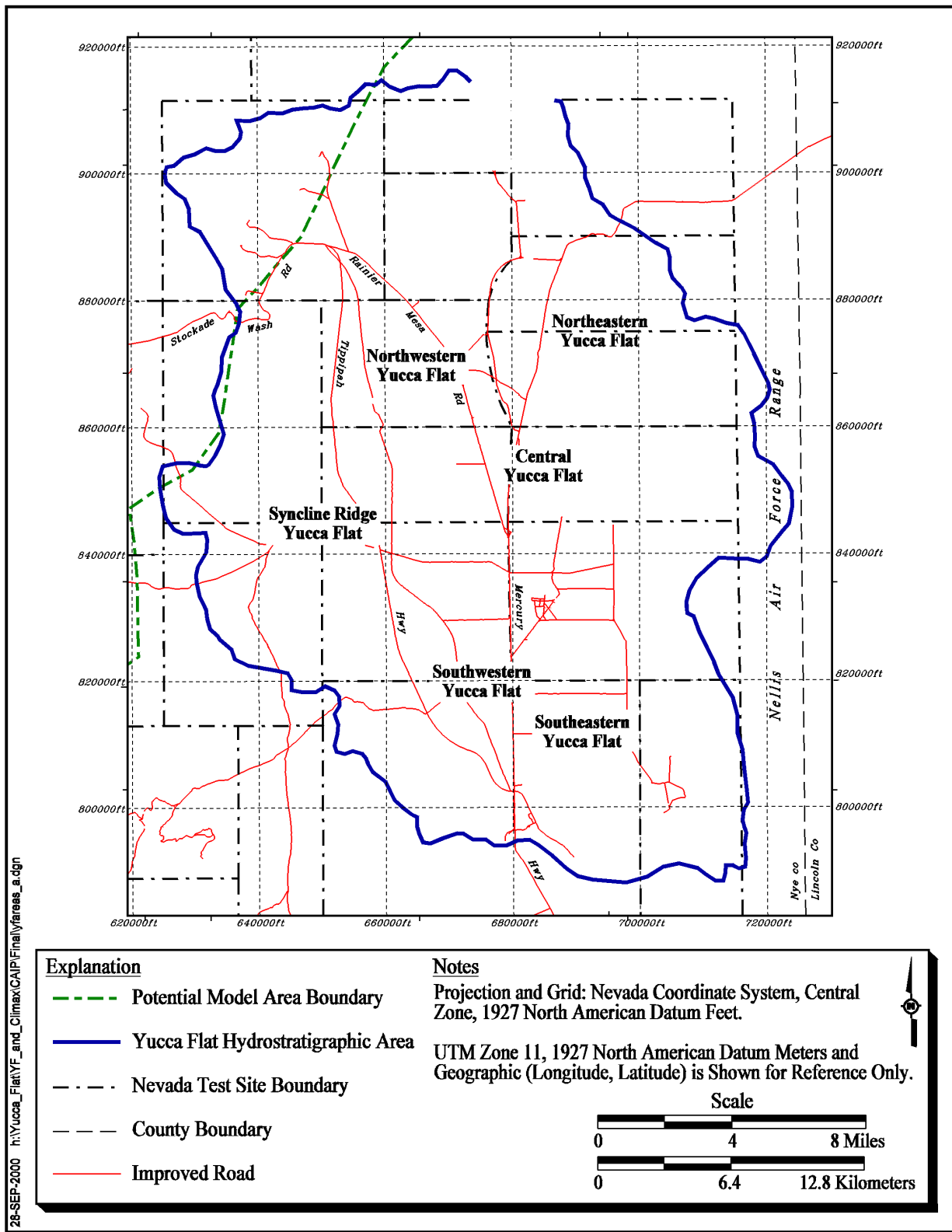


Figure 3-8
 Areas of Yucca Flat Shown in Table 3-7

eastern side of Yucca Flat, to the thrust sheet of Chainman Shale on the western side of Yucca Flat is not completely understood. On the western side of Yucca Flat, carbonate units thrust over the Eleana Formation and Chainman Shale, and Eleana is thrust over Chainman Shale. The nature of thrust faulting and the distribution of the Eleana Formation versus the Chainman Shale on the western side of Yucca Flat are not thoroughly understood (Cole et al., 1994). Where not eroded away, Pennsylvanian and minor Permian age carbonate rocks, the Tippipah Limestone, overlie the upper Devonian to Mississippian siliciclastics, and outcrop in the core of a syncline along the western margin of Yucca Flat, Syncline Ridge ([Plate 2](#)). The entire Paleozoic section is tilted to the west, and is erosionally truncated from top to bottom such that the lower carbonate section thins from west to east beneath the Tertiary volcanic cover. However, beneath central Yucca Flat, the entire section of lower Paleozoic carbonates (approximately 4,400 meters) should be present wherever the Chainman Shale remains above them.

West of Yucca Flat, an important north-southwest trending, westward dipping, structural feature exists, the Belted Range thrust fault system. Major east-directed, vertical displacement of Precambrian and Paleozoic strata has occurred along this fault. Ordovician, with minor Cambrian and Silurian, carbonates were thrust eastward over upper Devonian and Mississippian siliciclastics (Eleana Formation and Chainman Shale) and are exposed in outcrop overlying the Eleana Formation in the Eleana Range. Only four kilometers to the west of the Eleana outcrop in the Eleana Range, the Wood Canyon Formation (upper part of the Precambrian and Cambrian siliciclastics) is exposed at the surface at Gold Meadows, near the short, north-south segment of the northern NTS boundary ([Plate 2](#)). Farther west at Well ER-19-1, the Wood Canyon Formation was penetrated immediately beneath the volcanics. This juxtaposition of the Wood Canyon and Eleana Formation over a narrow geographic span is interpreted to be the result of reverse displacement along the Belted Range thrust fault system (Cole et al., 1994). Thus, the lower Paleozoic carbonates are truncated by the Belted Range fault under Rainier Mesa; they are absent on the west side of the fault where the Precambrian and lower Cambrian siliciclastics are structurally high.

In western Yucca Flat, several isolated, mostly buried segments of Devonian carbonate strata locally overlie younger, upper Devonian and Mississippian siliciclastics, and Pennsylvanian carbonates. These isolated carbonate rocks have been interpreted to be erosional remnants, or klippen, of an overthrust sheet emplaced over the younger sediments (Winograd and Thordarson, 1975;

Cole et al., 1994). The direction of displacement of the overthrust sheet over the corresponding decollement, named the CP Hills Back-thrust, was from east to west. The geometry of the CP Hills Back-thrust is not known because it is buried. The width of the thrust sheet is considered to extend northward from the CP Hills to at least northern Syncline Ridge (Cole et al., 1994).

Tertiary volcanic strata at Yucca Flat occur as erosional remnants, with greater thicknesses of preserved section in the deeper parts of the Tertiary structural basin. The volcanics outcrop in the mountain ranges surrounding the valley (Plate 2) and are irregularly down-faulted to depths as great as 1,607 m (3,500 ft) beneath the valley floor. Also, Tertiary paleocolluvium occurs along the basal contact of the volcanics.

The youngest, uppermost sediments present in the investigation area are Miocene to Quaternary age valley-fill deposits in Yucca Flat. Their surficial distribution is shown in Plate 2. The alluvium consists mainly of Tertiary tuff and pumice fragments, with minor contributions from other volcanic, and Paleozoic rock sources. The valley-fill deposits are in contact locally with either the Paleozoic carbonates, siliciclastics, or Tertiary volcanics. The thickest alluvium occurs just east of the Topgallant fault in south central Yucca Flat.

Yucca Flat is enclosed at its northern end where the structural high of the Halfpint Range converges with the Belted Range structure. The Halfpint Range is cored by Precambrian and lower Cambrian siliciclastics, with lower Paleozoic carbonates dipping away from the high. The Paleozoic carbonates were completely eroded off of the structurally high Precambrian and lower Cambrian siliciclastics prior to deposition of the volcanic rocks in Emigrant Valley. The Climax stock intrudes the lower Paleozoic carbonates at the convergence of the Halfpint Range and Belted Range at the extreme northern end of Yucca Flat. Based on observed magnetic anomalies, Bath et al. (1983) determined that the gross configuration of the stock is nearly circular at depth, over an area of 200 km² (77.3 mi²). Bath et al. (1983) also found that magnetic anomalies nearer to the ground surface reveal major displacements of magnetized units along the eastern and southeastern edges of the Climax Stock's exposures. The Climax Stock is interpreted to extend to a depth of 7.5 km below the outcrop (Jachens, 1999).

3.4.5 Hydrogeology

Descriptions of the regional hydrogeology of the NTS and the hydrology of Yucca Flat and vicinity are presented in this section. All descriptions are based on the regional evaluation report and supporting documentation (DOE/NV, 1997c; IT, 1996c-h; and IT, 1997b and c).

3.4.5.1 Regional Hydrogeology

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

3.4.5.1.1 Hydrostratigraphy

Groundwater flowing beneath the NTS region passes through diverse rocks that differ substantially in terms of age, composition, and water-bearing properties. These rocks form a complex three-dimensional framework of groundwater conduits and barriers that can be grouped into hydrostratigraphic units (HSUs) (rock units with similar hydraulic properties). The HSUs may be aquifers or confining units depending on their ability to store and transmit water.

During the regional evaluation, the NTS regional framework was subdivided into 26 HSUs as depicted in [Table 3-8](#) (IT, 1996f). Some of the HSUs were grouped into hydrostratigraphic model layers. A total of 20 hydrostratigraphic model layers were defined ([Table 3-8](#)). Seven HSUs were defined to represent the Yucca Flat basin. The details of the methodology used to group the stratigraphic units into HSUs are available in the *Regional Geologic Model Documentation Package* (IT, 1996f).

Three major aquifer types were identified: the carbonate aquifers, the volcanic aquifers (VA), and the alluvial aquifer (AA). The carbonate aquifers include the Yucca Flat Upper Plate of the Lower Carbonate Aquifer (LCA3) and the LCA ([Table 3-8](#)). The VAs include the Timber Mountain Aquifer, Belted Range Aquifer, Basal Aquifer, and the VA. The AA forms a single HSU. All other HSUs listed in [Table 3-8](#) are confining units. The LCA and Lower Clastic Confining Unit (LCCU) are the most expansive HSUs within the area. The LCA is the most important aquifer due to its wide

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

Model Layer Name	HSU Name	Description
Alluvial Aquifer (AA)	AA	Alluvial Aquifer
Timber Mountain Aquifer (TMA)	TMAQ-7	Uppermost Welded Tuffs
Tuff Cones (TC)	TPTC-6	Laterally Variable Tuffs and Lava Flows of Paintbrush Group Tuff Cone
	TPTC-5	Laterally Variable Tuffs and Lava Flows of Calico Hills
Bullfrog Confining Unit (TCB)	TCBCU-4	Non-welded Tuffs
Belted Range Aquifer (TBA)	TBAQ-3	Welded Tuffs above BCU-2
Basal Confining Unit (BCU)	BCU-2	Non-welded Tuffs
Basal Aquifer (BAQ)	BAQ-1	Welded Tuffs
Volcanic Aquifer (VA)	WTA	Welded-Tuff Aquifer
	VTA	Vitric-Tuff Aquifer
	TCU2	Zeolitized-Tuff Confining Unit (Upper)
	TPTA	Topopah Springs Tuff Aquifer
	WLA	Wahmonie Lava Aquifer
Volcanic Confining Unit (VCU)	TCU1	Zeolitized-Tuff Confining Unit (Lower)
	VCCU	Volcaniclastic Confining Unit (Volcanic-Tuff Confining Unit)
Volcanics Undifferentiated (VU)	VU	Volcanics Undifferentiated
Tertiary Sediments, Death Valley Section (TSDVS)	TS DVS	Tertiary Sediments Death Valley Section
Lower Carbonate Aquifer-Yucca Flat Upper Plate (LCA3)	LCA3	Lower Carbonate Aquifer (Yucca Flat Upper Plate), Upper Carbonate Aquifer in NTS Area
Upper Clastic Confining Unit (UCCU)	UCCU	Upper Clastic-Confining Unit
Lower Carbonate Aquifer (LCA)	LCA	Lower Carbonate Aquifer
Lower Clastic Confining Unit (LCCU)	LCCU	Lower Clastic-Confining Unit
Lower Carbonate Aquifer - Upper Plate (LCA1)	LCA1	Lower Carbonate Aquifer (Upper Plate)
Lower Clastic Confining Unit - Upper Plate (LCCU1)	LCCU1	Lower Clastic-Confining Unit (Upper Plate)
Lower Carbonate Aquifer - Lower Plate (LCA2)	LCA2	Lower Carbonate Aquifer (Lower Plate)
Lower Clastic Confining Unit - Lower Plate (LCCU2)	LCCU2	Lower Clastic-Confining Unit (Lower Plate)
Intrusives (I)	I	Intrusives

Source: Modified from DOE/NV, 1997c

distribution and high hydraulic conductivity. The LCCU generally underlies the other HSUs and has extremely low hydraulic conductivities (virtually impermeable). It was assumed to be the basement of the groundwater flow system. The LCA and LCCU predominantly control regional groundwater flow within the region. The regional distribution and thickness of the LCA is spatially variable and controlled by the structural position of the underlying LCCU. In general, the LCA is thin or missing on structural highs and is thickest in structural lows.

The available hydraulic conductivity data (Appendix A of Volume IV of regional evaluation documentation [IT, 1996d]) were compiled and reduced to provide estimated values for the major HSUs defined in the regional geologic model (IT, 1996f). These data were obtained from hydraulic tests conducted in selected wells of the NTS region. Results of the hydraulic testing only provide estimates of the local properties of the tested HSUs. These results have been extrapolated to incorporate the entire NTS regional groundwater flow system. Hydraulic tests considered in the analysis included mostly single-well tests from 89 wells (Appendix C of Volume IV of regional evaluation documentation [IT, 1996d]). Core hydraulic conductivities measured in the laboratory, although available, were not included. Hydraulic conductivity ranges for the main aquifers are summarized in [Table 3-9](#). The mean hydraulic conductivity of the AA is smaller than that of carbonate aquifers, but higher than that of the VAs. The ranges extend over many orders of magnitude. For example, within the LCA, the range of hydraulic conductivity is estimated to be between 0.0008 and 1,570 meters per day (m/d) (0.003 and 5,150 feet per day [ft/d]), representing interstitial and fracture porosity. This large range suggests that at the local scale, large variability in hydraulic conductivity can be expected. At the larger scales, the degree of fracturing controls the heterogeneity. Similar ranges of values for different rock types have been reported in Freeze and Cherry (1979), indicating that the data from the NTS region are not unusual. The details regarding the hydraulic parameters estimated for the HSUs are presented in the *Hydrologic Parameter Data Documentation Package* (IT, 1996d).

The hydraulic conductivity dataset (Appendix C of Volume IV of regional evaluation documentation package [IT, 1996d]) were also used to estimate the total depth of the flow system and define the relationship between hydraulic conductivity and depth for the major aquifers (IT, 1996d). The analysis of data available for all rock types show a decreasing linear trend exists in the logarithm of

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

Aquifer	Hydraulic Conductivity	
	Arithmetic Mean (m/d)	Range (m/d)
Alluvial Aquifer	8.44	0.00006-83
Volcanic Aquifers	1.18	0.0003-12
Carbonate Aquifers	31.71	0.0008-1,570

Source: DOE/NV, 1997c

hydraulic conductivity with increased depth; thus, hydraulic conductivity is interpreted to decrease exponentially with depth. The relationship is provided by the following equation:

$$K_{\text{depth}} = K_h(10^{-\lambda d}) \quad (3-1)$$

where:

K_{depth} = horizontal hydraulic conductivity at specified depth (m/d);

K_h = horizontal hydraulic conductivity at land surface (m/d);

λ = hydraulic conductivity decay coefficient (1/m); and

d = depth from land surface (m).

Equation 3-1 was applied to data available for all rock types, and to data available for each rock type individually. In equation 3-1, K_h is equal to K_0 for a depth of zero. Therefore, K_h represents a fictitious value of saturated hydraulic conductivity at the land surface. It is calculated as the intersection of the line regressed through the data with the land surface. The hydraulic conductivities calculated using Equation 3-1 and the data available for all rock types are meaningful only for depths greater than the depth-to-water at any given location. The hydraulic conductivities calculated using the data available for a particular rock type are meaningful only for depths greater than the depth to the top of the saturated portion of the rock type being considered. Using Equation 3-1 and the data available for all rock types, it was found that a depth of 3,000 m (9,843 ft) likely represents the

bottom of the flow system because at greater depths, the extrapolated hydraulic conductivity values are less than 10^{-7} m/d (3.3×10^{-7} ft/d). The amount of extrapolation was approximated 610 m (2,000 ft) for the AA, less than 152 m (500 ft) for the VAs, and less than 457 m (1,500 ft) for the LCA. Such low values are representative of virtually impermeable media. The analysis of hydraulic conductivity for each of the major aquifers (AA, VAs, LCA) showed that within each of the aquifers, hydraulic conductivity also decreases exponentially with depth. However, as shown in [Table 3-10](#), the rate of decrease varies from one aquifer to the next (IT, 1996d). Additional information about hydraulic conductivity versus depth may be found in Section 6.2 (pages 6-3 to 6-12) of Volume IV of the regional evaluation documentation package (IT, 1996d); and in Section 5.5.1.5 (pages 5-9 to 5-12) of the regional evaluation report (DOE/NV, 1997c).

Table 3-10
Hydraulic Conductivity Decay Coefficients with Depth

Aquifer	Decay Coefficient (day ⁻¹)			Hydraulic Conductivity at Land Surface meters per day (m/d)		
	Lower 95 Percent C.I.	Mean	Upper 95 Percent C.I.	Lower 95 Percent C.I.	Mean	Upper 95 Percent C.I.
Alluvial	0.00724	0.00563	0.00402	6.04	21.18	74.25
Carbonate	0.00160	0.00102	0.00044	2.60	6.76	17.59
Volcanics	0.00306	0.00256	0.00205	2.15	7.75	27.87

Source: IT, 1996d
C.I. = Confidence Interval

3.4.5.1.2 Groundwater

A conceptual model of the regional groundwater flow system was developed during the regional evaluation (DOE/NV, 1997c). A summary description of this conceptual model is provided in this section. A detailed description may be found in Section 6.0 (pages 6-1 to 6-32) of the regional model report (DOE/NV, 1997c). A map depicting the characteristics of the regional groundwater flow system, including the boundary, areas of recharge, and ET areas is presented in [Figure 3-9](#).

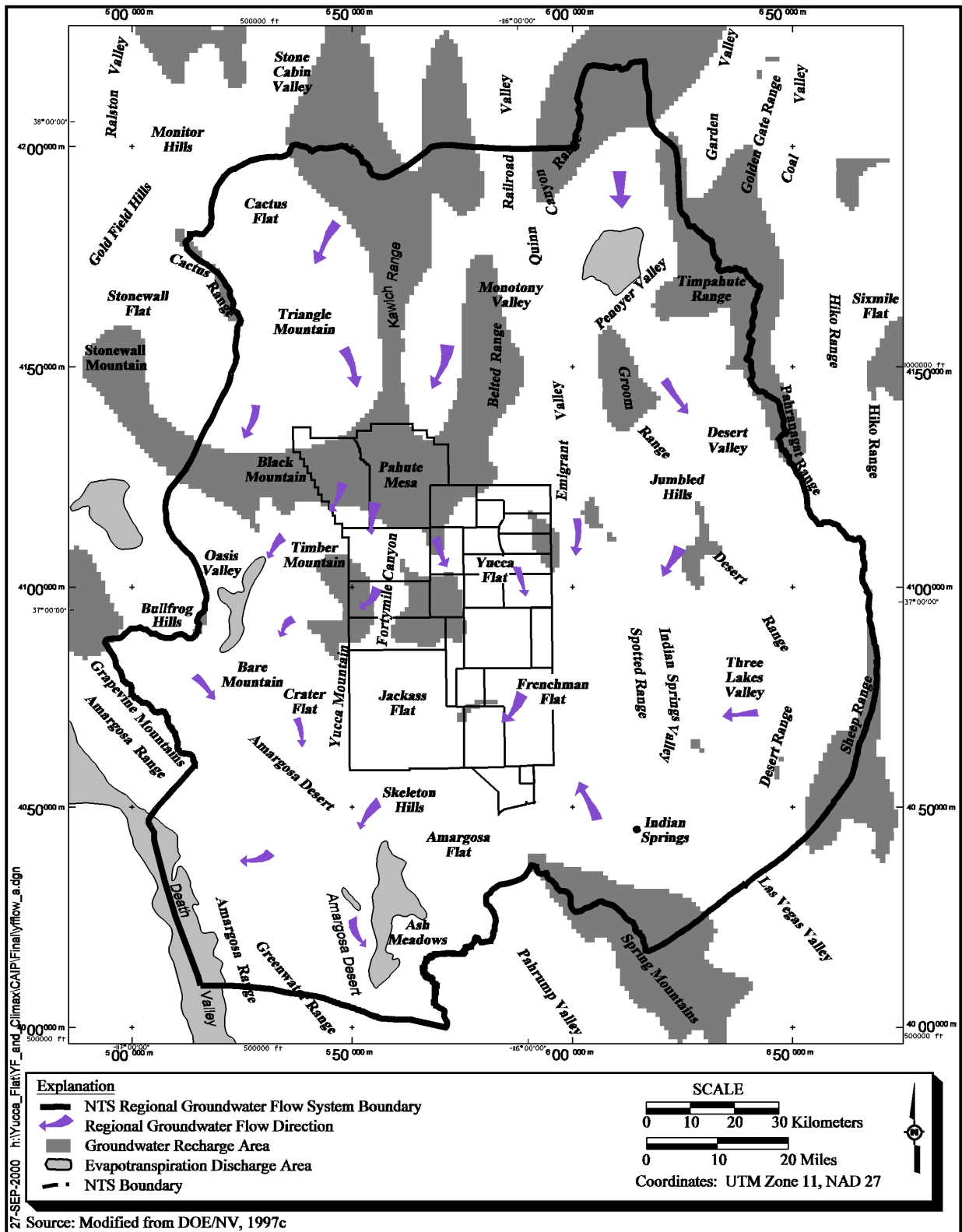


Figure 3-9
 Features of the Nevada Test Site Regional Groundwater Flow System

Saturated alluvial materials are present in central and southern Yucca Flat, Frenchman Flat, and Jackass Flats on the NTS and in the basins located throughout the regional flow system. Saturated Tertiary volcanics are present in the western section of the region. The distribution and thickness of alluvial and VAs are highly variable throughout the region and are not interpreted to be continuous. In most instances, an AA is confined to a basin by surrounding mountain ranges. In some basins, the AA is discontinuous due to structural controls elevating the bottom of the alluvium above the water table. In general, alluvial and VAs are considered depositional elements overlying the regional flow system and only influence regional flow in localized areas. The underlying LCA is the principal aquifer of the regional flow system. The LCA forms a nearly continuous aquifer across the region except where interrupted by calderas, truncated by structural controls, or penetrated by intrusive rocks.

Based on the water level dataset compiled during the regional evaluation (IT, 1996e [Appendix A, Pages A-1 to A-69]), depths to groundwater beneath the NTS and surrounding region vary greatly. Groundwater depths in the southern NTS range from about 23 m (75 ft) beneath upper Fortymile Wash to (687 ft) at WW5B in Frenchman Flat, compared to more than 610 m (2,000 ft) beneath Pahute Mesa in the northern NTS (IT, 1996e and DOE/NV, 1997c). Perched groundwater is found locally throughout the NTS and occurs within the tuff-confining units and, to some extent, overlying units. In the highlands, springs emerge from perched groundwater lenses. Spring discharge rates are low and this water is used only by wildlife.

Based on the existing water level dataset (IT, 1996e), the general direction of groundwater flow is from north to south in the northern portion of the regional flow system, and from northeast to southwest in the southern portion ([Figure 3-9](#)). The direction of groundwater flow is locally influenced in areas where structural and geologic conditions have controlled the distribution and thickness of the LCA. In some areas of the regional flow system, groundwater encounters structural and geologic conditions, such as structural highs of the LCCU, that promote an upward flow component. The upward flow component brings water to discharge at the surface in the form of a wet playa or springs. The discharge is then lost from the flow system through ET. Conversely, there is groundwater flow between basins in the form of subsurface inflow and outflow. Ultimately, however, groundwater is lost to ET at terminal surface discharge areas located downgradient.

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

Groundwater recharge and discharge descriptions provided here are based on the data gathered during the regional evaluation (IT, 1996c [Section 7.3.2, pages 7-12 to 7-18] and DOE/NV, 1997c [Section 5.7.1, pages 5-22 to 5-30]). Groundwater recharge from precipitation occurs by infiltration through the unsaturated zone. Discharge occurs naturally as evapotranspiration and potential underflow beneath the discharge areas to Death Valley. Artificial discharge occurs as groundwater pumpage from drinking water supply wells (public and domestic), agricultural wells, and industrial wells. Public, domestic, and industrial water supply wells for the NTS produce water from the carbonate, volcanic, and alluvial aquifers. South of the NTS, private and public water supply wells are completed in the valley-fill aquifer. At the regional scale, groundwater discharge from wells is not considered significant. An estimate of the regional, steady-state groundwater budget is provided in [Table 3-11](#). The groundwater budget for Yucca Flat is likely to be much different than that of the regional NTS groundwater flow system as a whole.

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

Recharge	
Recharge from precipitation	177,484 - 289,410 m ³ /d ^a
Subsurface inflow	5,405 - 70,100 m ³ /d
Total Natural Recharge	182,889 - 359,510 m³/d
Discharge	
Surface discharge (ET and springs)	135,340 - 300,700 m ³ /d
Subsurface outflow	850 - 5,100 m ³ /d
Total Natural Discharge	136,190 - 305,800 m³/d

Source: DOE/NV, 1997c

^aCubic meters per day

3.4.5.2 Hydrogeology of the Investigation Area

The hydrogeology of Yucca Flat and vicinity will be further investigated during the CAI. The current understanding is based on the regional evaluation results (DOE/NV, 1997c; IT, c through f; and IT, 1997b). A summary including descriptions of the hydrostratigraphy and groundwater of the area is provided here.

3.4.5.2.1 Hydrostratigraphy

The hydrostratigraphy of Yucca Flat has previously been described in Volume I of the regional evaluation documentation package (IT, 1996f). Specific descriptions may be found in Appendices C5 through C9 (pages C5-1 to C9-15), C15 (pages C15-1 to C15-10), E2, and F (IT, 1996f). The information was also summarized in Section 4.0 (pages 4-1 to 4-15) and Section 6.2.1 (pages 6-2 to 6-11) of the regional evaluation report (DOE/NV, 1997c). The hydrostratigraphy of Yucca Flat and vicinity based on the interpretations made during the development of the regional geologic model (IT, 1996f) is presented in this section. These interpretations will be refined during the CAI as described in [Section 5.1.3.2.3](#).

The HSU of the Yucca Flat/Climax Mine investigation area are the Lower and Upper Confining Clastic Units, the carbonate aquifers (LCA and LCA3), Volcanic Confining Unit (VCU), VA, AA, and the Intrusives (IT, 1996f). To aid in understanding the hydrostratigraphy of the investigation area, three cross-sections were constructed using the regional hydrostratigraphic model (IT, 1996f). The locations of these interpreted cross-sections, along with the distribution of surface exposures of HSUs, are presented in [Figure 3-10](#). All three cross-sections are presented in [Plate 3](#). Cross-section AA' is oriented roughly parallel to groundwater flow, and BB' and CC' are oriented generally perpendicular to groundwater flow. The faults are mapped as being vertical; however, they are believed to be high-angle normal faults and reverse faults. More detailed cross-sections of Yucca Flat (DD-DD', EE-EE', and FF-FF') are presented in [Plate 4](#). The locations of these cross-sections are presented in [Figure 3-11](#). The HSUs present within the investigation area and their relationships are described in the following text.

The LCCU is the hydrologic basement of Yucca Flat. It occurs throughout the Yucca Flat/Climax Mine investigation area. The LCCU represents the Precambrian and lower Cambrian siliciclastic sediments, previously described in [Section 3.4.4.2](#). The LCCU is the principal HSU beneath the

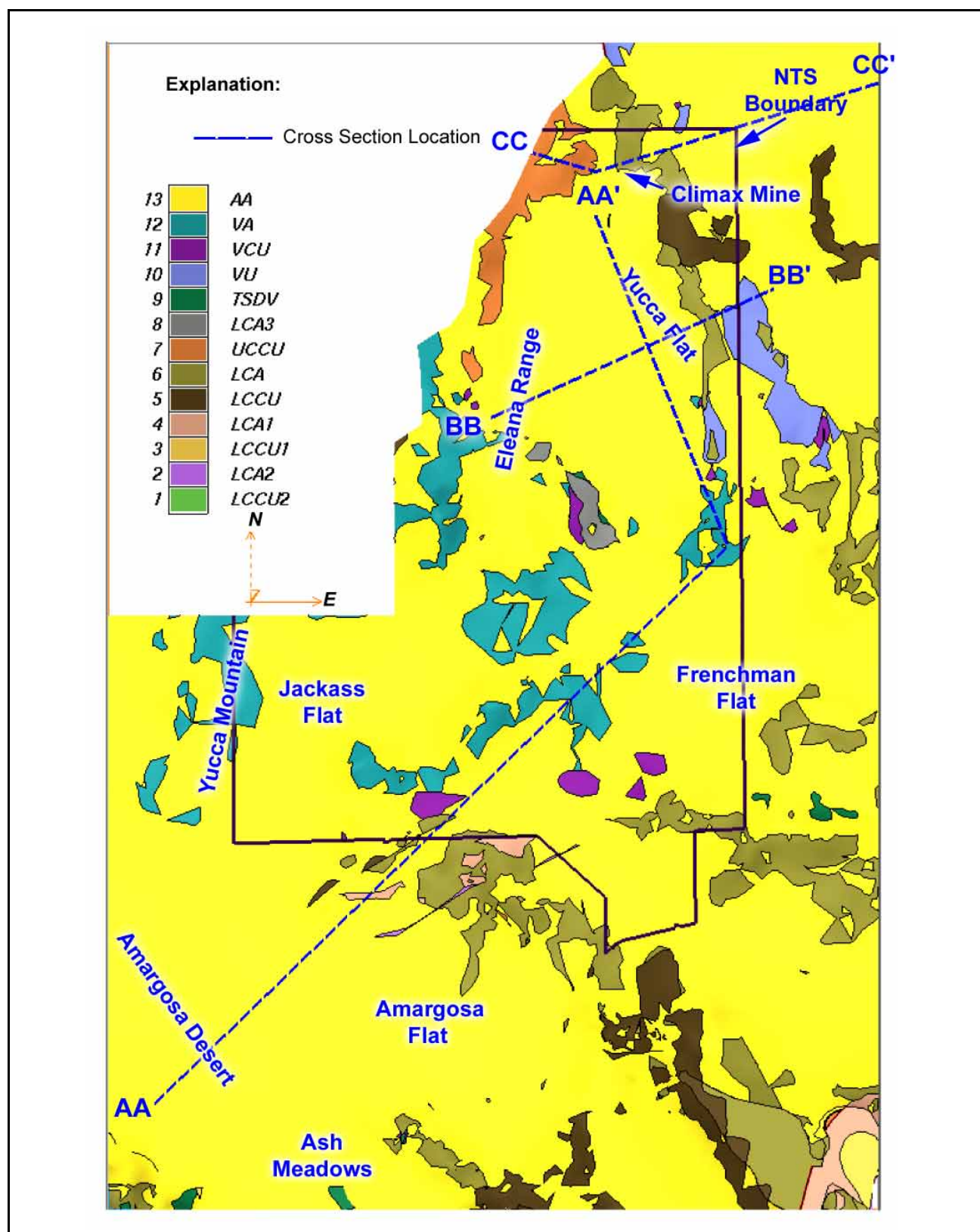


Figure 3-10
Surficial Hydrostratigraphy and Location of Hydrostratigraphic Cross Sections
within the Yucca Flat/Climax Mine Investigation Area

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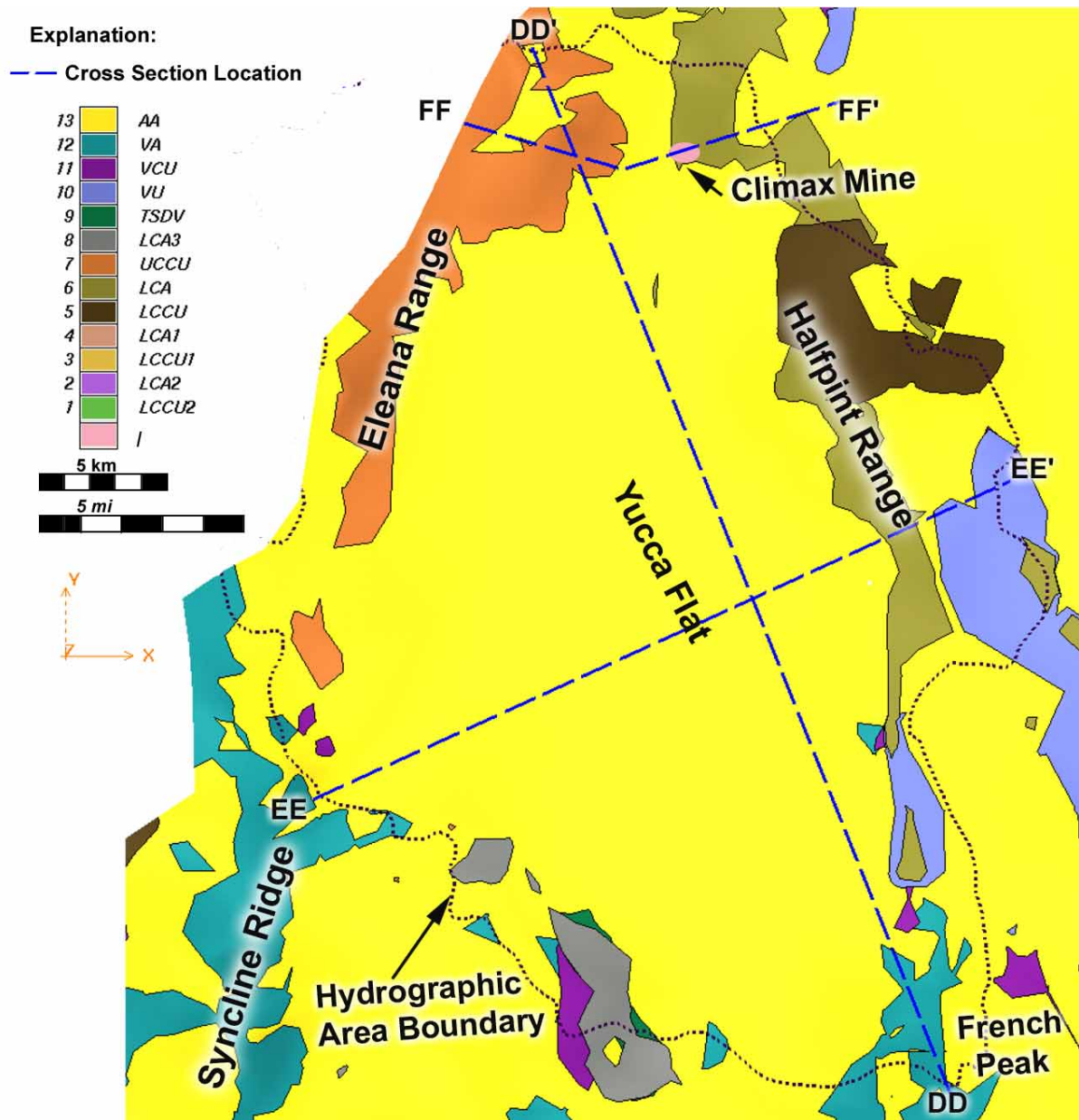


Figure 3-11
Surficial Hydrostratigraphy and Location of Hydrostratigraphic
Cross Sections within the Yucca Flat Area

ranges at the northeastern margin of the Yucca Flat basin. The structural position of the LCCU has controlled its elevation and the amount of LCA (the overlying aquifer) preserved on top of it.

The LCA is the regional aquifer in the Yucca Flat area. The LCA represents the lower Paleozoic carbonate section, which lies between the LCCU and the upper Devonian to Mississippian age siliciclastic sediments. The base of the LCA is exposed along with the LCCU in the structural uplift in the northern Halfpint Range. From this uplift, the LCA dips westward beneath Yucca Flat.

The upper Devonian to Mississippian age siliciclastic sediments are represented as the UCCU. The UCCU is the principal HSU beneath the western third of the valley and the ranges along the western margin. The UCCU overlies the LCA both in the subsurface and in outcrop west of Yucca Flat.

Pennsylvanian-age carbonate rocks overlie the UCCU and crop out at Syncline Ridge, in western Yucca Flat, and on the western slope of the Eleana Range. They are represented as the Upper Carbonate Aquifer in the NTS area, but are depicted as the LCA3 in the cross-sections ([Plate 3](#)). Actually, the LCA3 represents several isolated, mostly buried erosional remnants of mainly Ordovician, with minor Cambrian and Silurian, carbonates overlying the younger, upper Devonian to Mississippian age UCCU in western Yucca Flat. These carbonates are called LCA3 to distinguish them from the regional LCA, which occurs normally under the UCCU. The LCA3 carbonates have been interpreted to be remnant portions of the CP Hills overthrust sheet, which is thought to have been emplaced over the UCCU from the east. Because of the similar spatial positions of the UCA and LCA3 with respect to the LCA in Yucca Flat, they were mapped together as LCA3.

Overlying the LCA is the VCU which corresponds to the TCU 1 in Yucca Flat. This HSU represents the non-welded and altered (typically zeolitized) volcanic rocks of the area. The Tertiary paleocolluvium that occurs along the basal contact of the volcanic section acts as a local confining unit (Laczniak et al., 1996) and is included in the VCU. The VCU generally separates the upper Tertiary and Quaternary aquifers from the LCA. The VCU is fully saturated only in the central portion of the valley. The saturated thickness of the VCU probably ranges from a few meters (a few tens of feet) to around 450 m (1,500 feet) (Winograd and Thordarson, 1975).

Overlying the VCU is the VA, the HSU comprising the welded and unaltered volcanic rocks of the area. This unit has approximately the same distribution as the VCU in the area of interest, and also

occurs as erosional remnants which are preserved in the deeper parts of the Tertiary basin. The VA is fully saturated only where it is beneath saturated valley fill, which is in the central portion of the valley. The saturated thickness of the VA may be as much as 305 m (1,000 feet) (Winograd and Thordarson, 1975).

The Miocene to Quaternary age valley-fill deposits in Yucca Flat are represented as the AA. The AA occupies troughs formed by the block faulting of the older rocks within the basin. The AA is in contact locally with either the LCCU, LCA, or volcanics, in eastern Yucca Flat; and with the UCCU, LCA3, or volcanics, in central and western Yucca Flat. Maximum thickness of the alluvium occurs east of the Yucca Fault in the central portion of Yucca Flat, where it exceeds 610 m (2,000 ft). The alluvium is thick enough only in the central portion of the valley to extend below the water table into the saturated zone. The saturated thickness of the AA exceeds 300 m (1,000 ft) within the valley (IT, 1996e).

In the Climax Mine area, intrusive rocks consisting of the Cretaceous monzogranite and granodiorite of the cylindrical Climax Mine stock intrude the LCA, as shown in Cross Section CC-CC' ([Plate 3](#)). These rocks are relatively impermeable, but locally yield water from fractured zones. The juxtaposition of the intrusives and the LCA ([Plates 3 and 4](#)) provides a potential for a hydraulic connection between the two units.

The entire Paleozoic section present in the subsurface beneath Yucca Flat is tilted to the west, and is erosionally truncated from top to bottom underneath the Tertiary volcanic cover such that the LCA thins from west to east as shown on cross-section BB' ([Plate 3](#)). In western and central Yucca Flat, where the UCCU occurs, the full thickness of the LCA should be present beneath. The saturated thickness of the LCA ranges from a few meters to tens of meters (a few tens to hundreds of feet) at the eastern margin of the basin, to probably between 3,000 and 4,500 m (10,000 and 14,000 feet) near the center of the valley ([Plate 3](#)). This phenomenon is explained as being a result of the westward regional dip of the Paleozoic strata, and the accompanying progressive westward thickening of the Paleozoic carbonate sequence (Winograd and Thordarson, 1975).

The major structure that controls the HSU relationships under the Tertiary volcanics west of the Yucca Flat area is the Belted Range thrust fault system. At Gold Meadows, west of the Climax Mine and Eleana Range, the upper part of the LCCU is exposed at the surface. Further west, the LCA and

UCCU are not present in the subsurface; the upper part of the LCCU was penetrated immediately beneath the volcanics. However, the UCCU crops out in the Eleana Range just four kilometers east of the LCCU outcrop at Gold Meadows. This juxtaposition of the LCCU and UCCU over a narrow geographic area is interpreted to be the result of reverse displacement along the Belted Range thrust fault system (Cole et al., 1994). West of Yucca Flat, the LCCU1 is believed to be a thrust sheet of the LCCU over the UCCU. Therefore, the LCA and UCCU are interpreted to be present in the deep subsurface in this area.

Yucca Flat is enclosed at its northern end where the structural high of the LCCU in the Halfpint Range converges with the LCCU within the Belted Range structure. The structural high is cored by the LCCU with the LCA dipping away from the high. Cross-Section CC' (Plate 3) is an east-west cross section north of Yucca Flat to compare with Cross-Section AA' (Plate 3). The LCCU was interpreted to be present beneath Emigrant Valley between the Belted Range and the Groom Range. As interpreted, the LCA was completely eroded off of the LCCU prior to deposition of the volcanic rocks in Emigrant Valley (IT, 1996f).

Hydraulic conductivity data for the HSUs present within the area of interest were compiled during the regional evaluation (IT, 1996d [Appendices A and C]). Several single-well pump tests were conducted in 14 wells scattered across Yucca Flat: 2 tests in the AA, 2 tests in LCA3, 8 tests in the LCA, and 2 tests in the UCCU (Eleana). Figure 3-12 shows the locations of these wells. Figure 3-13 shows the ranges of hydraulic conductivities for each of these wells. A summary of the hydraulic conductivity data derived from these tests is provided in Table 3-12. Carbonate rocks (LCA and LCA3) have a larger hydraulic conductivity than the other HSUs. The UCCU has a lower hydraulic conductivity than the other HSUs. The range of hydraulic conductivity values in the carbonate HSU spans over nearly five orders of magnitude. The range of interpreted values in any one well is as much as two orders of magnitude. Hydraulic conductivity appears to decrease with depth of the center of the open interval. No clear spatial pattern of high hydraulic conductivity exists in the LCA. Hydraulic conductivity estimates for the other HSUs present in the Yucca Flat area may be obtained from the hydraulic conductivity dataset of the NTS area (IT, 1996d [Appendices A and C]). A summary of the regional dataset is provided in Table 3-9 of this document. The full hydrologic parameter dataset, including hydraulic conductivity data, is available in Appendices A and C of Volume IV of the regional evaluation documentation (IT, 1996d). A discussion is available in

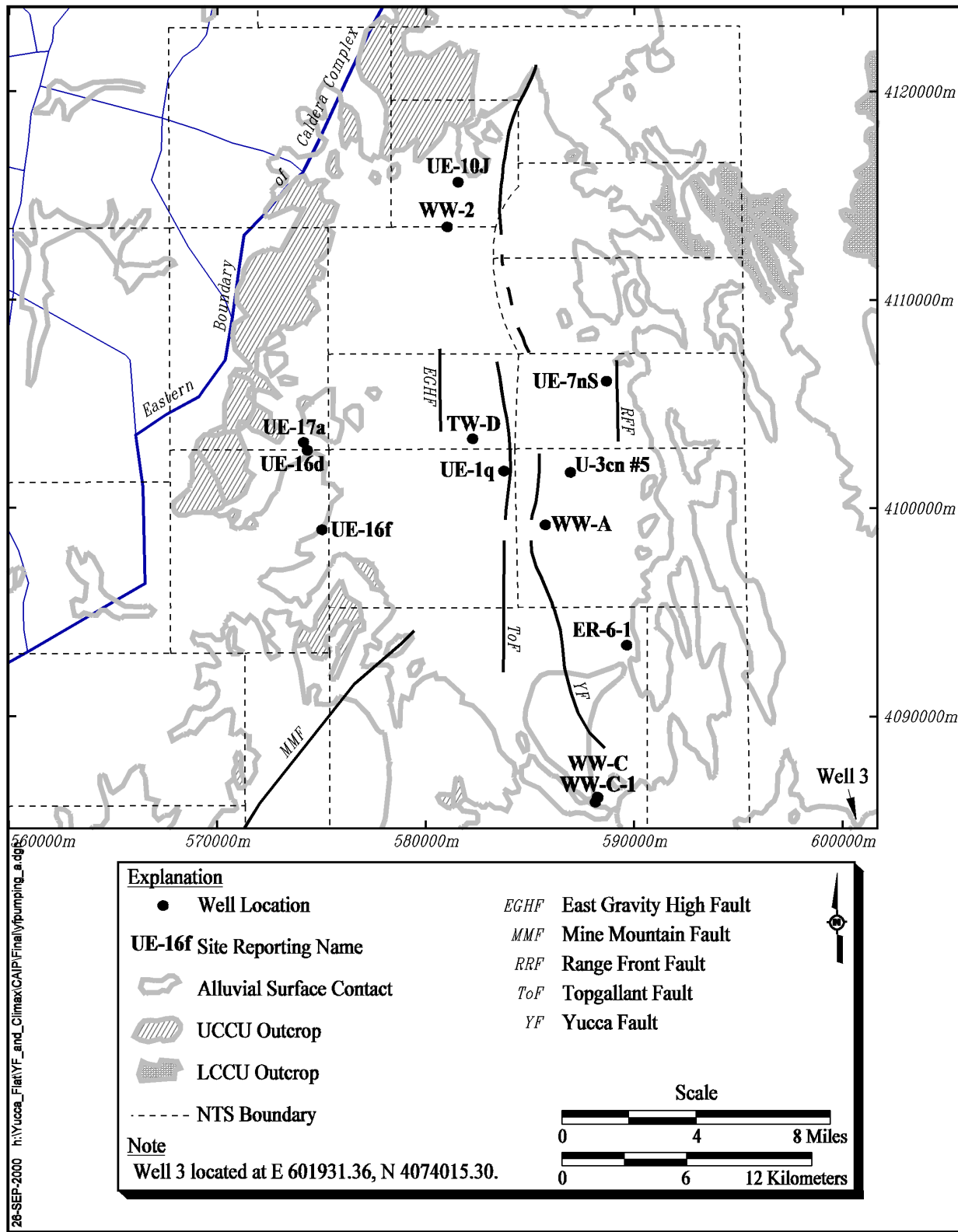


Figure 3-12
Location of Wells Subjected to Pump Tests in Yucca Flat and Vicinity

Table 3-12
Summary of Hydraulic Conductivity Data for the Yucca Flat/Climax Mine Area

HSU	Geometric Mean of Hydraulic Conductivity (m/d)	Minimum Hydraulic Conductivity (m/d)	Maximum Hydraulic Conductivity (m/d)	Number of Data Points
AA	0.25	0.06	2	7
LCA3	1.55	0.0008	20	51
LCA	0.45	0.005	228	26
UCCU	0.014	0.003	0.07	2

Source: Modified from IT, 1996d

Sections 3.0 to 8.0 (pages 3-1 to 8-3) of the regional evaluation documentation (IT, 1996d), and in Section 5.5 (pages 5-4 to 5-12) of the regional evaluation report (DOE/NV, 1997c).

3.4.5.2.2 Groundwater Hydrology

Groundwater occurrence, movement, and hydraulics within the investigation area are discussed in this section, with emphasis on the Yucca Flat/Climax Mine area and vicinity. The descriptions are based on the available water level data and recharge/discharge estimates compiled and assessed during the regional evaluation (IT, 1996e; DOE/NV, 1997c). Information on the water levels may be found in Sections 3.0 through 10.0 (pages 3-1 to 10-4), Appendix A (Pages A-1 to A-69), and Appendix C (Pages C-1 to C-54) of Volumes II of the regional evaluation documentation package (IT, 1996e). The same information is also summarized in Section 5.6 (pages 5-15 to 5-21) of the regional evaluation report (DOE/NV, 1997c). Information on recharge and estimates may be found in Sections 3.0 through 11.0 (pages 3-1 through 11-6) of Volume III (IT, 1996c).

The composite predevelopment hydraulic head contours are presented in [Figure 3-14](#). [Figure 3-15](#) through [Figure 3-17](#) show groundwater contours in the LCA, volcanic units and AA, respectively, within the Yucca Flat area. The groundwater contours are based on predevelopment hydraulic heads derived from the historical water level dataset (IT, 1996e). Borehole locations for which water level data were available and values of predevelopment hydraulic heads are also shown in [Figure 3-15](#) through [Figure 3-17](#).

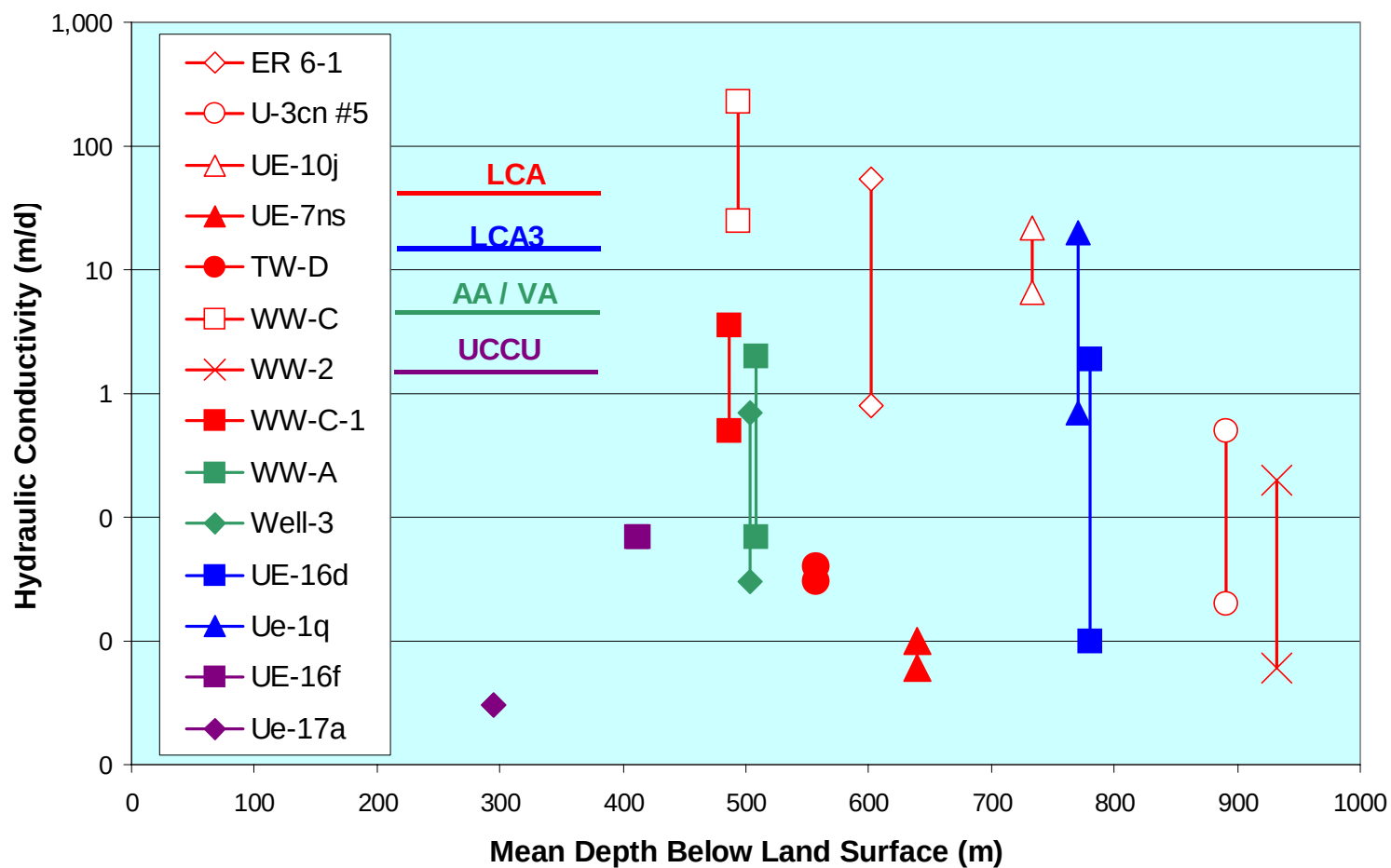


Figure 3-13
 Ranges of Hydraulic Conductivities for Yucca Flat

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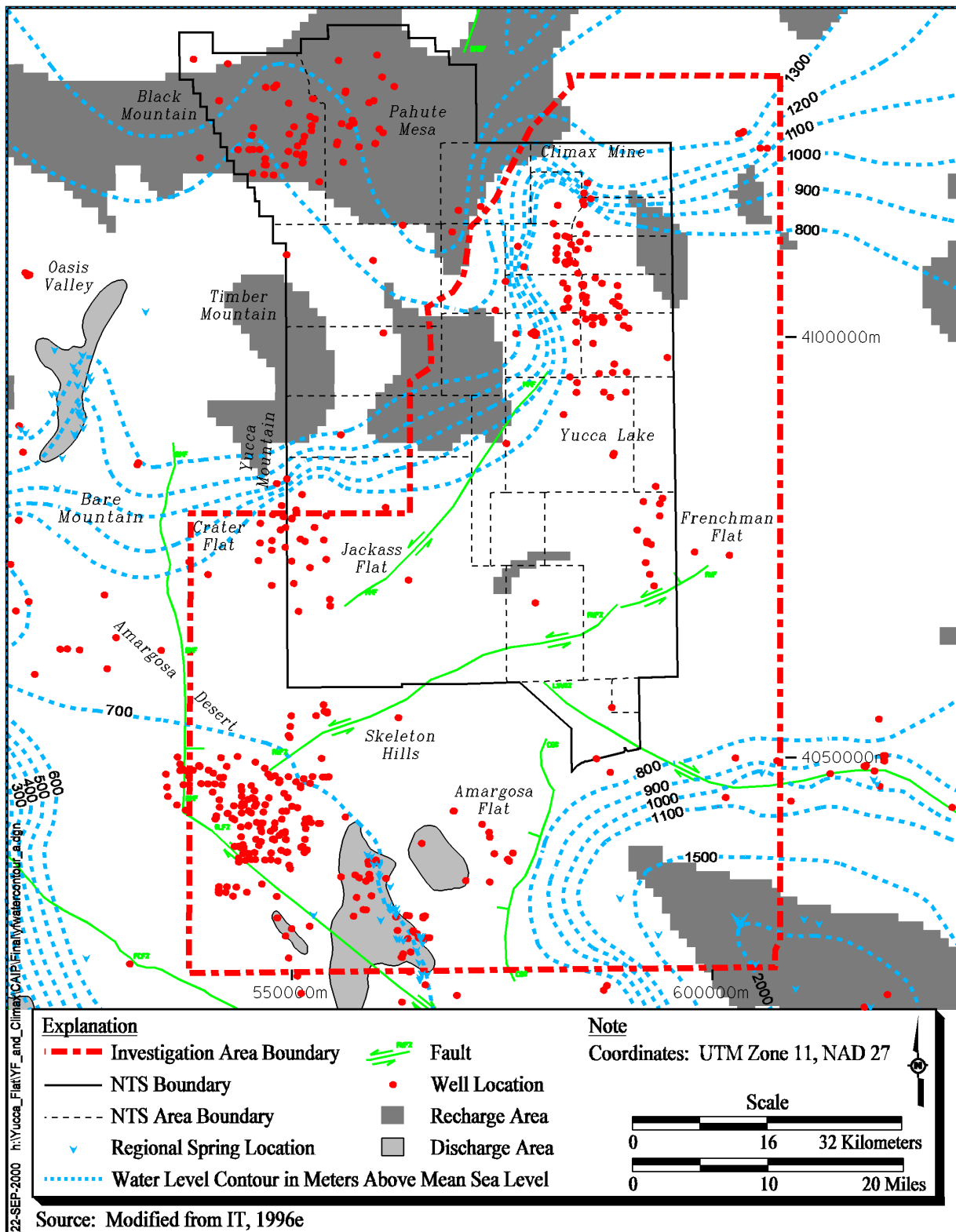


Figure 3-14
Composite Predevelopment Water Level Contour Map
for the Yucca Flat/Climax Mine Investigation Area

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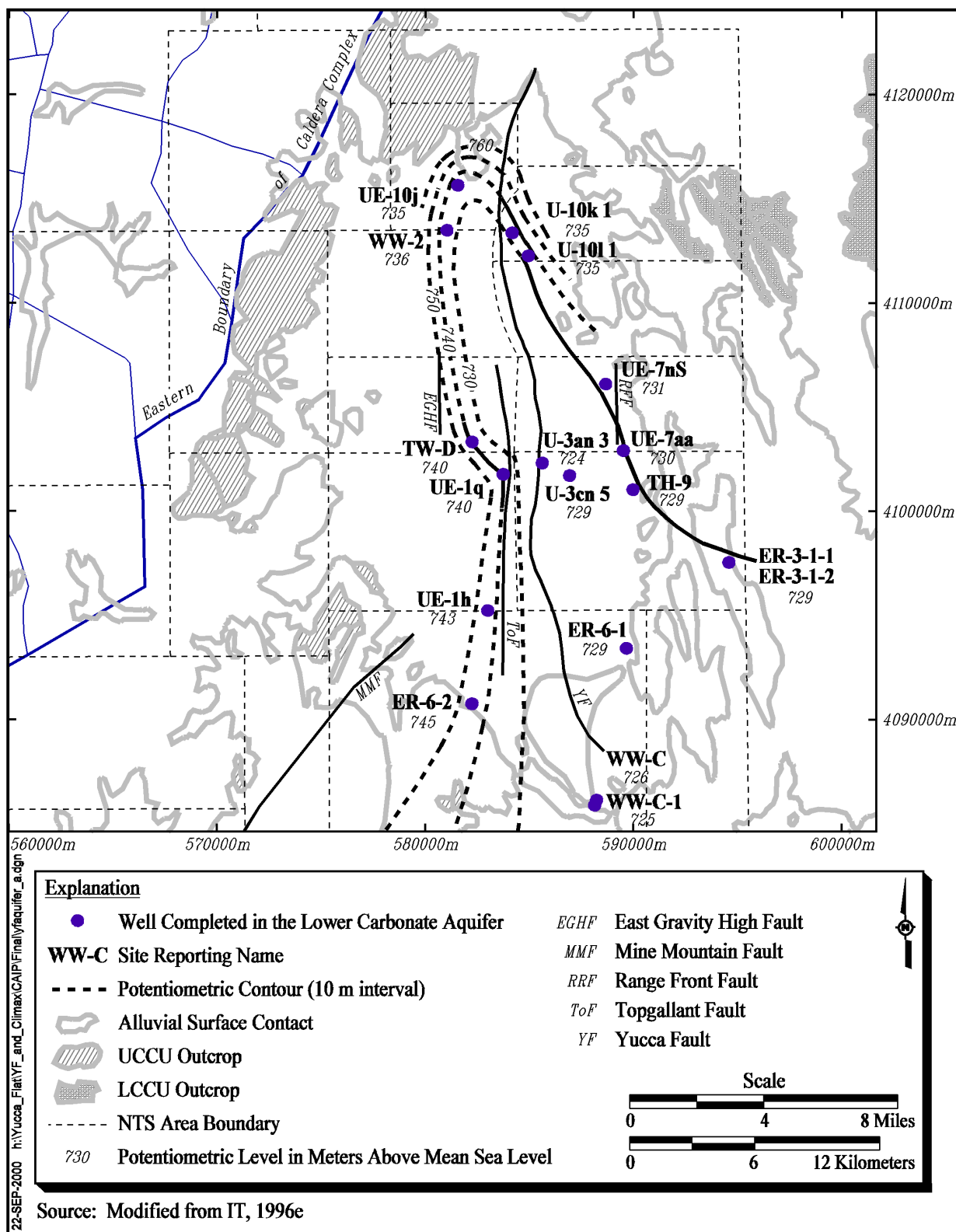


Figure 3-15
Predevelopment Potentiometric Surface Map of the Lower Carbonate Aquifer
of the Yucca Flat/Climax Mine Area

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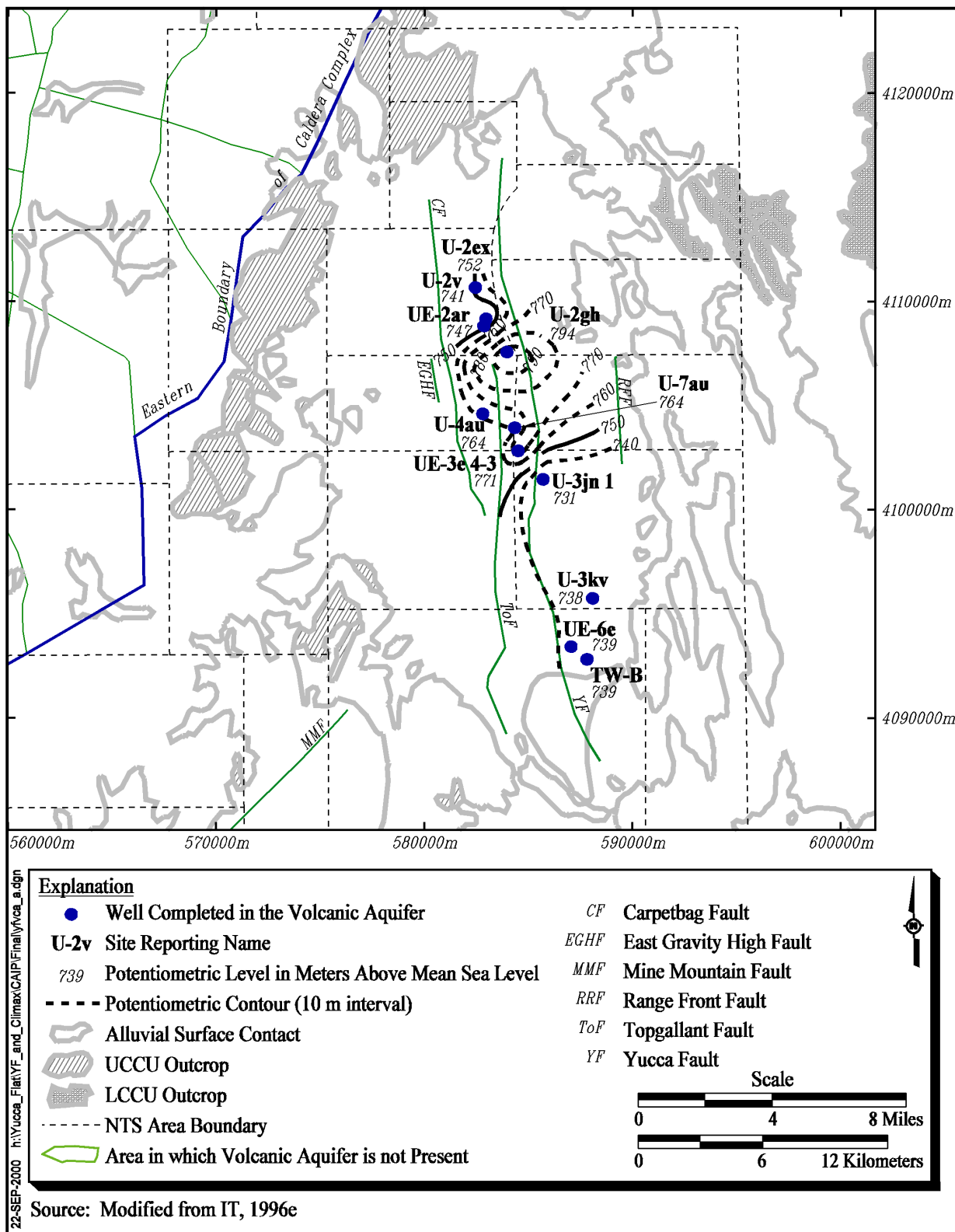


Figure 3-16
Predevelopment Potentiometric Surface Map of the Volcanic Aquifer
of the Yucca Flat/Climax Mine Area

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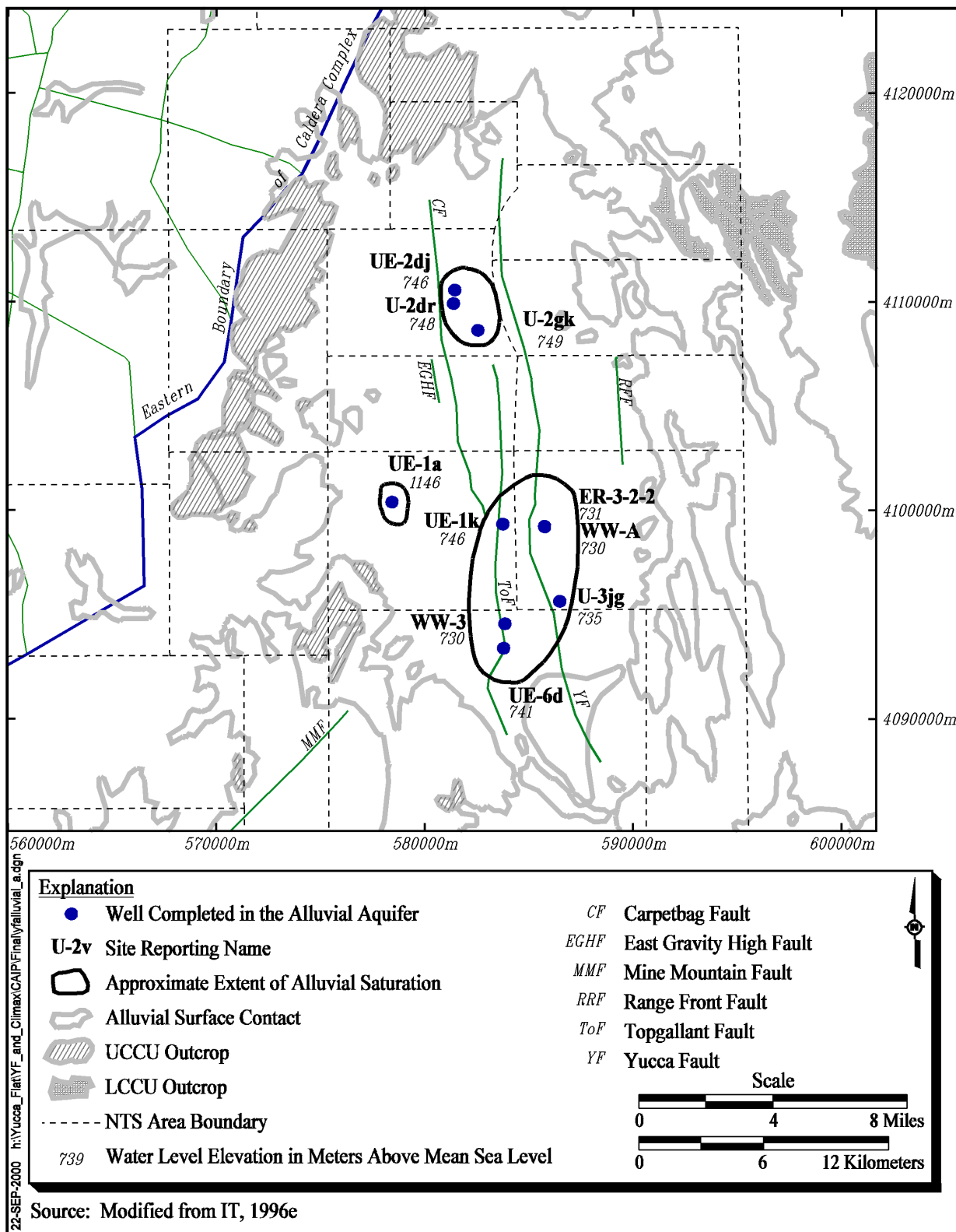


Figure 3-17
Predevelopment Water Levels in the Alluvial Aquifer
of the Yucca Flat/Climax Mine Area

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Within the central portion of the Yucca Flat basin, groundwater occurs within the LCCU, LCA, VA, VCUs, and the AA, all offset by normal faulting due to basin extension and growth. Along the sides of the basin, the AA is unsaturated, and the VAs and confining units are either partly saturated or unsaturated. In the western portion of Yucca Flat, the UCCU and LCA3 progress from being unsaturated or partly saturated at the basin margin to saturated toward the center.

Groundwater flow within the basin is driven by recharge from the north and northwest, and by subsurface inflow from the north, west, and northeast. Most recharge within the area of interest occurs as precipitation on Rainier Mesa and in the Belted Range (Laczniak et al., 1996).

Groundwater moves from these recharge areas, through the UCCU or LCCU in the north and northwest, into the LCA in the central portion of Yucca Flat. In addition, groundwater moves downward to the LCA in the central portion of the valley from the AA and the volcanics.

Groundwater discharge occurs within the area as springflow from perched groundwater lenses, and as subsurface outflow across the southern boundary of the basin, and from wells. Groundwater ultimately discharges at Franklin Lake Playa to the south and Death Valley to the southwest.

Based on the existing data and as interpreted from the regional groundwater flow model (DOE/NV, 1997c), the overall groundwater flow directions in the investigation area are to the south and southwest ([Figure 3-14](#)). A groundwater trough is coincident with the longitudinal axis of Yucca Flat; and surrounding groundwater flow patterns converge on the valley from the northeast, north, and west ([Figure 3-14](#)). The hydraulic gradient beneath the valley is relatively flat; whereas areas of high gradient exist along the western, northern, and northeastern boundaries. Within the valley, the potentiometric surface is at a level of about 739 m amsl (2,425 ft amsl) at the north end of the valley, and about 732 m amsl (2,400 ft amsl) at the south end (Laczniak et al., 1996), which translates to a gradient of approximately 0.0002. Potentiometric levels on Rainier Mesa to the northwest, the Belted Range to the north, and Emigrant Valley to the northeast, are more than 1,372 m amsl (4,500 ft amsl). Therefore, potentiometric levels decline by more than 609 m (2,000 ft) across the basin boundaries, which translates to a gradient of more than 0.15 between Emigrant Valley and Yucca Flat.

The local flow regime is influenced by a structural high of the LCCU located just north of Yucca Mountain. The structurally high LCCU may also be responsible for the higher water levels that are observed in Emigrant Valley and on Rainier Mesa ([Figure 3-14](#)). At the northern end of Yucca Flat,

the Climax stock intrudes the LCA but is not believed to be a major barrier to groundwater flow on a regional scale.

The LCA is under unconfined groundwater flow conditions beneath most of the mountain ranges that border the Yucca Flat basin to the east and southeast. However, the LCA is under confined conditions beneath much of the eastern portion of the valley where the VCU is the upper confining layer. Also, the LCA is confined on the western side of the basin where it is overlain by the UCCU. [Figure 3-15](#) shows the hydraulic head distribution in the LCA in the Yucca Flat/Climax mine area. Data from areas beyond the boundaries of the Yucca Flat basin were included in the generation of this potentiometric map. The LCA is bounded by the UCCU to the west and by the LCCU to the north and northeast of the flat. The general direction of groundwater in the LCA in this area is from the eastern, northern, and western edges of the flat towards the groundwater trough located along the axis of the flat and then southwest towards the Amargosa Desert and the discharge areas. Based on 16 measurements in the basin, there appears to be a trough approximately aligned with the Yucca Fault ([Figure 3-15](#)). The hydraulic gradient along the center line of the trough, passing through Wells UE-10j, U-3cn#5, and WW-C, ranges from 1×10^{-4} to 5×10^{-4} m/m.

[Figure 3-16](#) shows the hydraulic head distribution in the VA in the Yucca Flat/Climax Mine area. The VA consists of the WTA, VTA, TCU2, and Toppopah Springs Tuff Aquifer (TPTA) and extends over most of the flat. The VA is absent on the westernmost side of the flat. As shown on the potentiometric head map ([Figure 3-16](#)), the direction of flow is unclear and complicated by three regions of apparent groundwater mounds (areas of anomalously high hydraulic heads) ([Figure 3-16](#)). The cause of the central mound may be the residuals of pressures that were trapped and accumulated from repeated underground detonations in saturated low-permeability confining units such as the VCU (Hawkins et. al, 1987). These anthropogenic influences have substantially altered preexisting local hydraulic gradients and groundwater flow patterns (Laczniak et al., 1996). Available data from areas north and south of the mound suggest that perhaps predevelopment flow patterns in the VA were inward towards the center of the Cenozoic units. The northern and eastern mounds ([Figure 3-16](#)) may not be testing-related because there is some evidence they were present prior to testing (Hale et al., 1995).

Figure 3-17 shows water levels in the AA. The available data indicate that the alluvial deposits are unsaturated over most of the Yucca Flat/Climax Mine area. The alluvium is saturated in discrete places and forms a discontinuous aquifer within Yucca Flat. The AA is composed of two major areas. The largest of these areas is located in the central part of the flat and is crossed by major faults. The second area is located in the northern part of the flat and is smaller than the central one. Available data for the AA are not sufficient to draw potentiometric contours and to depict the direction of the horizontal movement. Therefore, the horizontal direction of groundwater flow within the AA is unclear based on the available data.

A qualitative analysis of the available water level data shows that in Yucca Flat, the observed trends of vertical hydraulic gradients are downward. The analysis results are presented in Table 3-13. Most of the calculations are based on the mean hydraulic head values calculated during the regional evaluation (DOE/NV, 1997c). The hydraulic head dataset may be found in Appendix A of Volume II of the regional evaluation documentation package (IT, 1996e). Additional data were used to supplement those used during the regional evaluation (DOE/NV, 1997c), their sources are indicated in the table. Vertical distances between the measuring points (Table 3-13) are only provided for a qualitative evaluation of the vertical hydraulic gradients.

As shown in Table 3-13, downward gradients are evidenced by data from several wells located throughout Yucca Flat. These includes wells with multiple completion zones and well pairs closely located. Water Well (WW) 2, for example, has five completion zones, two in the TCU1 and three in the LCA. The hydraulic heads in the TCU1 are approximately 24 m (79 ft) above the hydraulic heads measured in the LCA. The distance between the measuring points (middle of effective open interval) is approximately 328 m (1,076 ft). Volume II of the regional evaluation documentation package (IT, 1996e) provides additional information on the qualitative vertical hydraulic gradient analysis performed in support of the regional model.

3.4.6 Groundwater Chemistry

The data for this evaluation were obtained from the GEOCHEM99 (IT, 1999a) database. This comprehensive database contains groundwater chemistry data for samples collected from wells and springs on the NTS and the surrounding region. For Well ER-6-1, the data set was supplemented by analytical data from Gillespie (1993).

Table 3-13
Summary of Vertical Hydraulic Gradients in Yucca Flat

Well Name	Stratigraphy	Hydraulic Head Elevation (m amsl) ^a	EOI ^b Top (m bgs) ^c	EOI Bottom (m bgs)	EOI Middle (m bgs)	Source
UE-8e	Cenozoic	785.8	579.9	752.9	666.4	IT, 1996e
UE-10j	Carbonate	735.2	657.9	725.4	691.7	IT, 1996e
Hydraulic Head Difference (m)		50.6				
Distance between measurement points ^d (m)		-25.2				
U-8n	Cenozoic	819.8	-	-	-	Hale et al., 1995
U-8j	Cenozoic/Paleozoic	844.5	-	-	-	Hale et al., 1995
Hydraulic Head Difference (m)		-24.7				
Distance between measurement points (m)		-				
WW-2	Cenozoic	759.9	583.7	623.3	603.5	IT, 1996e
WW-2	Carbonate	736.2	823	1040	931.5	IT, 1996e
Hydraulic Head Difference (m)		23.7				
Distance between measurement points (m)		-328				
TW-E	Cenozoic	748.2	523.1	600.5	561.8	IT, 1996e
TH-9	Carbonate	728.8	544.1	595.3	569.7	IT, 1996e
Hydraulic Head Difference (m)		19.4				
Distance between measurement points (m)		-7.9				
U-7ca	Cenozoic	774.2	518.5	548.6	533.6	IT, 1996e
UE-7aa	Carbonate	729.6	335.9	656.5	496.2	IT, 1996e
Hydraulic Head Difference (m)		44.6				
Distance between measurement points (m)		37.3				
U-7cb	Cenozoic	761.9	543.2	563.9	553.6	IT, 1996e
UE-7nS	Carbonate	731.5	597.4	672.1	634.8	IT, 1996e
Hydraulic Head Difference (m)		30.4				
Distance between measurement points (m)		-81.2				
ER-6-1	Cenozoic	751.7	451.1	459.6	455.4	Gillispie, 1993
ER-6-1	Carbonate	729.8	547.1	648.9	598	Gillispie, 1993
Hydraulic Head Difference (m)		21.9				
Distance between measurement points (m)		-142.7				

^am amsl = Meters above mean sea level

^bEOI = Effective open interval

^cm bgs = Meters below ground surface

^dThe measurement point is the middle of the effective open interval.

3.4.6.1 General Groundwater Chemistry

Regional groundwater chemistry and a discussion of the groundwater chemistry of the Yucca Flat/Climax Mine investigation area are presented in this section.

3.4.6.1.1 Regional Groundwater Chemistry

Figure 3-18 is a piper diagram of groundwater chemistry for samples collected in the Yucca Flat/Climax Mine investigation area. Piper diagrams illustrate water chemistry types, based on the major ion composition. The lower triangles show the relative proportions of cations (left triangle) and anions (right triangle) in groundwater. The diamond-shaped plot in the center combines the cationic and anionic data. Piper diagrams are useful in evaluating trends in groundwater chemistry and identifying unique or anomalous groundwaters. Plotted on Figure 3-18 are average concentrations at each sampling location for which data are available. Data are grouped by area (e.g., Yucca Flat, Ash Meadows). Most groundwaters in the region are classified as either a sodium-potassium-bicarbonate or mixed type, based on the classification by Schoff and Moore (1964). Anions in groundwater from the NTS region plot along a trend ranging from predominantly bicarbonate to approximately 50 percent bicarbonate and 50 percent sulfate (lower right triangular plot, Figure 3-18). Chloride concentrations are relatively constant, with only a slight increase as sulfate increases, possibly reflecting the effects of evaporation on water chemistry. The cation composition of groundwater in the NTS region shows more scatter compared to the anion composition. Sodium generally constitutes greater than 40 percent of the total cationic charge, while calcium and magnesium typically constitute no more than 40 and 30 percent, respectively (lower right triangular plot, Figure 3-18). The following is a brief discussion of each group of data presented in Figure 3-18:

- Ash Meadows - groundwater samples from Ash Meadows plot in a relatively tight group on Figure 3-18. The samples were taken from a line of springs that represent a discharge location for the Ash Meadows groundwater subbasin. The regional carbonate aquifer is the major aquifer in the subbasin (Laczniak et al., 1996). The mixed type chemistry shown in Figure 3-18 indicates some influence of volcanic rocks on the groundwater in the flow system. Ash Meadows groundwater contains more sodium than would be expected if the flow system contained only carbonate rock.
- Death Valley - groundwater samples from Death Valley also plot in a relatively tight group in Figure 3-18. The samples were collected from springs, primarily in the Furnace Creek Ranch

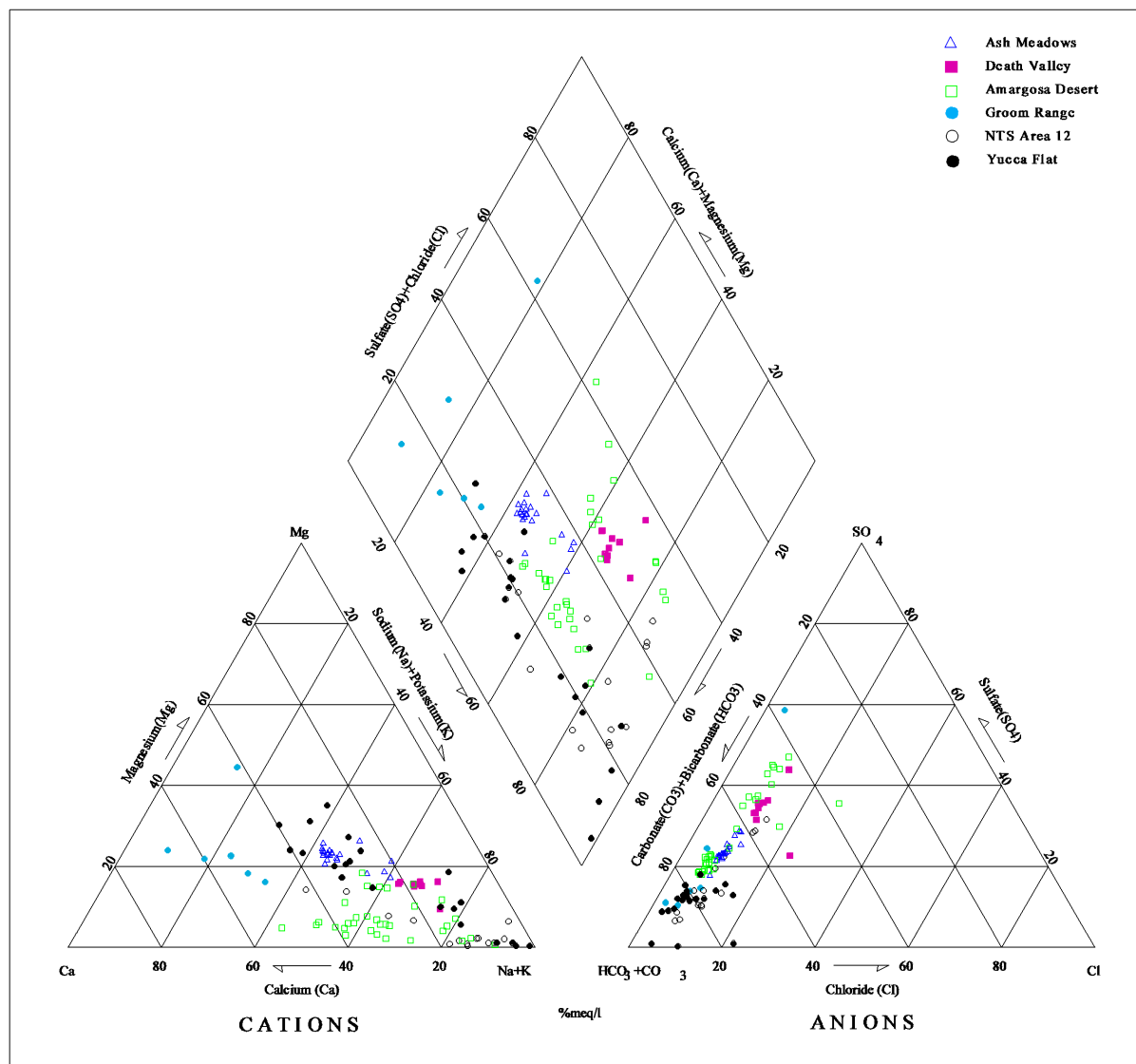


Figure 3-18
Groundwater Chemistry Piper Diagram for Yucca Flat Region

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area, that are discharge points for the Alkali Flat-Furnace Creek Ranch groundwater subbasin (Laczniak et al., 1996). Sodium is the predominant cation in groundwater from the Death Valley area, and bicarbonate, followed by sulfate are the dominant anions. The relatively higher chloride and sulfate content of waters from Death Valley suggests evaporation may have affected the chemistry.

- Amargosa Desert - Winograd and Thordarson (1975) concluded that the Amargosa Desert receives groundwater from several sources. The variability in groundwater chemistry shown in [Figure 3-18](#) supports their conclusion. Many of the samples from Amargosa Desert contain relatively lower concentrations of magnesium, compared to water from other areas. Also, the anionic composition of groundwater from the Amargosa Desert exhibits greater variability, relative to the composition in other areas of the NTS region.
- Groom Range - groundwater samples from the Groom Range are calcium-bicarbonate type waters. Based on the stable isotope composition ([Section 3.4.6.2.1](#)), the groundwater is most likely perched, discharging from springs in the Groom Range. The groundwater chemistry does not exhibit the influence of volcanic rock, and for that reason, is unlike the chemistry of groundwater from most other areas of the NTS region ([Figure 3-18](#)).
- NTS Area 12 - the composition from Area 12 groundwater ranges from sodium-bicarbonate, typical of water in volcanic units, to mixed type ([Figure 3-18](#)). The variation may reflect data from both the saturated and unsaturated zones.
- Yucca Flat - the averaged groundwater chemistry data from Yucca Flat are also plotted in [Figure 3-18](#) for comparison to data from other areas. The composition of Yucca Flat groundwater is variable, reflective of relatively complex Yucca Flat hydrogeology. Yucca Flat data are discussed in more detail in [Section 3.4.6.1.2](#).

3.4.6.1.2 Groundwater Chemistry of the Investigation Area

The major ion chemistry of Yucca Flat groundwater is variable and reflects the complex geology of the basin. Complex structure (e.g., basin and range faulting), combined with compositionally distinct geologic units (e.g., carbonate and silicious volcanic rocks) lead to the variations in groundwater chemistry observed in Yucca Flat.

[Table 3-14](#) presents concentration data for groundwater from several wells in Yucca Flat. The average concentration of major constituents are listed in [Table 3-14](#). Concentration ranges of trace elements are also presented in [Table 3-14](#). Overall, Yucca Flat groundwater chemistry is typical of southern Nevada. Predominant cations are calcium, magnesium, potassium, and sodium, with significant amounts of dissolved silica. The predominant anionic constituent is bicarbonate, with lesser amounts of chloride and sulfate. The pH values of Yucca Flat groundwater are typically in the

Table 3-14
Groundwater Chemistry Data for Yucca Flat Wells
(Page 1 of 2)

Well	Open Interval ^a		Water Well A	ER-3-1	ER-6-1	U-3cn #5 HTH	UE-10j (composite)	UE-15d Water Well	UE-1h	Test Well D	Water Well C	Water Well 2	Water Well C-1	Test Well 7	U-2bs	UE-10 ITS #3	Test Well B	UE-1a	UE-1b	UE-1c	UE-1q
Lithology of saturated			Alluvium	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Tuff	Tuff	Tuff	Tuff	Eleana argillite and quartzite; tuffaceous sediments (colluvium)	Eleana argillite, tuff	Tuff/ carbonate	Carbonate
Bicarbonate	average	(mg/L)	191	547	211	222	400	353	260	244	501	193	531	286	198	543	171	403	216	202	186
Calcium	average	(mg/L)	15.6	90.8	37.2	30.9	92.0	49.2	13.1	13.4	69.4	26.1	66.3	1.0	3.2	7.8	6.3	44.8	37.7	36.4	29.1
Chloride	average	(mg/L)	8.1	42.0	10.6	32.9	20.2	16.4	43.5	9.7	36.8	7.7	36.7	8.0	7.5	10.2	15.2	28.5	6.8	6.4	5.8
Fluoride	average	(mg/L)	0.7	1.2	NA	0.8	0.2	1.3	0.7	1.4	1.2	0.4	1.1	2.4	1.3	NA	1.1	NA	NA	0.5	NA
Magnesium	average	(mg/L)	8.7	33.7	13.1	20.1	37.8	16.2	8.6	6.0	30.7	14.8	29.9	0.2	0.5	0.4	1.5	28.1	13.6	13.6	15.0
Potassium	average	(mg/L)	9.1	18.3	7.7	9.1	10.9	15.1	24.0	9.3	14.8	6.6	14.0	4.6	6.0	21.5	4.3	10.5	11.1	12.6	4.8
Silica	average	(mg/L)	148	35	34	64	44	43	11	44	56	85	54	3.0	113	62	19	19	83	94	51
Sodium	average	(mg/L)	52	137	47	56	57	80	101	88	128	29	130	113	79	209	79	55	31	34	30
Sulfate	average	(mg/L)	18.5	66.7	31.1	35.7	71.4	43.4	1.8	34.9	65.2	21.1	66.2	2.1	24.5	42.8	27.6	1.0	20.3	33.1	22.1
pH	average	(pH units)	7.5	6.6	7.4	7.2	6.8	7.2	8.2	7.9	7.0	7.4	7.1	7.3	7.1	8.3	8.2	7.7	7.7	7.5	7.9
Specific Conductance	average	µS/cm	399	1216	478	549	921	695	1029	480	993	403	1023	466	389	927	370	760	440	464	376
TDS	average	(mg/L)	295	730	NA	342	472	422	515	315	637	245	625	281	274	621	280	392	262	284	NA
Aluminum	range	(mg/L)	0.01 U 1	0.0456 B 0.06 U	0.06 U	0.0336 U 1	0.06 U	0.02 1	0.005 U 0.043	0.005 U 0.4	0.01 U 1	0.02 1	0.01 U 1	0.1 0.16	0.01 0.16	NA NA	0.005 U 0.1	0.06 U	0.06 U	0.06 U 0.1	0.12b
Antimony	range	(mg/L)	NA	0.0272 U 0.0276 U	NA	0.0461 U	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Arsenic	range	(mg/L)	0.005 0.008	0.0033 0.043	0.02 U 0.1 U	0.043 0.0045 B	0.005 0.03	0.002 0.01	0.0032 0.0056	0.0136 0.0188	0.004 0.0092	0.003 0.003	0.005 0.008	NA NA	NA NA	NA NA	0.0008 0.0008	0.1 U	0.1 U	0.1 U 0.09b 0.1b	0.1 U 0.04b
Barium	range	(mg/L)	0.01 0.1 U 0.12	0.161 0.328 0.824	0.15b 0.2 U	0.159 B 0.16 0.17	0.07 0.135 0.33	0.1 U 0.7 0.12	0.0553 0.064 0.173	0.0188 0.28	0.1 U 0.6 0.5	0.01 0.012 U 0.08	0.03 0.13 0.5	NA NA NA	NA NA NA	NA NA NA	0.0854 0.2 0.274	0.45b	0.12b	0.09b 0.1b	0.04b 0.14b
Boron	range	(mg/L)	0.001 U 0.006 0.005 U	0.0023 U 0.005 U 0.0038 B	0.005 U	0.003 U	NA	0.005 0.007 0.02	NA NA NA	NA NA NA	0.001 U 0.009 0.005 U	0.003 U 0.003 U 0.02	0.001 U 0.005 0.005 U	NA NA NA	NA NA NA	NA NA NA	NA NA NA	NA	NA	NA	NA
Cadmium	range	(mg/L)	0.001 U 0.006 0.005 U	0.0023 U 0.005 U 0.0038 B	0.005 U	0.003 U	NA	0.005 0.007 0.02	NA NA NA	NA NA NA	0.001 U 0.009 0.005 U	0.003 U 0.003 U 0.02	0.001 U 0.005 0.005 U	NA NA NA	NA NA NA	NA NA NA	NA NA NA	NA	NA	NA	NA
Chromium	range	(mg/L)	0.003 0.01 0.001 U	0.0111 B 0.0121 B 4.98	0.025 U	0.0357	NA	0.007 0.059 0.01 U	NA NA 0.02 U	NA NA 0.03	0.003 0.03 0.01 U	0.006 0.01 U 0.01 U	0.007 U 0.616 0.003 U	NA NA NA	NA NA NA	NA NA NA	NA NA NA	NA	NA	NA	NA
Copper	range	(mg/L)	0.003 0.01 0.01 U	0.0111 B 0.0121 B 4.98	0.025 U	0.0357	NA	0.007 0.059 0.01 U	NA NA 0.02 U	NA NA 0.03	0.003 0.03 0.01 U	0.006 0.01 U 0.01 U	0.007 U 0.616 0.003 U	NA NA NA	NA NA NA	NA NA NA	NA NA NA	NA	NA	NA	NA
Iron	range	(mg/L)	0.002 U 0.005 U 0.001 U	0.0008 U 0.114 0.473	0.0008 U	0.001 U	0.001 U	0.005 U 0.059 0.08	0.00044 0.00224 0.083	0.0025 0.01 0.01	0.00068 0.02 0.15	0.002 U 0.02 0.007	0.0012 0.02 0.03	NA NA NA	NA NA NA	NA NA NA	0.0007 0.036 0.1 U	0.0008 U	0.0008 U	0.0008 U 0.0009	0.0089 0.01
Lead	range	(mg/L)	0.002 U 0.005 U 0.001 U	0.0008 U 0.114 0.473	0.0008 U	0.001 U	0.001 U	0.005 U 0.059 0.08	0.00044 0.00224 0.083	0.0025 0.01 0.01	0.00068 0.02 0.15	0.002 U 0.02 0.007	0.0012 0.02 0.03	NA NA NA	NA NA NA	NA NA NA	0.0007 0.036 0.1 U	0.0008 U	0.0008 U	0.0008 U 0.0009	0.0089 0.01
Lithium	range	(mg/L)	0.003 0.04 0.003 U	0.105 0.52 0.0003 U	0.015 U	0.01 U	0.08	0.01 U 0.06 0.0001 U	0.0237 0.33 0.00224	0.0233 0.1 U 0.004	0.01 U 0.32 0.001 U	0.01 U 0.02 0.001 U	0.001 U 0.34 0.001 U	NA NA NA	NA NA NA	NA NA NA	0.02 0.1 U 0.12	0.1	0.01	0.015 0.03 U	0.03 U 0.02 U
Manganese	range	(mg/L)	0.003 0.1 0.0003 U	0.105 0.201 0.0002 U	0.015 U	0.01 U	0.08	0.01 U 0.06 0.0001 U	0.0237 0.33 0.00224	0.0233 0.1 U 0.004	0.01 U 0.32 0.001 U	0.01 U 0.02 0.001 U	0.001 U 0.34 0.001 U	NA NA NA	NA NA NA	NA NA NA	0.02 0.1 0.12	0.1	0.01	0.015 0.03 U	0.03 U 0.02 U
Mercury	range	(mg/L)	0.003 U 0.001 U	0.0001 U 0.0002 U	0.0002 U	0.0001 U	0.0004	0.001 U 0.002	NA NA	NA NA	0.0003 U 0.001 U	0.004 0.001 U	0.0003 U 0.001 U	NA NA	NA NA	NA NA	NA NA	NA	NA	NA	NA
Molybdenum	range	(mg/L)	NA	0.005 U 0.01 U	0.02 U	0.0077 U 0.01 U	0.00152 0.01 U	NA 0.01 U	0.0608 0.066	0.0055	0.001 0.00116	NA	0.001 0.00128	NA	NA	NA	0.0102	0.02 U	0.02 U	0.02 U	0.02 U

Table 3-14
Groundwater Chemistry Data for Yucca Flat Wells
(Page 2 of 2)

Well	Open Interval ^a		Water Well A	ER-3-1	ER-6-1	U-3cn #5 HTH	UE-10j (composite)	UE-15d Water Well	UE-1h	Test Well D	Water Well C	Water Well 2	Water Well C-1	Test Well 7	U-2bs	UE-10 ITS #3	Test Well B	UE-1a	UE-1b	UE-1c	UE-1q
Lithology of saturated			Alluvium	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Carbonate	Tuff	Tuff	Tuff	Tuff	Eleana argillite and quartzite; tuffaceous sediments (colluvium)	Eleana argillite, tuff	Tuff/ carbonate	Carbonate
Nickel	range	(mg/L)	NA	0.0134 U 0.03	0.05 U	0.03 U 0.062	0.03 U 0.043	NA	0.001 U 0.0104	0.001 U	0.01 U	NA	0.002 0.0024	NA	NA	NA	0.001 U	0.05 U	0.05 U	0.05 U	0.05 U
Selenium	range	(mg/L)	0.001	0.0008 U 0.021444444	0.005 U 0.1 U	0.0007 U 0.01 U	0.01 U	0.001 U 0.02	0.004 U 0.0044	0.004 U	0.001 U 0.052	0.001 U 0.01 U	0.001 U 0.01 U	NA	NA	NA	0.004 U	0.1 U	0.1 U	0.1 U	0.1 U
Silver	range	(mg/L)	0.001 U 0.005 U	0.006 U 0.01 U	0.01 U	0.0049 U	NA	0.001 U 0.005 U	NA	NA	0.001 U 0.005 U	0.014	0.001 U 0.02	NA	NA	NA	NA	NA	NA	NA	NA
Strontium	range	(mg/L)	0.21 0.24	0.884 0.97	0.18	0.21 0.235	0.32 0.47	0.45 0.49	0.169 0.2	0.1 0.1246	0.77 0.83	0.08 0.13	0.78 0.84	0.1 U	0.04 0.05	NA	0.0149 0.1	0.63	0.47	0.41 0.42	0.14
Uranium	range	(mg/L)	0.0044 0.0066	0.003 0.127 U	0.0033	0.001 U 0.0942 U	0.0014 0.00592	0.0027 0.0028	0.0001 0.0004 U	0.0007	0.00636 0.0075	0.0011	0.0064 0.0072	NA	NA	NA	0.0004 0.0008	0.0006 U	0.0043	0.0041 0.0044	0.0023
Zinc	range	(mg/L)	0.007 U 0.227	0.013 B 0.0378	0.02 U	0.0304	NA	0.02 0.072	NA	NA	0.01 0.06	0.01 U 0.21	0.01 0.132	NA	NA	NA	NA	NA	NA	NA	NA
Carbonate	range	(mg/L)	NA	5 U	NA	5 U	10 U	NA	NA	2.6 2.8	NA	NA	6	NA	NA	1.6	1.1 53	NA	NA	NA	NA
Nitrate/Nitrite	range	(mg/L)	0.879 13.5	0.05 U 0.147	0.11 0.58	0.019 0.08853	4	0.053 3.5	NA	0.029 4.2	0.01 U 2.4	0.9 11	0.019 3.4	NA	0.41 0.8	5.489	0.029 1.3	0.04427	2.745	0.019 2.39	NA
Phosphate	range	(mg/L)	0.002 0.16	NA	NA	0.002 0.007	0.02	0.002 0.1 U	NA	0.002 0.38	0.002 0.018	0.002 0.01 U	0.002 0.01 U	NA	0.09 0.12	NA	0.003	NA	NA	0.002	NA
Dissolved Oxygen	range	(mg/L)	NA	NA	2.6 5	NA	2	NA	NA	4	3	NA	1.8 2.5	NA	NA	NA	3	3	4	5 6	NA
Water Temperature	range	(oC)	26 27	37.8 45	39 43.7	42.4	25.56 34	30 35.5	25.3	23.9	35 37	34.5	32.7 38	69	25.5 26	NA	20.1	25.4	27.4	26.2 36.2	31.2

^aLithology from Arteaga et al. (1991), Thordarson et al. (1967), Emerick (1964), Drellack et al. (1992), DOE/NV (1995), DOE/NV (1996a), and IT (1993).

^bValue from GEOCHEM99 database was divided by 1,000 to obtain the listed value. This is based on the assumption that incorrect concentration units were reported (microgram per liter versus milligram per liter).

B = Reported value is less than the contract-required detection limit, but greater than or equivalent to the instrument detection limit.

µS/cm = Microsiemens per centimeter

mg/L = Milligrams per liter

NA = Data were not available

pCi/L = Picocuries per liter

TDS = Total dissolved solids

U = Analyzed for but not detected; reported value is detection limit.

range of 7 to 8. Groundwaters are typically dilute, with total dissolved solids well below 1,000 milligrams per liter. Yucca Flat groundwater is relatively oxidized, based on the presence of dissolved oxygen.

Figure 3-19 is a Piper diagram of Yucca Flat groundwater chemistry. Individual samples, which meet a charge balance requirement of 10 percent of the total charge, are plotted on Figure 3-19. Yucca Flat groundwaters trend from a mixed calcium-magnesium-sodium water type to a predominantly sodium water type. Bicarbonate generally comprises greater than 70 percent of the total anionic milliequivalents of Yucca Flat groundwater. Sulfate ranges from 5 to 20 percent and chloride ranges approximately 5 to 10 percent of the total anionic milliequivalents. Higher sulfate concentrations are correlated with higher levels of chloride.

Several anomalous groundwater analyses are identified in Figure 3-19. These groundwaters contain higher levels of sulfate and chloride and lower concentrations of magnesium relative to the trends discussed above. The groundwaters plot below the predominant cation trend (right triangle) and above and to the right of the anion trend (left triangle). The anomalous samples were collected from post-test drill back holes or satellite wells located adjacent to nuclear tests. The samples appear to be impacted by underground testing or well installation.

Figure 3-20 is a Piper diagram showing the average concentration data for Yucca Flat wells. The anomalous groundwaters discussed above are not included in this figure. Groundwater chemistries cluster into several groups on the cation triangle in Figure 3-20. The groups are as follow:

- Group 1 - mixed, sodium < 40% - groundwaters in this group plot at left end of the cation trend (black symbols). Sample locations include wells in the carbonate aquifer at the northwest end of Yucca Flat (e.g., Water Well 2) and test holes sampling water from the Eleana Formation and/or carbonate units on the west side of Yucca Flat (e.g., UE-1a).
- Group 2 - mixed, sodium 50% - this water chemistry (green symbols) is observed at several wells in carbonate rock in northeast (UE-15d), central (U-3cn #5), eastern (ER-3-1 and ER-6-1), and southern (Water Wells C and C-1) Yucca Flat. Also included in this group are two wells in alluvium in central Yucca Flat (Water Wells A and 3).
- Group 3 - sodium dominant, calcium + magnesium 20% - this water chemistry group (blue symbols) is generally observed in wells located along the Carpetbag/Topgallant fault system in central Yucca Flat. These locations include carbonate wells UE-1h and Test Well D and a well in alluvium or tuff (Well UE-6d).

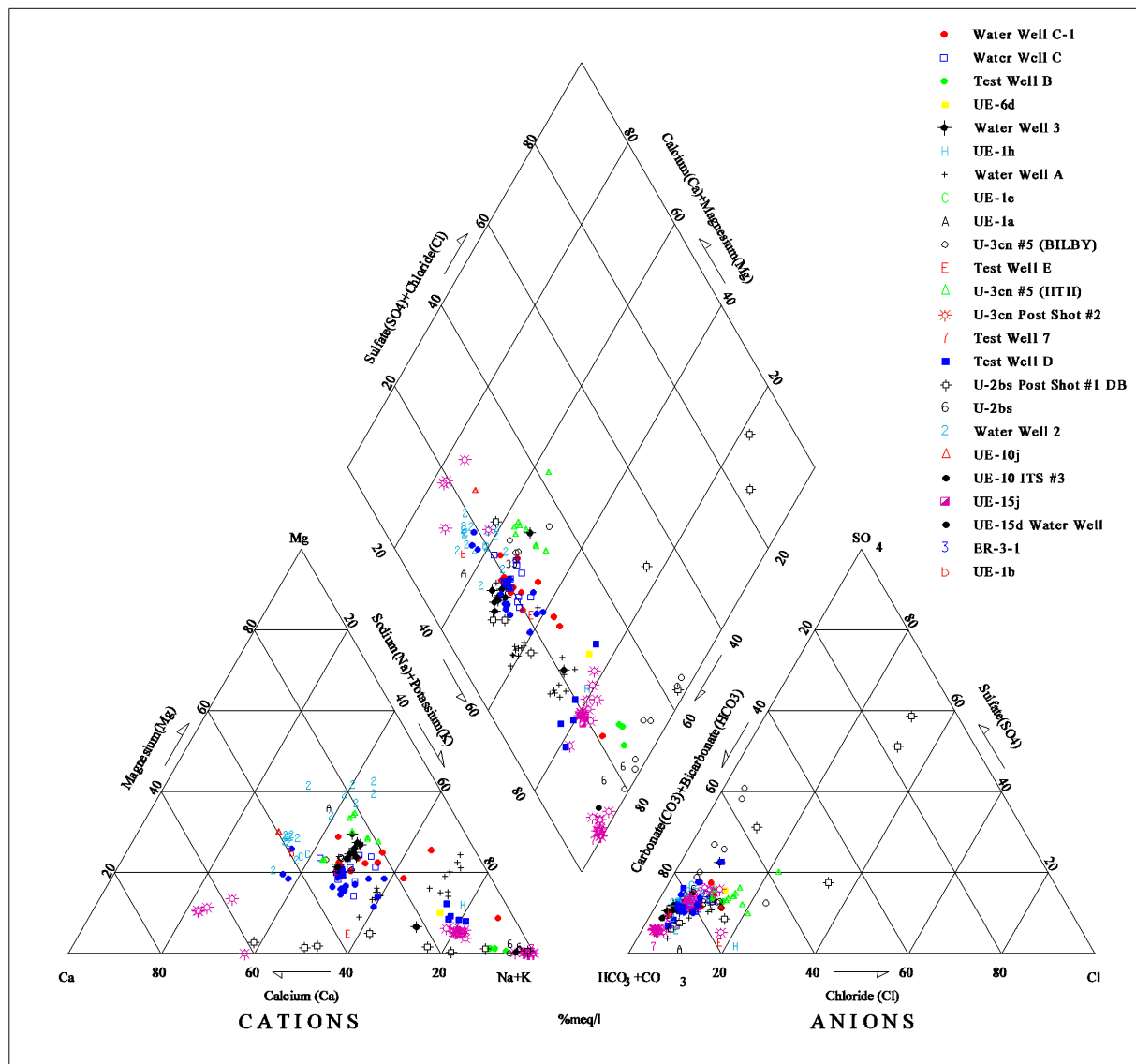


Figure 3-19
Groundwater Chemistry Piper Diagram for Yucca Flat

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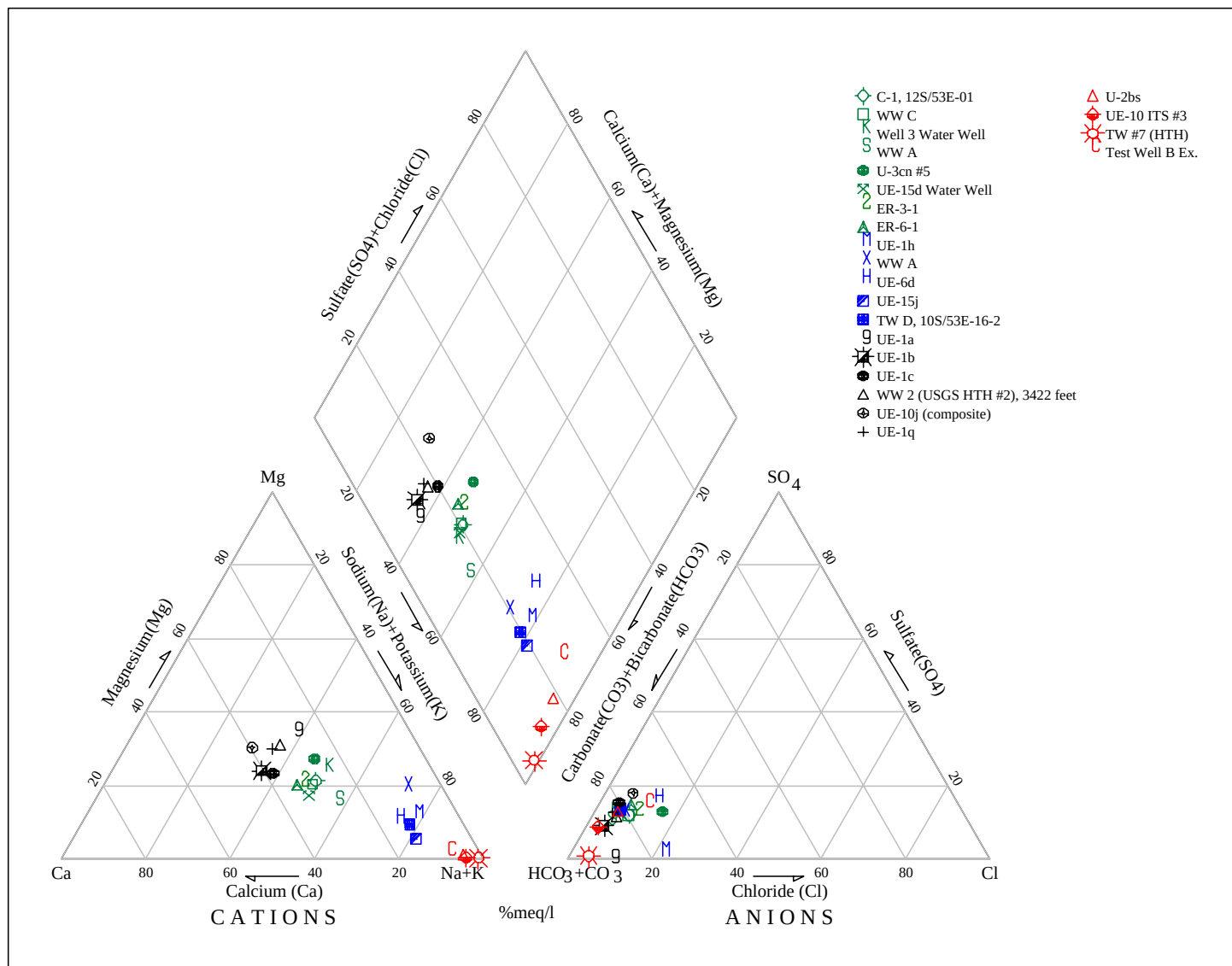


Figure 3-20
Piper Diagram Showing Average Concentration Data for Yucca Flat Wells

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- Group 4 - sodium 90% - these groundwaters plot at the right end of the cation trend (red symbols). Sample locations are wells and test holes in volcanic units (e.g., UE-10 ITS #3 and Test Well B Ex.).

Groups 1 and 2 are in the mixed hydrochemical facies and Groups 3 and 4 are in the sodium-potassium-bicarbonate facies of Schoff and Moore (1964). Groundwater flow paths for Group 1 chemistry are through the Paleozoic clastics and carbonates on the west side of Yucca Flat. Group 2 may be most representative of the chemistry of groundwater in the regional carbonate aquifer east of the major fault systems in Yucca Flat. Interestingly, groundwater chemistry at Water Well 3, which is completed in tuffaceous alluvium is Group 2. This may be because Water Well 3 is located near a fault, across which, Paleozoic sedimentary formations are present at similar depths as the opened interval of Water Well 3 (based on review of cross sections prepared for the regional model [IT, 1996f]). Group 3 chemistry observed in samples from carbonate wells is somewhat unusual and suggests the influence of volcanic units on groundwater chemistry. The unusual chemistry combined with the location of these wells, near the Carpetbag/Topgallant fault system, may be indicative of downward water movement from overlying volcanic units into the carbonates along the fault zone. More information on well construction and hydrostratigraphy are required to confirm this observation. Group 4 chemistry is typical of groundwater in volcanic units. The relatively small concentrations of calcium and magnesium may reflect low concentrations of these elements in volcanic rock. Ion exchange for sodium on alteration products such as clays and zeolites may further reduce concentrations of calcium and magnesium in groundwater flowing through volcanic rock.

3.4.6.2 Isotope Chemistry

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

3.4.6.2.1 Hydrogen and Oxygen

Stable hydrogen and oxygen isotopes are affected by meteorological processes but are generally not affected by water-rock interactions in the saturated zone of groundwater flow systems. Thus, stable hydrogen and oxygen isotopes are useful in evaluating the link between precipitation, recharge, and groundwater.

Figure 3-21 shows the stable oxygen (delta [δ] Oxygen-18 [^{18}O]) and hydrogen isotope (δ deuterium [D]) composition of groundwater in the Yucca Flat/Climax Mine investigation area. Also plotted in Figure 3-21 are precipitation-amount weighted average compositions of precipitation for sampling stations on the NTS (Ingraham et al., 1990). A local meteoric water line (MWL) derived from the precipitation data of Ingraham et al. (1990) and the global MWL (Craig, 1961) are also shown. Data are presented in Figure 3-21 as isotope ratios expressed in δ as per mil ‰ (parts per thousand) differences relative to an arbitrary standard known as standard mean ocean water (SMOW).

Precipitation data lie along the local MWL. Most groundwater data lie roughly parallel to, but below, the MWLs. This isotopic shift in the groundwater data has been ascribed to fractionation during evaporation of rainfall, sublimation of snowpack, or fractionation during infiltration (White and Chuma, 1987; Clark and Fritz, 1997). White and Chuma (1987) also claim that the shift in the stable isotope composition of groundwater may be related to changes in past climatic conditions, compared to present conditions. Rose et al. (1998) reports that the stable isotope signature of Nevada groundwaters are inherited during and after snowpack melting due to evaporation of surface runoff and shallow groundwater.

Groundwater in the Yucca Flat/Climax Mine CAU study area, including water discharging at Ash Meadows and Death Valley, has a stable isotope signature that cannot be derived from local precipitation. Recent precipitation is isotopically heavier than groundwater in the region (Figure 3-21). One explanation for isotopically lighter groundwater is that the recharge areas are located north of the study area. Davisson et al. (1999) report that the oxygen and hydrogen isotope composition of NTS groundwater is similar to the composition of groundwater and alpine spring waters in Central Nevada. The implications are that significant regional groundwater flow occurs from recharge areas to the north of the NTS. An alternative explanation is that groundwater was recharged during cooler climatic conditions that existed during the last glacial period. Both of these explanations may be required to account for the stable isotopic composition of groundwater in Yucca Flat. Groundwater in the regional carbonate aquifer beneath Yucca Flat may have been recharged in areas to the north of the NTS. However, the alluvial and volcanic water-bearing units of Yucca Flat are generally not thought to be part of the regional flow system; thus, groundwater in these units may

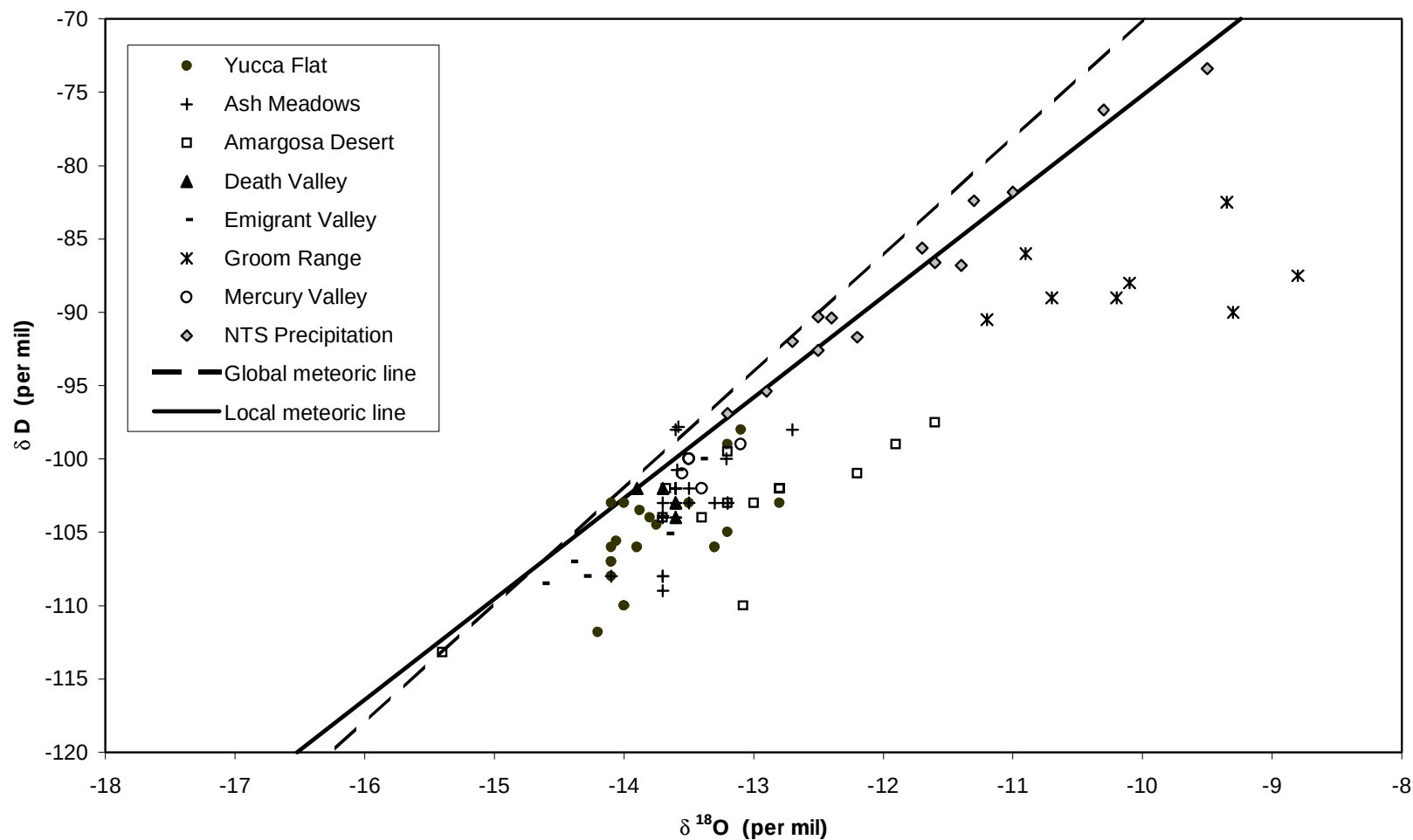


Figure 3-21
Stable Isotope Composition of Groundwater in and Surrounding Areas

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have been derived from local recharge. The distribution of modern recharge combined with stable isotope data indicate this would require a colder and wetter climate than presently exists at the NTS.

Unlike other groundwaters in the Yucca Flat/Climax Mine area, the stable isotope composition of water from springs in the Groom Range appears to be related to the composition of modern precipitation, modified by evaporative enrichment (Figure 3-21). This indicates that the springs are discharge points for localized perched flow systems, and travel times to the springs may be relatively short compared to travel times in the regional flow system.

3.4.6.2.2 Carbon Isotopes

Carbon isotopes provide insight into the evolution of carbonate and carbon cycling in groundwater, which in turn, provide information for geochemistry-based studies of groundwater flow paths and travel times. Table 3-15 presents the carbon isotope data for Yucca Flat groundwater. Shown on Table 3-15 are δ carbon-13 ($\delta^{13}\text{C}$) (measure of the carbon-13 to carbon-12 isotopic ratio, relative to the ratio of the Pee Dee Belemnite reference standard), Carbon-14 (^{14}C), and uncorrected ^{14}C groundwater age. Where more than one value was available for a well, the arithmetic average is listed. Also shown on Table 3-15 are the carbon isotope data for Ash Meadows and Amargosa Desert; these data are arithmetic averages of all data for each area. The ^{14}C groundwater ages presented in Table 3-15 cannot be interpreted as the actual groundwater ages. Corrections based on modeling the behavior of dissolved carbon in the flow system are required to estimate actual groundwater age and travel times from ^{14}C data. This is discussed further below.

Figure 3-22 shows groundwater ^{14}C activity as a function of $\delta^{13}\text{C}$. In addition to groundwater data, also plotted are data for primary carbonate and perched waters springs. Primary carbonate, which is Paleozoic-age marine carbonate, contains essentially no ^{14}C , and Thomas et al. (1996) reports the $\delta^{13}\text{C}$ of primary carbonates in southern Nevada ranges from -1.4 to +3.7 ‰ (Figure 3-22). The data for perched spring waters obtained from a report by Rose et al. (1997) and other unpublished reports are thought to be representative of recharge, as indicated by ^{14}C greater than 100 percent and a $\delta^{13}\text{C}$ signature similar to the $\delta^{13}\text{C}$ of soil zone carbon dioxide (Clark and Fritz, 1997).

If radioactive decay alone was responsible for observed changes in ^{14}C activity along the flow path, the carbonate isotopic signature of groundwater would follow the arrow marked " ^{14}C decay" in

Table 3-15
Carbon Isotopes in Yucca Flat and Regional Groundwater

Well	Lithology of saturated open interval ^a	$\delta^{13}\text{C}^b$ (per mil PDB)	C^{14}	
			(percent modern carbon)	(years before present)
ER-3-1	carbonate	-2.3	0.7	41000
ER-6-1	carbonate	-0.7	2.1	31989
U-3cn5	carbonate	-6.8	3.2	28466
UE-10j, Zone 1c	carbonate	-4.6	7.5	21455
UE-10j, Zone 2c	carbonate	-5.8	11.4	17959
UE-10j, Zone 3c	carbonate	-7.9	12.6	17157
UE-1h	carbonate	-11.2	18.1	14617
USGS Test Well D	carbonate	-5.5	2.8	29570
USGS Water Well C	carbonate	-4.2	0.6	42309
Water Well 2	carbonate	-14.5	15.9	15200
Water Well C-1	carbonate	-3.1	2.0	33542
Test Well B	tuff	-10.2	20.3	13175
UE-1a	Eleana argillite and quartzite; tuffaceous sediments (colluvium)	-8.6	60.5	4155
UE-1b	Eleana argillite, tuff	-4.5	16.0	15155
UE-1c	tuff/carbonate	-5.0	2.6	30183
UE-1q	carbonate	-2.4	7.7	21204
Ash Meadows	NA	-5.9	6.6	24105
Amargosa Desert	NA	-6.0	18.5	14594

^aLithology from Arteaga et al. (1991), Thordarson et al. (1967), Emerick (1964), Drellack et al. (1992), DOE/NV (1996a), DOE/NV (1995), and IT (1993).

^bRatio of carbon-13 to carbon-12 in sample, relative to the ratio in the Pee Dee Belemnite reference standard.

^cZones 1, 2, and 3 are lower, middle, and upper zones, respectively

NA = Not applicable

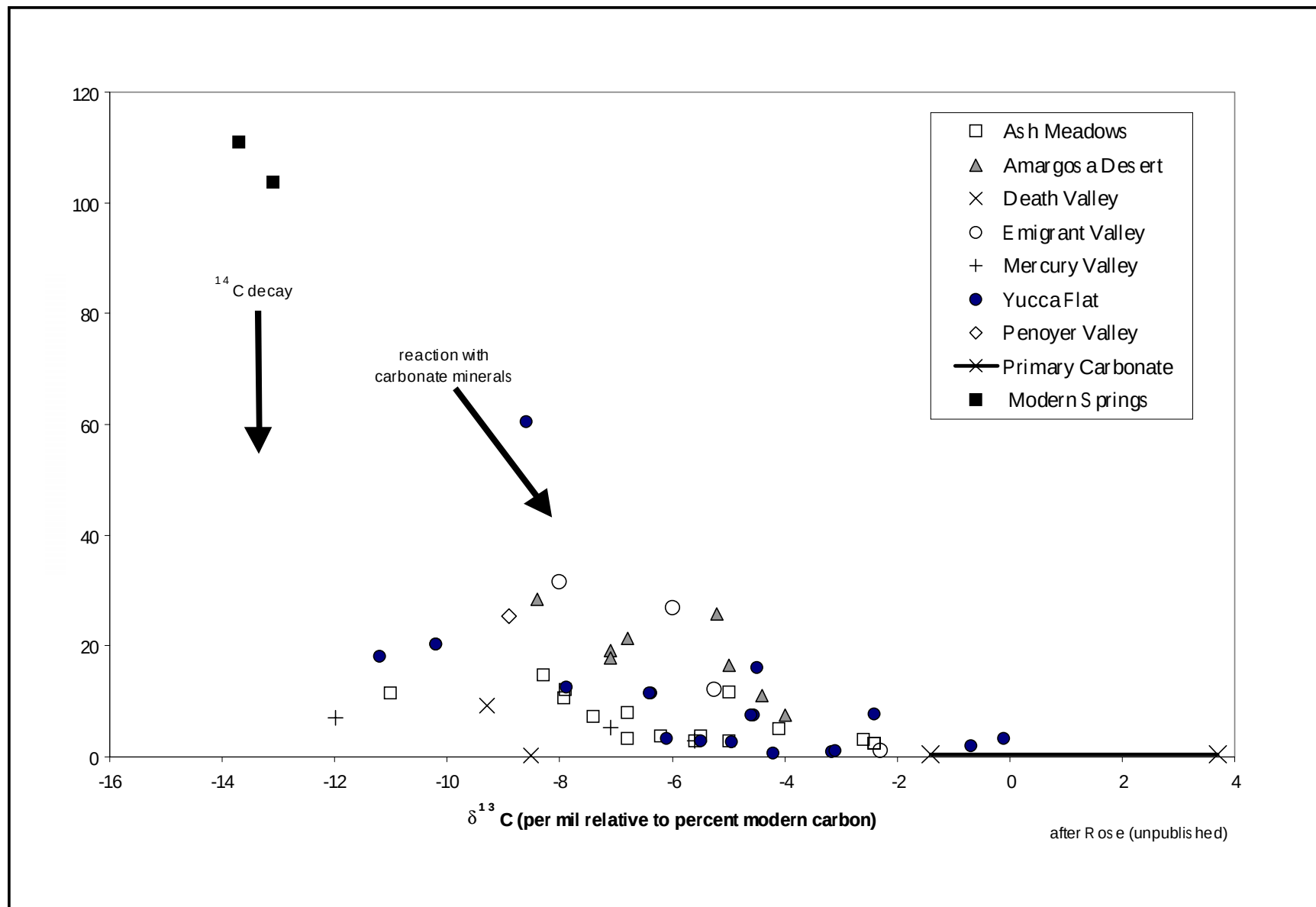


Figure 3-22
Carbon-14 Versus Delta Carbon-13 for Groundwater

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[Figure 3-22](#). However, this is not the case with groundwaters in the NTS region, as decreasing ^{14}C activity is correlated with increasing (heavier) $\delta^{13}\text{C}$ values. The data shown in [Figure 3-22](#) indicate that dissolved carbonate reacts with carbon-containing materials, most likely carbonate minerals, in the flow system. As with the major ion chemistry, the carbon isotope data for Yucca Flat exhibit a broad range ([Figure 3-22](#)), which is related to the complex hydrogeology of Yucca Flat. The heaviest (least negative) $\delta^{13}\text{C}$ values are observed in groundwater from the carbonate aquifer ([Table 3-15](#)). This probably reflects reaction with primary carbonate minerals.

Thomas (1996) and Thomas et al. (1996) have estimated groundwater ^{14}C ages for the Ash Meadows groundwater subbasin using geochemical mass-balance models to account for reactions occurring along the flow path and the influence of mixing. Using four different models based on inorganic ^{13}C , Thomas et al. (1996) obtained ^{14}C ages ranging from modern to 10,100 years before present (ybp) for Ash Meadows spring discharge. Geochemical factors indicate that two of the four models are not realistic; therefore, the estimated age of groundwater discharging at Ash Meadows can be narrowed to between 2,300 and 5,000 ybp (Thomas et al., 1996). Thomas (1996) calculated dissolved organic carbon (DOC) ^{14}C ages ranging from 2,500 to 4,600 ybp for water discharging in the Ash Meadows Springs. Dissolved organic carbon may be better than dissolved inorganic carbon (DIC) for estimating ^{14}C groundwater ages because the ^{14}C content of DOC is less likely to be affected by reactions or isotopic exchange processes that affect DIC in the subsurface environment.

3.4.7 Groundwater Radiochemistry

To date, radiological contamination of groundwater in Yucca Flat has been observed only in areas that are relatively close to the origin of the contamination (i.e., nuclear test locations). This section presents information on the nature and extent of radioactivity in groundwater. The information was obtained from groundwater sampling conducted in Yucca Flat and other areas of interest. Pertinent findings and data are summarized in the following sections. The sections are organized according to the characterization programs (e.g., HRMP and LTHMP) that were primarily responsible for generating the data.

3.4.7.1 Hydrologic Resources Management Program

Since the mid 1970s, the radiochemistry of Yucca Flat groundwater has been investigated as part of the HRMP, which was previously known as the Hydrology and Radionuclide Migration Program and the Radionuclide Migration Project. The HRMP is sponsored by the DOE/NV; program participants include BN, DRI, U.S. Environmental Protection Agency (EPA), LANL, LLNL, and USGS. The following objectives of the HRMP are pertinent to the Yucca Flat/Climax Mine CAI:

- Behavior of radionuclides in the NTS underground environment
- Geologic and hydrologic consequences of nuclear testing
- Factors controlling transport of radionuclides by groundwater (Thompson, 1998).

Figure 3-23 shows the locations of HRMP investigations conducted in the Yucca Flat and Climax Mine area. The investigations were generally focused on the near-field environment.

Radiochemistry data have been obtained for groundwater in the chimney/cavity structure of several underground test locations. At several test locations, a satellite well was installed alongside or angle-drilled beneath test cavity, and the satellite well was pumped to induce the transport of contaminants from the cavity area. Radionuclides, primarily tritium, were detected beyond the near-field environment in several emplacement and exploratory boreholes in Yucca Flat. These locations were subsequently investigated by the HRMP. Recent annual reports include those by Thompson (1996, 1997, 1998, and 1999). The results of HRMP groundwater investigations are presented, by location, in the following subsections. Unless specifically stated, all tabulated radionuclide activity concentration data have been decay-corrected to January 1, 2000.

3.4.7.1.1 NASH (U-2ce)

The NASH test took place on January 19, 1967. The working point was in a Paleozoic carbonate unit at a depth of 367.5 m (1,205 ft) bgs, approximately 68 m (223 ft) above the regional groundwater table (Buddemeier and Isherwood, 1985). A satellite well (UE-2ce) was drilled to a total depth of 503 m (1,650 ft), cased to 495 m (1,624 ft), and perforated from 422 to 495 m (1,384 to 1,624 ft) bgs (Buddemeier and Isherwood, 1985). Well UE-2ce is approximately 183 m south of the U-2ce ground zero. Buddemeier and Isherwood (1985) claim that UE-2ce produces water exclusively from the LCA, assuming the well was properly installed. UE-2ce was pumped intermittently and sampled from 1977 to 1984; during the period approximately 42,000 cubic meters (m³) (1,482,000 ft³) of

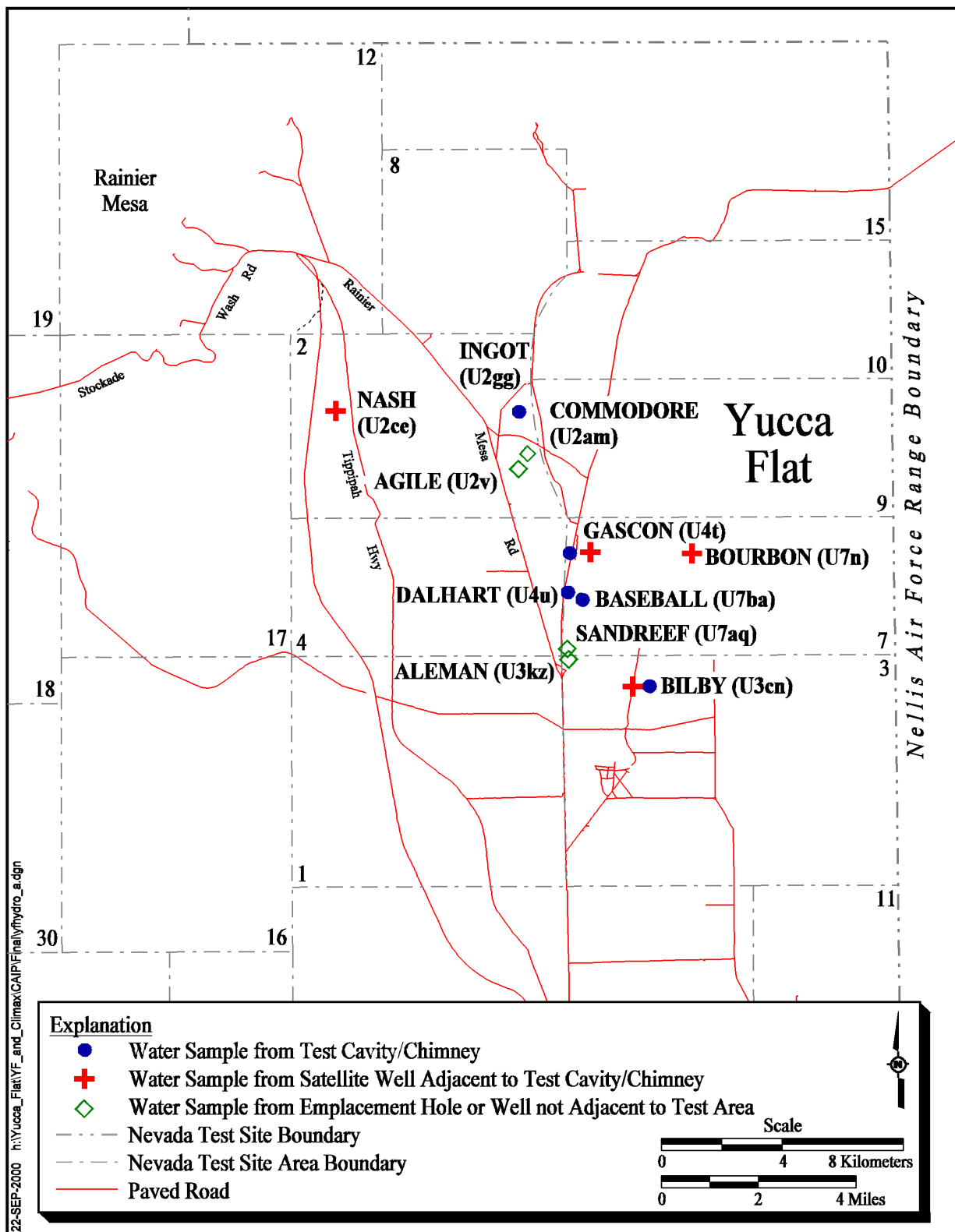


Figure 3-23
 Hydrologic Resources Management Program Study Location in Yucca Flat

water were removed from the well (Buddemeier and Isherwood, 1985). A groundwater sample was also collected and analyzed from UE-2ce in August 1993 (Thompson, 1995a). [Table 3-16](#) is a statistical summary of radionuclide concentrations in groundwater at UE-2ce.

As indicated by the data in [Table 3-16](#), pumping of satellite well UE-2ce induced radionuclide transport from NASH. Nimz and Thompson (1992) report that the NASH cavity does not intersect the water table; therefore, the radionuclides detected at UE-2ce may have entered the saturated zone through prompt injection. However, Nimz and Thompson (1992) stated that water level fluctuations could have been sufficient to cause flooding of the lower cavity.

3.4.7.1.2 BILBY (U-3cn)

The BILBY test, the first detonation below the water table at the NTS, took place on September 13, 1963 (Buddemeier and Isherwood, 1985). The working point was in volcanic tuff, 713 m bgs (2,339 ft bgs), well below the pretest water table, which is approximately 495 m bgs (1,624 ft bgs) (Thompson, 1998). Based on a reported yield of 249 kilotons (DOE/NV, 1998), the BILBY test is one of the largest underground tested conducted in Yucca Flat. A post-shot hole (U-3cn ps2) was drilled into the chimney and cavity in 1963; the hole subsequently collapsed, preventing access to the cavity and lower chimney. Perforations were made in the U-3cn ps2 casing at 512 and 527 m (1,679 and 1,729 ft) bgs and the hole was pumped periodically for hydrologic testing and water sampling through 1981 (Thompson, 1998). Samples were also collected from U-3cn ps2 in 1997, during recompletion activities at the BILBY site (DOE/NV, 1998).

In 1965, a satellite well (U-3cn5) was completed 122 m (400 ft) southeast of U-3cn ps2. U-3cn5 is opened to the formation from 863 to 922 m bgs (2,831 to 3,024 ft bgs) and produces water only from Paleozoic carbonate rocks below the volcanics (Buddemeier and Isherwood, 1985). Thompson (1998) reports approximately $3 \times 10^6 \text{ m}^3$ ($11 \times 10^7 \text{ ft}^3$) of water was pumped from U-3cn5 in the period from 1967 to 1981; pumping was not continuous during the entire period. Groundwater samples were collected intermittently from satellite well U-3cn5 during the pumping period, and samples were also collected in 1997, during recompletion activities at the BILBY site (DOE/NV, 1998).

Table 3-16
Radionuclides in Groundwater at Satellite Well UE-2ce (NASH)

Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	< 3.8E-05	< 1.7E-01	NC	NC	7
Carbon-14	< 3.2E+03	< 3.2E+03	NC	NC	1
Cesium-137	< 2.7E-03	1.2E+00	2.4E-01	4.1E-01	9
Cobalt-60	< 5.1E-05	< 1.3E-01	NC	NC	7
Europium-155	7.3E-04	6.9E-03	3.2E-03	2.7E-03	6
Krypton-85	2.1E+04	2.4E+04	2.2E+04	2.1E+03	2
Plutonium-238	< 9.7E-02	< 9.7E-02	NC	NC	1
Plutonium-239/240	< 8.6E-02	< 8.6E-02	NC	NC	1
Ruthenium-106	< 9.9E-09	< 2.2E-07	NC	NC	6
Sodium-22	1.9E-04	2.7E-03	1.2E-03	8.8E-04	6
Strontium-90 ^b	1.5E-01	3.3E+00	1.6E+00	1.2E+00	12
Technetium-99	< 2.3E-01	< 2.3E-01	NC	NC	1
Tritium	8.9E+04	1.4E+07	6.1E+06	2.2E+06	81
Uranium-235	5.0E-02	1.3E-01	8.3E-02	2.7E-02	6
Uranium-238	9.6E-01	1.9E+00	1.5E+00	4.2E-01	6

Data Sources: Buddemeier and Isherwood (1985), Daniels (1983), Daniels and Thompson (1984), Smith et al., (1998), Thompson (1985), and Thompson (1995a)

^a All activity concentrations were decay-corrected to January 1, 2000.

^b Does not include a value of <6.2E+00 picocuries per liter.

NC = Not calculated; values below detection preclude calculation or only one value was reported.

pCi/L = Picocuries per liter

Buddemeier and Isherwood (1985) considered the U-3cn ps2/U-3cn5 chimney-satellite pair to be in an ideal location to evaluate the possibility of contamination of the LCA. They cited the following reasons: (1) the satellite well (U-3cn5) is opened at the top of the LCA, (2) the BILBY test cavity is below the water table and near the Tertiary/Paleozoic boundary, and (3) rapid transmission of hydraulic pressure during the test suggests the possibility of communication between the overlying saturated volcanic units and the LCA. Despite these factors and pumping the well for 14 years, no

radioactivity attributable to the BILBY test was measured in groundwater from U-3cn5 (Thompson, 1998). However, Buddemeier and Isherwood (1985) caution that the duration of pumping may not have been sufficient to observe contaminant breakthrough at Well U-3cn5. [Table 3-17](#) presents a statistical summary of the radiological data for groundwater from Wells U-3cn ps2 and U-3cn5.

3.4.7.1.3 BOURBON (U-7n)

The BOURBON test was detonated on January 20, 1967, at a working point of 560 m bgs (1,837 ft bgs) in Paleozoic-age silty limestone. Buddemeier and Isherwood (1985) report although the working point is approximately 40 m (131 ft) above the static groundwater level of 601 m bgs (1,971 ft), it is close enough that the bottom of the BOURBON cavity is probably saturated. In 1976, a satellite well (UE-7ns) was drilled 137 m (449 ft) southeast of the U-7n ground zero to a total depth of 672 m bgs (2,204 ft bgs). The bottom 62 m (203 ft) of the casing is slotted, entirely within the LCA. UE-7ns was pumped and sampled intermittently from 1976 to 1984; it was also sampled in 1993 (Thompson, 1995a). A statistical summary of radionuclide data for UE-7ns groundwater is given in [Table 3-18](#).

Above-background levels of tritium and krypton-85 (^{85}Kr) were detected at satellite well UE-7ns. It appears that the radionuclides migrated in groundwater from the BOURBON cavity region in response to pumping. Nimz and Thompson (1992) report that tritium levels at UE-7ns slowly increased throughout the duration of low-volume pumping. This increase is evidence of transport in groundwater as opposed to prompt injection.

3.4.7.1.4 DALHART (U-4u)

The DALHART test was conducted on October 13, 1988, at a working point depth of 640 m bgs (2,099 ft bgs) in volcanic rock. The working point is well below the pretest depth to water of 508 m bgs (1,666 ft bgs) (Thompson, 1995a). In 1990, post-shot hole U-4u ps2a was drilled into the DALHART chimney region, and a tube opened from 472 to 501 m bgs (1,548 to 1,643 ft bgs) was inserted into the hole. This interval is above the pretest water depth; however, in 1996, the depth to water was 462 m bgs (1,515 ft bgs) (Thompson, 1998). [Table 3-19](#) presents a statistic summary of the radiological data for groundwater from U-4u ps2a. Elevated levels of radionuclides indicate that groundwater at U-4u ps2a is in contact with radiological material in the chimney region.

Table 3-17
Radionuclide in Groundwater at U-3cn (BILBY)

Post-Shot Hole U-3cn ps2					
Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125 ^b	1.0E-03	4.7E-03	2.9E-03	1.3E-03	9
Cesium-137	9.7E-01	2.6E+00	1.7E+00	5.1E-01	14
Cobalt-60 ^c	7.2E-04	1.7E-02	8.0E-03	6.5E-03	11
Europium-155	< 6.8E-05	< 6.8E-05	NC	NC	9
Plutonium-239/240 ^d	9.0E-04	2.4E-03	3.9E-03	4.1E-03	3
Ruthenium-106	< 8.6E-08	4.7E-07	2.4E-07	1.1E-07	10
Sodium-22	< 2.4E-06	< 2.4E-06	NC	NC	9
Strontium-90 ^e	3.8E-02	3.7E-01	2.0E-01	2.4E-01	2
Technetium-99	4.1E+01	5.9E+01	5.0E+01	1.3E+01	2
Tritium	9.8E+06	3.1E+07	1.2E+07	5.7E+06	13
Uranium-235	< 7.7E-02	8.6E-01	3.8E-01	3.5E-01	9
Uranium-238	< 8.3E-01	2.7E+01	1.3E+01	1.2E+01	9
Satellite Well U-3cn#5					
Radionuclide	Minimum Activity Concentration (pCi/L)	Maximum Activity Concentration (pCi/L)	Average Activity Concentration (pCi/L)	Standard Deviation (pCi/L)	Number of Observations
Antimony-125	< 1.7E-05	< 1.7E-05	NC	NC	2
Cesium-137	< 8.1E-04	< 9.3E-03	NC	NC	3
Cobalt-60	< 7.2E-05	< 7.2E-05	NC	NC	2
Europium-155	3.4E-03	3.4E-03	3.4E-03	0.0E+00	2
Plutonium-239/240	2.1E-04	2.3E-04	2.2E-04	1.6E-05	2
Ruthenium-106	< 4.8E-09	< 8.5E-09	NC	NC	2
Sodium-22	< 2.4E-06	< 2.4E-06	NC	NC	2
Strontium-90	2.0E-03	2.9E-03	2.4E-03	4.8E-04	3
Tritium ^f	6.6E-01	2.5E+00	1.6E+00	1.3E+00	2
Uranium-235	3.6E-02	4.5E-02	4.1E-02	6.4E-03	2
Uranium-238	4.9E-01	5.9E-01	5.4E-01	7.0E-02	2

Data Sources: Buddemeier and Isherwood (1985), Smith et al. (1998), and Thompson (1998)

^aAll activity concentrations, including those in footnotes, were decay-corrected to January 1, 2000.

^bDoes not include a value of 8.6E-02 picocuries per liter; sample collected 12/9/1964.

^cDoes not include a value of 1.9E+00 picocuries per liter; sample collected 12/9/1964.

^dDoes not include a value of 8.6E+01 picocuries per liter; sample collected 9/29/1977.

^eDoes not include a value of <1.7E+00 picocuries per liter; sample collected 7/1/1964.

^fDoes not include a value of <8.5E+02 picocuries per liter; sample collected 1/22/1997.

NC = Not calculated; values below detection preclude calculation or only one value was reported.

pCi/L = Picocuries per liter

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Table 3-18
Radionuclide in Groundwater at Satellite Well UE-7ns (BOURBON)

Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	< 7.1E-05	< 1.2E-01	NC	NC	2
Carbon-14	< 3.2E+03	< 3.2E+03	NC	NC	1
Cesium-137	2.8E-02	< 2.2E-01	NC	NC	2
Cobalt-60	1.0E-03	< 1.1E-01	NC	NC	2
Europium-155	< 1.6E-04	< 1.6E-04	NC	NC	1
Krypton-85	2.5E+02	2.5E+02	NC	NC	1
Plutonium-238	< 6.5E-02	< 6.5E-02	NC	NC	1
Plutonium-239/240	< 7.4E-02	< 7.4E-02	NC	NC	1
Ruthenium-106	< 3.0E-07	< 3.0E-07	NC	NC	1
Sodium-22	< 1.1E-05	< 1.1E-05	NC	NC	1
Technetium-99	< 2.3E-01	< 2.3E-01	NC	NC	1
Tritium	3.2E+02	1.2E+03	8.0E+02	2.8E+02	11
Uranium-235	3.2E-03	3.2E-03	NC	NC	1
Uranium-238	< 1.2E-01	< 1.2E-01	NC	NC	1

Data Sources: Buddemeier and Isherwood (1985), Buddemeier (1988), Smith et al. (1998), and Thompson (1995a)

^aAll activity concentrations were decay-corrected to January 1, 2000.

NC = Not calculated; values below detection preclude calculation or only one value was reported.
pCi/L = Picocuries per liter

Downhole gamma-ray spectroscopic logging of the DALHART chimney detected radioactivity related to testing in the depth interval of 532 to 657 m bgs (1,746 to 2,156 ft bgs). Tritium, antimony-125 (¹²⁵Sb), cesium-134, cesium-137 (¹³⁷Cs), cobalt-60, ruthenium-106 (¹⁰⁶Ru), manganese-54, and zinc-65 were detected in sidewall samples of cavity material collected from approximately the same depth interval (Mathews et al., 1994).

Table 3-19
Radionuclides in Groundwater at U-4u ps2a (DALHART)

Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	3.1E+01	7.4E+01	5.2E+01	2.1E+01	3
Carbon-14	4.7E+01	2.4E+02	1.4E+02	1.4E+02	2
Cesium-137	1.8E+00	7.3E+01	4.6E+01	3.8E+01	3
Cobalt-60	4.4E-01	7.5E+00	4.6E+00	3.7E+00	3
Krypton-85	2.7E+04	1.2E+06	4.3E+05	7.0E+05	3
Plutonium-238	2.6E-02	< 1.2E-01	NC	NC	2
Plutonium-239/240	1.3E-01	1.9E-01	1.5E-01	3.6E-02	3
Ruthenium-106	5.0E+00	6.2E+00	5.6E+00	8.7E-01	2
Strontium-90	2.9E+00	2.9E+00	NC	NC	1
Tritium	1.4E+07	4.2E+07	2.8E+07	1.3E+07	11

Data Sources: Smith et al. (1998), Smith et al. (1999), Thompson (1995a), and Thompson (1998).

^aAll activity concentrations were decay-corrected to January 1, 2000.

NC = Not calculated; values below detection preclude calculation or only one value was reported.

pCi/L = Picocuries per liter

3.4.7.1.5 GASCON (U-4t)

The GASCON test was detonated in volcanic rock on November 14, 1986, at a depth of 593 m bgs (1,945 ft bgs), well below the static water table, which is estimated at 505 m bgs (1,656 ft bgs) (Marsh, 1991). Two months after the test, satellite well UE-4t was drilled to a depth of 736 m bgs (2,414 ft bgs). Hole UE-4t is located 170 m (558 ft) from the GASCON ground zero (Thompson, 1993). In 1990, two strings of tubing were cemented into UE-4t to access groundwater at depths of 607 and 525 m bgs (1,991 and 1,722 ft bgs) (Thompson, 1994). Thompson (1994) reports that as of 1993, the HRMP has never detected tritium or other radionuclides from the GASCON test in groundwater at UE-4t (Table 3-20).

Groundwater samples were also collected from post-shot hole U-4t ps3a. This hole, drilled in 1993, is close to the chimney and cavity but does not penetrate them. Piezometer tubing emplaced in U-4t ps3a is slotted in the depth range of approximately 516 to 618 m bgs (1,692 to 2,027 ft bgs)

Table 3-20
Radionuclides in Groundwater at U-4t ps3a/UE-4t (GASCON)

Post-Shot Hole U-4t ps3a		
Radionuclide	Date of Collection	Activity Concentration ^a (pCi/L)
Antimony-125	8/31/1993	< 8.8-01
Carbon-14	8/31/1993	< 3.2E+03
Cesium-137	8/31/1993	< 3.4E-01
Cobalt-60	8/31/1993	< 3.3E-01
Krypton-85	8/31/1993	2.7E+00
Plutonium-238	8/31/1993	< 8.5E-02
Plutonium-239/240	8/31/1993	< 4.2E-02
Tritium	8/31/1993	1.1E+03
		2.9E+04
		6.7E+04
Satellite Well UE-4t		
Radionuclide	Date of Collection	Activity Concentration (pCi/L)
Krypton-85	4/20/1992	< 1.1E+00
	7/1/1992	< 1.1E+00
Tritium	4/20/1992	< 1.1E+03
	7/1/1992	< 1.1E+03

Data sources: Smith et al. (1998), Thompson (1993), Thompson (1995a)

^aActivity concentrations are as of the date of collection shown, no decay correction was made.

pCi/L = Picocuries per liter

(Thompson, 1995a). Tritium and ⁸⁵Kr were detected in groundwater from the GASCON post-shot hole. Table 3-20 lists radiological data for groundwater samples collected from holes U-4t ps3a and UE-4t. The data shown in Table 3-20 were not decay-corrected because the dates are provided.

3.4.7.1.6 ALEMAN (U-3kz)/SANDREEF (U-7aq)

In 1984, emplacement hole U-3kz was drilled to a depth of 686 m bgs (2,250 ft bgs) for the upcoming ALEMAN (U-3kz) underground test. A liner used to keep water out of the hole leaked, and during dewatering operations in 1985, tritium and ⁸⁵Kr were detected (Table 3-21). Subsequent sampling of the groundwater in U-3kz revealed high concentrations of tritium and detectable amounts of various other fission products (Professional Analysis, Inc., 1992). Rhodium isotope ratios indicated that the

Table 3-21
Radionuclides in Groundwater at U-3kz (prior to ALEMAN Test)
and UE-3e Exploratory Boreholes

Emplacement Hole U-3kz					
Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	5.6E+00	5.6E+00	NC	NC	1
Cesium-137	8.0E+00	8.0E+00	NC	NC	1
Krypton-85	2.0E+04	2.5E+04	2.3E+04	2.2E+03	4
Ruthenium-106	1.3E-03	1.3E-03	NC	NC	1
Strontium-90	1.5E+00	1.5E+00	NC	NC	1
Tritium	2.1E+07	2.4E+07	2.3E+07	1.2E+06	7
Exploratory Borehole UE-3e#1					
Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	1.4E+00	1.4E+00	NC	NC	1
Cesium-137	2.9E+01	2.9E+01	NC	NC	1
Krypton-85	1.9E+04	2.0E+04	1.9E+04	8.3E+02	2
Ruthenium-106	5.4E-03	5.4E-03	NC	NC	1
Tritium ^d	6.4E+06	9.7E+06	8.8E+06	1.6E+06	4
Exploratory Borehole UE-3e#2					
Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	1.2E-02	8.3E-01	4.2E-01	5.8E-01	2
Cesium-137	3.7E+00	7.5E+01	3.9E+01	5.0E+01	2
Rhodium-106 ^c	5.4E-05	5.4E-05	NC	NC	1
Exploratory Borehole UE-3e#4					
Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	< 1.6E-01	< 2.6E-01	NC	NC	2
Carbon-14	< 3.2E+03	4.8E+03	NC	NC	3
Cesium-137	< 2.5E-01	< 4.1E-01	NC	NC	2
Cobalt-60	< 1.2E-01	< 1.9E-01	NC	NC	2
Krypton-85	8.1E+00	9.2E+03	2.0E+03	3.2E+03	8
Plutonium-238	< 7.4E-02	< 1.2E-01	NC	NC	3
Plutonium-239/240	< 6.4E-02	< 7.8E-02	NC	NC	3
Tritium	4.0E+03	7.0E+06	1.7E+06	2.6E+06	14

Data Sources: Smith et al. (1998), Smith et al. (1999), Thompson (1995a), and Professional Analysis, Inc. (1992).

^aAll activity concentrations, including those in footnotes, were decay-corrected to January 1, 2000.

^bDoes not include values of 1.9E+02 and 4.2E+02 picocuries per liter.

^cListed in reference Professional Analysis, Inc. (1992) as rhodium-106; may actually be ruthenium-106.

NC = Not calculated; values below detection preclude calculation or only one value was reported.

pCi/L - Picocuries per liter

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SANDREEF (U-7aq) test, conducted on November 9, 1977, approximately 350 m (1,148 ft) to the north of U-3kz ([Figure 3-23](#)), was the source of the observed radioactivity.

From 1986 to 1990, four additional exploratory holes (UE-3e #1, #2, #3, and #4) were drilled in the vicinity of U-3kz to intercept the transport path of radionuclides from SANDREEF (Professional Analysis, Inc., 1992; Thompson, 1991a). Groundwater from UE-3e #1 contained tritium and the same suite of fission products found at U-3kz. Logging of UE-3e #1 indicated that gamma activity was confined to a narrow band at a depth of 658 m bgs (2,158 ft bgs) (Thompson, 1987). Subsequent attempts to intersect this band of gamma radiation failed at holes UE-3e #2 and #3 (Thompson, 1988; Thompson, 1989). Elevated radioactivity was identified in sidewall core samples from UE-3e #4. Thompson (1995a) reports that three piezometer tubes were cemented into this hole at monitor groundwater at various depths.

Statistical summaries of the radiological data from UE-3e #1, #2, and #4, and U-3kz are listed in [Table 3-21](#). Laboratory studies of rock core recovered from UE-3e #4 suggest that fission products found in UE-3e #4 did not move to that location as either dissolved species or with colloids in groundwater (Nimz and Thompson, 1992). Although they could not rule out transport in groundwater, Nimz and Thompson (1992) conclude that fracture injection appears to be the migration mechanism. Fracture injection is the result of elastic failure produced by fracturing associated with the high pressure of detonation. The fracturing occurs along intervals of preexisting weakness within the geologic medium and allows volatile and semivolatile radionuclides to be emplaced at early time, typically more than two cavity radii away from the working point.

3.4.7.1.7 AGILE (U-2v)/COMMODORE (U-2am)

Crow (1976) reported that in April 1974, above-background tritium levels were detected in groundwater in emplacement hole U-2aw and exploratory hole UE-2aw. The COMMODORE (U-2am) test, located 465 m (1,525 ft) southeast of U-2aw, is believed to be the source of the tritium. The COMMODORE test was detonated on May 20, 1967. During May 1975, in the same general area, levels of tritium above background were also found in groundwater at exploratory hole UE-2ar. The AGILE (U-2v) test, located approximately 360 m (1,181 ft) northeast of UE-2ar, is believed to be the source of the tritium (Crow, 1976). AGILE was detonated on February 23, 1967. [Table 3-22](#) presents data obtained from HRMP reports on the occurrence of radionuclides in groundwater in the

Table 3-22
Radionuclides in Groundwater in the Vicinity of COMMODORE and AGILE (Area 2)

Location	Date of Collection	Radionuclide	Activity Concentration ^a (pCi/L)	Comments
UE-2aw	4/14/1974	tritium	1.1E+05	
U-2aw	4/8/1974	tritium	2.4E+06	
U-2aw	8/28/1974	tritium	1.1E+07	
U-2aw	9/11/1974	tritium	1.2E+07	
UE-2ar	5/10/1975	Cs-137	1.3E+00	filtered
UE-2ar	5/10/1975	Cs-137	2.1E+01	nonfiltered
UE-2ar	5/10/1975	K-40	1.6E+02	filtered
UE-2ar	5/10/1975	tritium	2.7E+05	reanalysis
UE-2ar	5/10/1975	tritium	1.1E+05	lower limit of range
UE-2ar	5/10/1975	tritium	4.7E+05	upper limit of range
UE-2ar	5/10/1975	tritium	3.0E+05	averaged value

Sources: Buddemeier (1988) and Crow (1976).

^aActivity concentrations are as of the date of collection shown, no decay correction was made.

vicinity of COMMODORE and AGILE. Collection dates are listed; therefore, the data are not decay-corrected.

In both cases, the hydraulic gradient favors groundwater transport from the cavity to the boreholes where tritium was observed (Crow, 1976). However, Nimz and Thompson (1992) claim that groundwater velocities would have to be anomalously high, if transport occurred under existing hydrologic conditions. Crow (1976) postulates that the high flow velocities may have been induced by the forces related to underground testing; Nimz and Thompson (1992) speculate that prompt injection may have played a role in the radionuclide transport.

The working points of COMMODORE and AGILE and the boreholes in which radionuclides were detected are all in volcanic units. None of the underground tests or boreholes discussed in this subsection are within the underlying Paleozoic carbonate units.

3.4.7.1.8 BASEBALL (U-7ba)

The BASEBALL test was conducted on January 15, 1981, at a depth of 564 m bgs (1,850 ft bgs) in volcanic rock. The test was well below the reported groundwater level of approximately 512 m bgs (1,679 ft bgs) (Thompson, 1995b). In June 1994, a post-shot hole (U-7ba ps1as) was completed in the cavity and lower chimney region by cementing a tube in place with slots from 585 to 604 m bgs (1,919 to 1,981 ft bgs) (U-7ba ps1as was slant-drilled).

Groundwater at U-7ba ps1as was sampled in July 1995 and analyzed for tritium. Tritium activity ranged from 1.2×10^7 to 9.7×10^7 picocuries per liter (pCi/L) (Thompson, 1995b) when corrected to the date of the BASEBALL test. Samples were also analyzed for gamma emitters (Thompson, 1995b). However, too much solid material was present in the samples and the results were not representative of groundwater concentrations. For this reason, the data are not presented here.

Based on the analysis of 48 solid samples collected from the cavity and lower chimney of BASEBALL, Thompson (1996) evaluated the distribution of radionuclides associated with the test. Thompson (1996) found that little migration of radionuclides (including tritium) occurred subsequent to the BASEBALL test. Thompson (1996) noted that the hydraulic gradient in the area is small, the hydraulic conductivity is relatively low, and thus groundwater flow is minimal.

3.4.7.1.9 INGOT (U-2gg)

INGOT was detonated on March 9, 1989, at a depth of 500 m (1,640 ft) bgs in volcanic rock. The working point was approximately 65 m (213 m) above the static water level of 565 m bgs (1,853 ft bgs) (Smith et al., 1996). In April 1994, a borehole was slant drilled to pass within 10 m (33 ft) of the edge of the INGOT cavity at the working point level. This borehole, U-2gg ps3a, was drilled to a total slant depth of 726.5 m bgs (2,383 ft bgs) and cased. The bottom 46 m (151 ft) of casing was slotted to allow subsequent groundwater sampling from the saturated below the cavity (Smith et al., 1996). Samples were collected in September 1994, and the results are summarized in [Table 3-23](#).

Gamma logging of U-2gg ps3a detected Cesium-137 (^{137}Cs) in the vadose zone adjacent to the INGOT cavity. This indicates a mechanism other than groundwater transport is responsible for the migration and distribution of radionuclides outside of the cavity. Smith et al. (1996) claims the

Table 3-23
Radionuclides in Groundwater at Well U-2gg ps3a (INGOT)

Radionuclide	Minimum Activity Concentration ^a (pCi/L)	Maximum Activity Concentration ^a (pCi/L)	Average Activity Concentration ^a (pCi/L)	Standard Deviation ^a (pCi/L)	Number of Observations
Antimony-125	< 2.6E-01	< 3.3E-01	NC	NC	2
Carbon-14	6.0E+03	2.0E+04	1.3E+04	9.9E+03	2
Cesium-137	8.0E-01	2.4E+00	1.6E+00	1.2E+00	2
Krypton-85	6.9E+00	7.1E+00	7.0E+00	1.4E-01	2
Plutonium-238	< 3.6E-03	< 4.3E-03	NC	NC	2
Plutonium-239/240	< 2.7E-03	< 3.1E-03	NC	NC	2
Tritium	4.1E+03	5.6E+03	4.8E+03	7.8E+02	3

Data Sources: Smith et al. (1998) and Thompson (1995a).

^aActivity concentrations are as of the date of collection shown, no decay correction was made.

NC = Not calculated; values below detection preclude calculation or only one value was reported.
pCi/L = Picocuries per liter

mechanism is relatively late-stage transport of gaseous radionuclides and precursors along reactivated preexisting and test-induced fractures. Smith et al. (1996) cites observed isotopic ratios and the absence of refractory radionuclides as evidence for late-stage transport rather than prompt injection.

3.4.7.1.10 PILEDRIIVER (U-15.01)

The PILEDRIIVER test was conducted on June 2, 1966, in the Climax Mine area of the NTS (Area 15). The working point was 463 m (1,518 ft) bgs in granodiorite (Borg, 1970), approximately 275 m (902 ft) below the static water level. Groundwater samples were not collected; however, the HRMP examined the phenomenology (e.g., cavity size and fracturing) of the test (Borg, 1970). The HRMP also evaluated physical, chemical, and radiochemical characteristics of cavity material collected from a post-shot hole (U-15.01 PS-3) and material collected during reentry operations. Borg (1975) reported the presence of tritium and various fission and activation products in PILEDRIIVER melt glass samples. Analysis of radionuclides in rubble samples enabled Borg (1975) to evaluate fractionation between the rubble and glass. Borg (1975) reported that relative to other

underground tests studied (with working points in alluvium or tuff), a greater fraction of volatile radionuclides were retained in the melt glass from PILEDRIVER.

3.4.7.1.11 Summary of the HRMP Data

The HRMP sample locations were grouped into three general categories: (1) cavity/chimney region, (2) satellite wells and immediately adjacent to cavity/chimney, and (3) away from the near-field environment. The data listed in the preceding sections were divided among these categories, and radionuclide concentration ranges for each category were determined. The concentration ranges are shown in [Figure 3-24](#). All data used in constructing [Figure 3-24](#) were decay-corrected to January 1, 2000. The concentration ranges of short-lived radionuclides (e.g., ruthenium-106 and antimony-125) were relatively large ([Figure 3-24](#)) because the data were decay-corrected and the detonation dates of the tests studied were variable (1963 through 1989).

[Figure 3-24](#) shows that tritium, ^{85}Kr , and ^{14}C are the radionuclides detected in the highest concentrations in groundwater impacted by underground testing in Yucca Flat. Relatively higher concentrations of ^{14}C observed in satellite wells and away from the near-field environment are probably an artifact of the sampling and analytical program, rather than an actual occurrence. Compared to concentrations in the cavity/chimney region, the tritium and ^{85}Kr ranges are much wider in groundwater from satellite wells and sampling locations away from the near field ([Figure 3-24](#)).

3.4.7.2 Long-Term Hydrological Monitoring Program

The DOE/NV instituted the LTHMP in 1972 to detect the presence of any radioactivity in groundwater that may be related to nuclear testing. Under the interagency agreement, the EPA operates the LTHMP. The EPA Radiation and Indoor Environment National Laboratory - Las Vegas (formerly the Radiation Sciences Laboratory and Environmental Monitoring Systems Laboratory) performs routine radiological monitoring of groundwater from wells on the NTS and wells and springs in off-site areas around the NTS. As of 1999, the Routine Radiological Environmental Monitoring Plan (RREMP) has replaced the LTHMP (BN, 1998b). Bechtel Nevada operates the RREMP for DOE/NV.

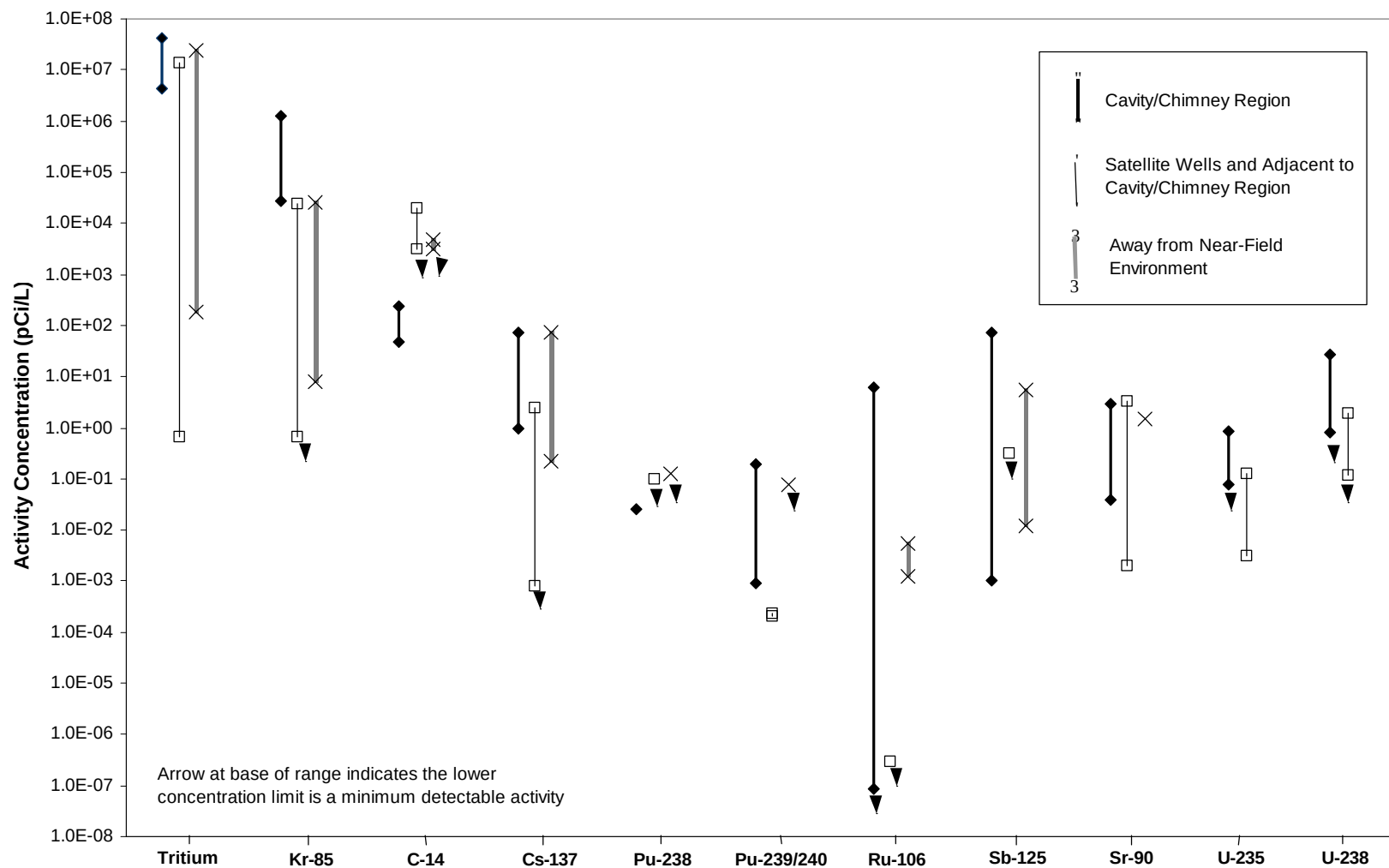


Figure 3-24
Summary of HRMP Radiological Data
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Results of the LTHMP for the period 1989 to 1998 applicable to the Yucca Flat/Climax mine CAU, are summarized in the following text. These results are published in the NTS annual site environmental reports (REECo and EPA, 1990; REECo, 1991, 1992, 1993, 1994, and 1995; and BN, 1996a, 1996b, 1997a, 1997b, 1998a, and 1999). [Figure 3-25](#) shows the LTHMP sampling locations in Yucca Flat, and [Figure 3-26](#) shows the LTHMP locations in surrounding off-NTS areas. These sampling points are existing well and spring locations that are readily available for sampling; they do not represent or function as a groundwater monitoring network. The sampling frequency varied during the program; some locations were sampled monthly and others semiannually. Generally, at least one analysis per year from each location was performed for gamma-emitting radionuclides and for tritium. Tritium analyses were performed using either the conventional or electrolytic enrichment method. The minimum detectable concentration (MDC) for the conventional method was several hundred pCi/L, while the MDC by enrichment was approximately 10 pCi/L.

Tritium results from the LTHMP are presented in [Table 3-24](#). If the date listed in [Table 3-24](#) is given as a year only (e.g., 1994), the tritium result is an annual average; otherwise, the tritium result is for a discrete sample collected on the date listed. [Table 3-24](#) indicates that tritium was detected in groundwater at Test Well B; Water Wells A, C, and C-1; and Wells UE-6d, UE-6e, UE-7ns, and UE-15d. These wells are located in Yucca Flat ([Figure 3-25](#)). Well UE-7ns is discussed further in [Section 3.4.7.1.3](#), and several of the other wells listed above are also discussed in [Section 3.4.7.5](#). [Table 3-24](#) shows that tritium was not consistently detected in groundwater from any of the off-NTS sampling locations.

3.4.7.3 DOE/NV Annual Environmental Monitoring

Annual on-site environmental monitoring for radioactivity has been conducted at the NTS by the DOE/NV and its contractors. Groundwater from water supply wells has been sampled and analyzed periodically for radioactivity. Average annual results of the monitoring program are published in the annual site environmental reports referenced in [Section 3.4.7.2](#).

For the time period of 1989 to 1998, [Table 3-25](#) presents the average annual activities of gross alpha, gross beta, and several radionuclides in groundwater from Water Wells 2, C, C-1 and UE-15d. The locations of these wells are shown in [Figure 3-25](#). These are water supply wells in Yucca Flat that have been periodically sampled each year as part of an on-site environmental monitoring network.

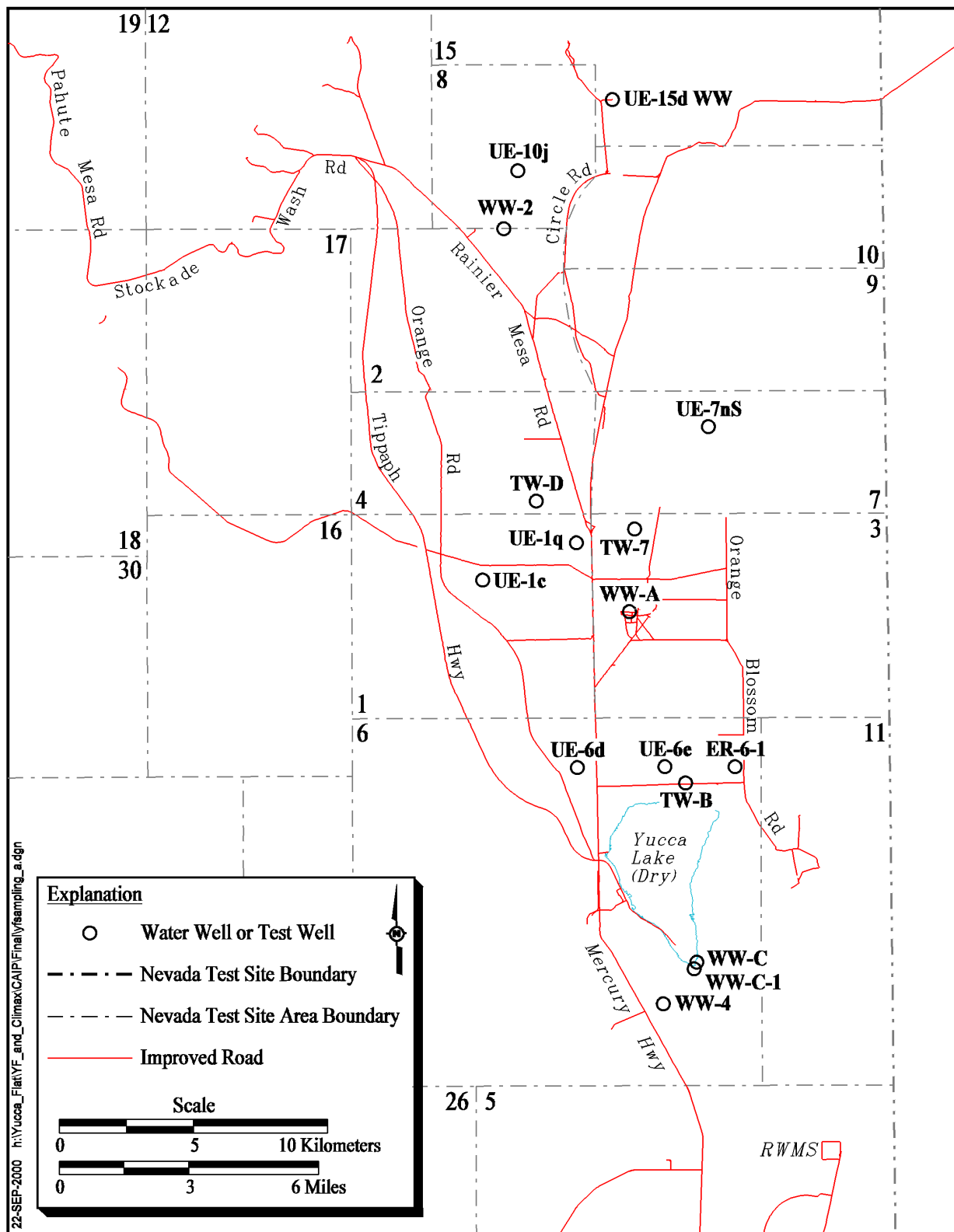


Figure 3-25
Groundwater Sampling Locations in Yucca Flat included in the
Long-Term Hydrological Monitoring Program between 1989 and 1998

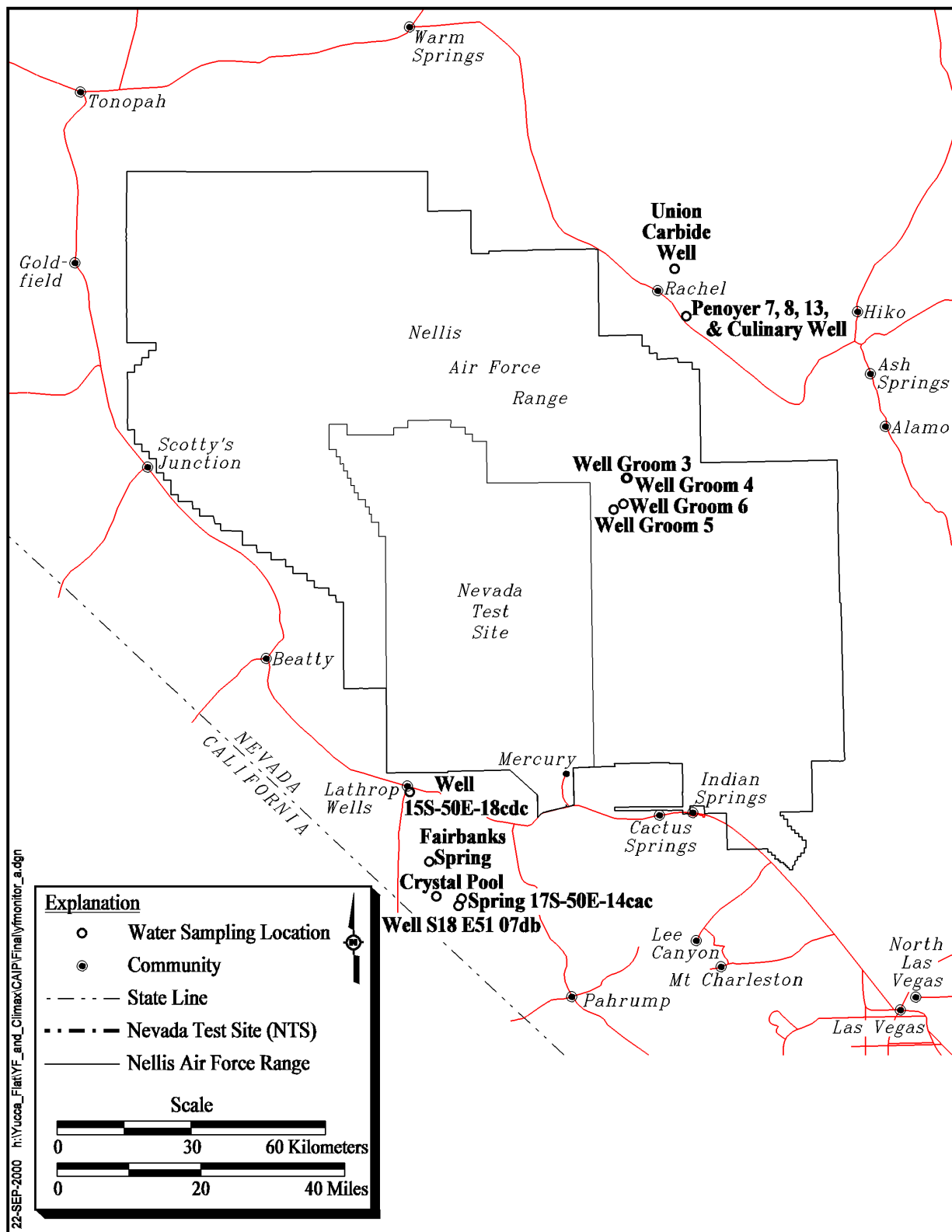


Figure 3-26
Wells and Springs Outside the NTS included in the Long-Term
Hydrological Monitoring Program between 1989 and 1998

Table 3-24
Tritium Concentrations in Groundwater from the Long-Term Monitoring Program
(Page 1 of 2)

Spring 17S-50E-14CAC (Ash Meadows, NV)		Well 18S-51E-7DB (Ash Meadows, NV)		Crystal Pool (Ash Meadows, NV)		Fairbanks Springs (Ash Meadows, NV)		Well 15S-50E-18CDC (Lathrop Wells, NV)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
02/01/89	-1.1 ± 6.3 ^a	02/01/89	0.0 ± 6.7a	02/01/89	3.9 ± 6.6a	02/17/89	-10 ± 6.0a	01/04/89	-1.8 ± 6.8a
09/07/89	-75 ± 290a	06/01/89	22 ± 290	09/07/89	38 ± 290	03/01/89	-5 ± 6.0a	06/06/89	-2.1 ± 6.8a
12/12/90	-36 ± 140a	05/09/90	4.9 ± 2.8a	05/09/90	-0.2 ± 2.8a	09/07/89	0 ± 300a	04/05/91	2.6 ± 3a
06/11/91	-0.9 ± 2.3a	11/21/90	320 ± 140a	11/21/90	320 ± 140a	05/09/90	-1 ± 3.5a	10/01/91	130 ± 94a
12/02/91	220 ± 126a	05/10/91	2.9 ± 2.9a	05/10/91	-2.8 ± 2.8a	11/21/90	170 ± 140a	04/06/92	1.5 ± 2.2a
06/08/92	-4.1 ± 1.7a	11/19/91	40 ± 73a	11/19/91	80 ± 73a	05/10/91	0.4 ± 2.8a	10/16/92	-14 ± 140a
12/14/92	370 ± 140a	05/07/92	1.9 ± 3.8a	05/07/92	4.6 ± 3.7a	11/14/91	0 ± 73a	04/09/93	4.1 ± 1.6a
06/17/93	-0.8 ± 1.4a	11/02/92	52 ± 140a	11/02/92	140 ± 140a	05/07/92	-2.3 ± 4.6a	10/06/93	-1.3 ± 1.9a
10/06/93	1.4 ± 1.5a	05/12/93	2.3 ± 1.5a	05/12/93	-1.6 ± 1.4a	11/02/92	-410 ± 140a	1994	-0.46a
1994	0.8a	11/09/93	1.4 ± 1.5a	11/09/93	1.1 ± 1.5a	05/12/93	2.0 ± 1.7a	1995	-0.12a
1995	-0.97a	1994	3a	1994	0.77a	11/09/93	-0.9 ± 2.1a	1996	-0.08a
1996	0.8a	1995	0.88a	1995	0.77a	1994	2.3a	1997	-0.5a
1997	-57a	1996	1.0a	1996	-0.3a	1995	-1.5a	1998	11a
1998	42a	1997	-19a	1997	0.3a	1996	-0.8a		
		1998	-15a	1998	0.37a	1997	0.7a		
						1998	0.76a		
Wells 7 & 8, Penoyer (Rachel, NV)		Well 13, Penoyer (Rachel, NV)		Penoyer Culinary Well (Rachel, NV)		Union Carbide Well (Tempiute, NV)		Test Well D (NTS Area 4)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
02/01/89	112 ± 290a	08/16/89	4.8 ± 6.3a	07/06/89	27 ± 7.0	08/09/89	-2 ± 6.0a	03/21/89	8 ± 6.3a
07/06/89	27 ± 6.0	04/11/90	180 ± 130a	04/04/90	310 ± 130a	02/07/90	-58 ± 130a	09/06/89	9 ± 6.6a
04/11/90	-74 ± 130a	10/01/90	6.3 ± 3.4a	10/01/90	-3.6 ± 3.9a	08/08/90	-0.6 ± 3.1a	01/03/90	5.1 ± 3.3a
10/01/90	0.6 ± 3.2a	04/23/91	85 ± 135a	04/01/91	-72 ± 134a	02/06/91	20 ± 138a	07/19/90	-9.0 ± 140a
05/07/91	-130 ± 132a	05/07/91	85 ± 133a	10/02/91	1 ± 2.8a	09/11/91	0.9 ± 6a	01/02/91	7.6 ± 2.3a
10/02/91	0.6 ± 2.5a	06/03/92	-160 ± 110a	10/02/91	-3.8 ± 2.1a	02/12/92	-150 ± 130a	07/10/91	0 ± 126a
06/03/92	44 ± 100a	09/09/92	-0.89 ± 1.8a	04/01/92	39 ± 130a	08/06/92	-2.0 ± 1.9a	1992	4.3a
09/21/92	0.63 ± 1.4a	04/28/93	-0.3 ± 1.7a	10/06/92	-0.21 ± 1.6a	05/05/93	3.1 ± 1.4a	1993	3.2a
05/10/93	3.8 ± 1.4a	10/05/93	-1.4 ± 1.7a	07/13/93	-1.7 ± 1.4a			1994	0.61a
10/05/93	-1.4 ± 1.5a	1994	2.2a	12/07/93	-2.2 ± 1.6a			1996	38a
1994	0.39a			1994	-0.21a			1997	3.0a
				1995	0.69a			1998	28a
				1996	1.2a				
				1997	0.0a				
				1998	-22a				
Groom Well 3 (NAFR)		Groom Well 4 (NAFR)		Groom Well 5 (NAFR)		Groom Well 6 (NAFR)		Water Well A (NTS Area 3)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
1989	0.36	1989	-2.2	1989	2.9	1991	-0.7 ± 4.0a	1994	170
1990	2.0	1990	0.7	1990	2.6	1992	-0.2a		
1991	1.5 ± 8.8a	1991	0.6 ± 8.7a	1991	0.5 ± 8.8a	1993	-0.7a		
1992	2.0a	1992	-0.1a	1992	0a	1994	1.2a		
1993	1.0a	1993	0.1a	1993	-0.2a				
1994	4.1a			1994	1.6a				

Table 3-24
Tritium Concentrations in Groundwater from the Long-Term Monitoring Program
(Page 2 of 2)

Well UE-1c (NTS Area 1)		Test Well B Ex. (NTS Area 6)		Water Well C (NTS Area 6)		Water Well C-1 (NTS Area 6)		Water Well 2 (NTS Area 2)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
02/14/89	-0.8 ± 6.3a	1989	120	1989	20	02/15/89	2.5 ± 6.5a	1989	0.82
06/29/89	8 ± 300a	1990	100	1990	19	09/05/89	8.5 ± 6.3a	1990	-0.9
01/02/91	0.9 ± 2.3a	1991	120 ± 10	1991	23 ± 8.0	04/16/90	0.8 ± 2.9a	1997	19a
07/10/91	150 ± 126a	1992	100	1992	16	11/20/90	-260 ± 140a	1998	-56a
1992	1.2a	1993	98	1993	12	1991	22 ± 3.5		
1993	5.1a	1994	79	1994	4.8a	1992	11.0		
1994	0.41a	1996	230	1995	11	1993	9.8		
1995	2.4a	1997	46			1994	22.0		
1996	100a	1998	46			1995	3.3a		
1997	32.0a					1996	270		
1998	-18a					1997	0.46a		
						1998	9.3		
Water Well 4 (NTS Area 6)		Well UE-6d (NTS Area 6)		Well UE-6e (NTS Area 6)		UE-7ns (NTS Area 7)		Test Well 7 (NTS Area 3)	
Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)	Date	Tritium Concentration (pCi/L)
1989	-4.2	1994	710	04/20/89	48 ± 7.0	1992	410	08/21/89	-180 ± 290a
1990	0.8	1995	670	09/17/91	300 ± 132a	1993	295	07/11/91	-110 ± 125a
1991	-0.8 ± 7.9a	1996	680	1992	26.0	1994	270	1992	3.0a
1992	-0.6a	1997	520	1994	12.5	1995	550	1993	5.5
1993	-0.3a	1998	580	1995	16.0	1996	480	1994	2.2a
1994	0.6a			1996	180a	1997	420		
1997	-3.1a			1997	13a	1998	300		
1998	120a			1998	24a				
Water Well UE-15d (NTS Area 15)									
Date	Tritium Concentration (pCi/L)								
01/10/89	100 ± 7.0								
02/15/89	83 ± 7.0								
08/09/89	79 ± 7.0								
11/02/89	58 ± 290a								
04/16/90	8.4 ± 2.5								
11/20/90	270 ± 140a								
1991	76 ± 3.0								

Sources: REEC Co and EPA, 1990; REEC Co, 1991, 1992, 1993, 1994, and 1995; and BN, 1996a, 1996b, 1997a, 1997b, 1998a, and 1999.

^aWhere information was available to make a determination, the given concentration was less than the minimum detectable activity.

Table 3-25
Average Annual Groundwater Activity Data
for the NTS Environmental Monitoring Program

Well	Date	Gross Alpha (pCi/L)	Gross Beta (pCi/L)	Tritium ^a (pCi/L)	Plutonium-239/240 (pCi/L)	Plutonium-238 (pCi/L)	Strontium-90 (pCi/L)
Water Well 2 (Area 2)	1989	ND	6.2	140	1.90E-03	6.60E-03	ND
	1990	3	6.7	21	7.00E-03	3.40E-02	-0.13
Water Well C (Area 6)	1989	ND	14	200	1.00E-03	-4.10E-02	ND
	1990	13	14	200	6.90E-03	5.40E-02	-3.80E-02
	1991	19	18	-17	1.00E-04	1.00E-04	-0.12
	1992	1.1	14	8.4	-1.30E-05	4.30E-03	0.11
	1993	9.3	13	25	-1.10E-02	-8.60E-03	0.14
	1994	5.7	6.9	6.6	4.90E-04	-5.90E-03	6.10E-02
	1995	16	21	-4.6	3.30E-03	-8.30E-04	0.17
Water Well C-1 (Area 6)	1989	ND	15	67	-3.00E-03	-1.10E-02	ND
	1990	11	15	77	2.10E-02	-1.70E-03	-6.40E-03
	1991	17	16	22	2.60E-02	6.40E-02	0.16
	1992	9.3	14	-1.6	-7.70E-04	-1.30E-02	0.71
	1993	8.3	12	5.5	-5.80E-03	3.50E-03	0.1
	1994	8.2	10	12	1.50E-03	-7.70E-04	5.40E-02
	1995	13	16	17	-1.40E-03	-6.60E-04	0.14
	1996	8.3	14	4.2	-2.70E-03	1.50E-03	-6.40E-03
	1997	11	9.8	2.6	-1.80E-03	-3.30E-03	4.90E-02
	1998	12	14	3.6	3.40E-03	-2.70E-03	0.22
Water Well UE-15d (Area 15)	1989	ND	17	140	2.90E-03	2.00E-03	ND
	1990	14	19	190	4.50E-03	3.30E-02	-0.11
	1991	ND	20	40	-3.00E-02	2.40E-02	ND
Median MDA ^b	1992	1.2	0.85	10	1.70E-02	3.80E-02	0.13
	1993	0.86	0.76	9	1.10E-02	1.10E-02	0.14
	1994	0.86	0.16	12	1.30E-02	1.30E-02	0.12
	1995	1.5	1.4	16	2.40E-02	2.40E-02	0.32
	1996	1.4	1.2	14	2.00E-02	1.90E-02	0.29
	1997	1.4	1.2	13	1.70E-02	2.10E-02	0.34
	1998	1.7	1.2	14	1.70E-02	2.00E-02	0.28

Sources: REECo and EPA, 1990; REECo, 1991, 1992, 1993, 1994, and 1995; and BN, 1996a, 1996b, 1997a, 1997b, 1998a, and 1999.

^aTritium activity variability is due to the use of both conventional and enrichment methods to analyze samples.

^bThe MDAs were not reported prior to 1992. The MDA for tritium by the conventional method is typically several hundred picocuries per liter.

ND = No data

The list of analytes and the frequency of sampling have varied over time. Details of changes in the sampling program are beyond the scope of this document and are available in the annual site environmental reports. Sampling at Water Wells 2 and UE-15d ceased in the early 1990s because the pumps in these wells were shut down. Also listed in [Table 3-25](#) are the minimum detectable activities (MDA) for the 1992 to 1998 data; MDAs were not listed in the annual reports prior to 1992.

Comparison of sample data to these MDAs indicates that radionuclide activities in groundwater at Water Wells 2, C, C-1 and UE-15d were generally below detection during the period of observation. Detected gross alpha and beta activities are due to the presence of naturally occurring radionuclides (e.g., potassium-40, radium-226, and radium-228) in groundwater. Variability in the tritium data is due to changes in the analytical method. Prior to 1992, tritium was analyzed by the conventional method and corresponding sample results and detection limits were high. The tritium content of groundwater in water-supply wells is discussed further in [Section 3.4.7.5](#).

3.4.7.4 DOE/NV Environmental Restoration Program

As part of the ER Program (UGTA Project and predecessor Groundwater Characterization Program), DOE contractors have collected groundwater samples from Yucca Flat wells during aquifer testing, well completion, or development activities. The wells for which groundwater radiological data are available include UE-1q, UE-10j, ER-3-1, and ER-6-1 ([Table 3-26](#)). Other than naturally occurring radionuclides, such as radium and uranium, the data indicate that radionuclides are not present in groundwater at these well locations. None of these wells are associated with underground nuclear tests, so these results are not surprising.

3.4.7.5 Tritium Variations In Yucca Flat Groundwater

This section briefly addresses temporal tritium concentration variations observed in groundwater at several Yucca Flat wells. [Table 3-27](#) presents a summary of the information contained in Lyles (1990 and 1993). These wells, shown in [Figure 3-25](#), are not associated with underground test locations (i.e., they are not satellite or post-shot wells). Tritium data are presented in [Table 3-27](#) as concentrations at the time of sampling and also as concentrations decay-corrected to January 1, 2000. To eliminate the effect of radioactive decay on temporal concentration trends, only decay-corrected values were used to evaluate potential trends.

Table 3-26
Yucca Flat Groundwater Radionuclide Activity Data From DOE/NV Environmental Restoration Program Sampling

Well	Sample Date	Antimony-125 (pCi/L)	Cesium-137 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)	Iodine-129 (pCi/L)	Plutonium-238 (pCi/L)	Plutonium-239/240 (pCi/L)	Strontium-90 (pCi/L)	Technetium-99 (pCi/L)	Tritium (pCi/L)	Radium-226 (pCi/L)	Radium-228 (pCi/L)	Uranium (µg/L)
ER-3-1 String 1 (Area 3)	11/09/1995	ND	< 12.8	ND	ND	< 1.2	< 0.019	< 0.012	< 0.57	< 24.7	< 283	ND	ND	5.0
	10/16/1996	ND	< 5.5	ND	ND	< 0.92	< 0.14	< 0.11	0.27 ± 0.13	3.2 ± 1.4	< 181	ND	ND	ND
ER-6-1 (Area 6)	08/24/1992	ND	ND	< 4.3	9.3	ND	ND	ND	ND	ND	ND	0.93	< 1.9	2.5
	10/09/1992	ND	ND	6.2	8.37	ND	ND	ND	ND	ND	ND	1.18	< 2.5	2.5
UE-10j (Area 8)	04/30/1993	< 1.6	< 0.57	ND	ND	ND	ND	ND	< 0.5	< 4.5	< 2	ND	ND	5.8
	04/30/1993	ND	< 7.35	ND	ND	ND	< 0.09	< 0.08	< 1.3	< 15.8	< 280	ND	ND	ND
		ND	< 5.44	ND	ND	0.04 ± 0.70	0.28 ± 0.09	0.07 ± 0.05	< 1.5	< 9.6	< 280	ND	ND	ND
UE-10i Zone 1 ^a (Area 8)	03/17/1997	ND	< 6.8	ND	ND	ND	ND	ND	ND	ND	< 190	ND	ND	6
		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4.9
UE-10j Zone 2a (Area 8)	03/20/1997	ND	< 8.0	ND	ND	ND	ND	ND	ND	ND	< 190	ND	ND	4
		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.0
UE-10j Zone 3a (Area 8)	03/24/1997	ND	< 7.9	ND	ND	ND	ND	ND	ND	ND	< 210	ND	ND	4
		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.0
UE-1q (Area 1)	04/01/1992	< 1.1	< 1.0	18	21	ND	ND	ND	ND	ND	ND	ND	ND	ND
	06/08/1992	< 3.4	< 1.3	3.3	5.3	ND	ND	ND	ND	ND	< 75	1.1	< 2.1	2.1
	07/10/1992	< 1.8	< 0.65	ND	ND	ND	ND	ND	< 0.9	< 4.5	< 1.0	ND	ND	2.3
		ND	ND	<1.0	ND	ND	ND	ND	ND	ND	< 10	0.61	< 1.4	2.4

Sources: Davisson et al. (1993), DOE/NV (1996a), Gillespie (1993), IT (1995 and 1997a), LLNL (1996 and 1997), and Smith (1993).

^aZones 1, 2, and 3 are lower, middle, and upper zones, respectively.

ND = No data

Tritium concentrations at Water Well A increased steadily from background levels in 1985 to greater than 50 pCi/L in 1988. The LTHMP reported a tritium concentration of 170 pCi/L for a sample collected in 1994 from Water Well A ([Table 3-24](#)). Lyles (1990) reports that the June 1962 HAYMAKER test (U-3auS), located approximately 700 meters from Water Well A, is the closest potential source of the tritium.

Tritium concentrations at Water Well UE-15d appear to have increased from 1973 to 1990. However, concentrations have fluctuated between nondetection and detections in the range of 50 to 100 pCi/L (Lyles, 1993). Additional tritium data for this well have been reported by the DOE/NV annual environmental monitoring program ([Section 3.4.7.3](#)) and the LTHMP ([Section 3.4.7.2](#)). The pattern of tritium occurrence in Water Well UE-15d is anomalous.

A tritium tracer test between Water Wells C and C-1 was attempted by the USGS in 1964, when approximately 0.1 to 0.2 curies of tritium was injected into Well C-1 (Lyles, 1990). This may explain the overall decreasing tritium concentration trend observed in both wells from the early 1970s to the present. Lyles (1990) also reports that recharge via cracks in the Yucca Lake playa could have played a role in the tritium observed in groundwater at Water Wells C and C-1. Neither of these wells are located in the vicinity of underground nuclear tests. More recent data ([Sections 3.4.7.2](#) and [3.4.7.3](#)) indicate that tritium concentrations in groundwater at Wells C and C-1 may be less than the analytical detection limit.

Lyles (1993) reports tritium concentrations in groundwater at Test Well B Ex. have been relatively constant from approximately 1980 to 1990. The LTHMP data presented in [Table 3-24](#) confirm Lyles' (1993) findings. Test Well B Ex. is completed in tuffaceous rock near Yucca Lake. Lyles (1990) reports that similar to Water Wells C and C-1, recharge via cracks in the Yucca Lake playa could have played a role in the tritium observed at Test Well B Ex. However, underground nuclear testing cannot be ruled out as a source.

3.4.8 Transport Parameters

Data on contaminant transport parameters including porosity, dispersivity, matrix diffusion coefficient, distribution coefficient, and colloidal transport are discussed in this section. Data gathered and evaluated during the regional evaluation may be found in Sections 3.0 through 5.0 of

Table 3-27
Tritium Variations in Yucca Flat Groundwater^a

Well	Period of Observation	Tritium Concentration (pCi/L) ^b				Comments
		Minimum	Maximum	Mean	Latest	
Water Well A (Area 3)	1972 - 1988	5.7 (1.2)	52.3 (27.9)	14.6 (6.0)	52.3 (27.9)	Increasing concentration trend. Increasing sharply since 1985. Downgradient from the major testing areas in Yucca Flat.
Water Well UE-15d (Area 15)	1973 - 1990	6.4 (1.5)	103 (54.0)	37.4 (16.7)	8.4 ^c (4.9)	Linear increase over observation period. Not near, but downgradient from underground nuclear tests in Climax Mine area. EPA farm complex surface water basins and sumps are potential sources (Lyles, 1993).
Water Well C (Area 6)	1972 - 1987	10.6 (4.7)	276 (101)	53.2 (16.4)	48.9 (24.8)	Slight decrease over period of observation. No underground testing conducted in the immediate vicinity. Tritium tracer injected into Water Well C-1 in 1964 (Lyles, 1990).
Water Well C-1 (Area 6)	1973 - 1984	10.1 (3.6)	135 (52.0)	43.3 (12.6)	14.6 (6.1)	Decreasing concentrations until 1970s. Stable concentrations in 1980's, except for 2 elevated values. No underground testing conducted in the immediate vicinity. Tritium tracer injected into Water Well C-1 in 1964 (Lyles, 1990).
Test Well B Ex. (Area 6)	1976 - 1991	56.9 (33.7)	330 (147)	149 (61.8)	128 (77.1)	Tritium levels show slight increasing trend since early 1980s. Elevated tritium concentration may be associated with recharge from Yucca Lake playa. Downgradient from underground nuclear testing areas in Yucca Flat.

Sources: Lyles, 1990 and Lyles, 1993.

^aData with counting errors greater than the associated concentrations were not included.

^bConcentrations decay-corrected to January 1, 2000 are in parentheses.

^cConcentrations in 1989 ranged from 79 to 100 pCi/L (decay-corrected 44 to 54 pCi/L, respectively).

Volume V (Pages 3-1 to 5-3) of the regional evaluation documentation package (IT, 1996g), and in Section 8.0 (pages 8-1 to 8-12) of regional evaluation report (DOE/NV, 1997c). Additional information may also be found in Section B.2.0 of Appendix B (pages B-8 to B-10) of the VOIA report (IT, 1999c).

3.4.8.1 Porosity

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

During the regional evaluation, a database of measured porosity values for geologic units of the NTS region was developed using data from the literature (IT, 1996g). The contents of this database may be found in Appendices A of Volume V of the regional evaluation documentation package (IT, 1996g). Additional porosity data reported in the literature as an average per well, or per stratigraphic unit, may be found in Appendix B of the same document (IT, 1996g). Many data points in the porosity database had multiple values of porosity obtained from different methods such as multiple geophysical logs. The dataset was statistically reduced to provide an estimate of the mean and variance of the porosity of each HSU by type. The results of this analysis may be found in Appendix C of Volume V of the regional evaluation documentation package (IT, 1996g). The results for matrix and bulk porosity for HSUs that are relevant to the Yucca Flat/Climax Mine CAI are provided in [Table 3-28](#). The alluvial and volcanic units have significantly larger porosities than the Paleozoic carbonate and clastic units. The differences in volcanic unit porosity values may be due to the large variations in lithology, both lateral and vertical, that are inherent in volcanic rocks.

Estimates of effective porosity for geologic units of the NTS were also derived from the existing tracer test data during the regional evaluation (Section 3.4.3 [pages 3-6 to 3-11] of Volume V of the

Table 3-28
Statistical Summary of Porosity Data
(Porosity is in percent of bulk volume)

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

Source: IT, 1996g.

^aNot available

regional evaluation documentation package [IT, 1996g]). Information on the three tracer tests is provided in [Table 3-29](#), along with the estimates for effective porosity. Leap and Belmonte (1992) examined data from the U.S. Geological Survey's Amargosa Tracer Calibration Site (south of the NTS) and determined an effective porosity of 10 percent for a fractured 10-m (33-ft) thick interval of the Bonanza King dolomite of the LCA. Burbey and Wheatcraft (1986) used an effective porosity of 32 to 36 percent for the alluvium at the CAMBRIC site in Frenchman Flat. A preliminary assessment of the tracer experiment at Wells C and C-1 (Winograd and West, 1962) yielded effective porosity between 0.064 and 0.5 percent for the LCA. The 10 percent value may be accurate for the Amargosa site, but it is unlikely to be representative for the NTS as a whole. The Amargosa Tracer Site is a very thin (less than 10 m [32.8 ft]) aquifer about 200 m (656.2 ft) below land surface; these conditions are not typical of the study area as a whole.

To supplement the tracer studies, data from core fractures were used to calculate fracture porosity values on the NTS during the regional evaluation. Details are provided in Section 3.4.4 (pages 3-11

Table 3-29
Effective Porosity Estimates from Tracer Tests Conducted
at or Near the Nevada Test Site

Site Location	Test Site Geology	Test Scale meters (feet)	Test Method	Effective Porosity (percent)	References
Amargosa Desert, near NTS	Cambrian Bonanza King Dolomite (fractured)	122.8 (403)	Doublet recirculation (tritium, sulfur-35, bromide)	10	Leap & Belmonte, 1992
Yucca Flat, NTS	Fractured Limestone	29.3 (96)	Radial converging (fluorescein) test at Water Wells C and C-1	0.064 to 0.5	Winograd & West, 1962
Cambrian Site, Frenchman Flat, NTS	Tuffaceous Alluvium	91.0 (298)	Radial converging with monitoring the elutions of tritium and chlorine-36 at pumping well RNM-2S	31 to 35	Burbey & Wheatcraft, 1986

Source: IT, 1996g.

to 3-12) of Volume V of the documentation (IT, 1996g). Two studies of carbonate (IT, 1996i) and volcanic (Drellack et al., 1997) core provided insights into fracture porosity values:

- **Volcanic Rock** - A study was conducted to characterize fractures in the volcanic units of Pahute Mesa (Drellack et al., 1997). Cores from seven boreholes were analyzed. The boreholes are UE-19x, UE-18t, UE-18r, UE-20e#1, UE-20bh#1, U-20c, UE-20c, UE-20f, ER-20-5#1, and ER-20-2#1 (Drellack et al., 1997). In the analysis, only open fractures were included. A range of fracture porosities, calculated from aperture, density, orientation, and percent open-area data are presented in [Table 3-30](#). For comparison, Klavetter and Peters (1986) estimated fracture porosities ranging from 1.3×10^{-3} to 1.8×10^{-2} percent for the Welded-Tuff Aquifer near Yucca Mountain. This range compares favorably with the range of fracture porosities shown in [Table 3-30](#).
- **Carbonate Rock** - Core from Well ER-6-2 (IT, 1996i) was examined and described with respect to fracture density (number of fractures per 1.5-m [5-ft] interval), fracture aperture, and fracture dip angle. The fracture porosity obtained for carbonate rock from Well ER-6-2 is 0.4 percent, which is estimated as the aperture divided by the true spacing. This value compares well with the larger values obtained from the tracer test in Water Wells C and C-1 ([Table 3-29](#)). Schoff and Winograd (1961) report fracture porosities ranging from 0.5 to 1.6 percent for carbonate rocks at the northern end of Yucca Flat, near the Climax intrusives. These porosities are also higher than the value obtained by IT (1996i); however, the carbonates studied by Schoff and Winograd (1961) were influenced by contact metamorphism.

Table 3-30
Fracture Porosity Obtained from the Study of Volcanic Core

Hydrostratigraphic Unit	Fracture Porosity Range (percent)
Uppermost Welded Tuff(s) (Timber Mountain Aquifer)	2.2×10^{-3} to 5.6×10^{-3}
Tuff Cone(s)	2.6×10^{-4} to 1.3×10^{-2}
Welded Tuffs Above Basal Confining Unit	1.2×10^{-3} to 1.2×10^{-2}
Basal Aquifer	6.1×10^{-4} to 6.1×10^{-3}

Source: IT, 1996g.

In addition, several literature sources for fracture porosity were examined to determine if the data from the NTS were consistent with other work. Lee and Farmer (1993) summarized a large amount of information on fluid flow in fractured rocks. They showed that fracture porosity typically ranges from 5×10^{-4} to 5×10^{-2} percent for clastic, metavolcanic, and crystalline rocks. This range is similar to the ranges shown in Table 3-30. At the Stripa Site in Sweden, the fracture porosity is in the range of 1×10^{-3} to 2×10^{-2} percent (Neretnieks et al., 1989). In the fractured basalts of eastern Washington, Gelhar (1982) measured a porosity of 4.3×10^{-2} percent using a two-well tracer test. For carbonate rocks, the measured porosities tend to be larger. In the Culebra Dolomite of eastern New Mexico, a range of values from 2×10^{-2} to 2 percent has been proposed (Tomasko et al., 1989).

3.4.8.2 Dispersion

Estimates of dispersivity may be obtained from tracer test data or through calibration of a transport model. A summary of the longitudinal, and horizontal and vertical transverse dispersivity data assessed during the regional evaluation (DOE/NV, 1997c) is provided in this section. The details may be found in Section 4.0 (pages 4-1 to 4-22) of Volume V of the regional evaluation documentation package (IT, 1996g), and in Section 8.6 (pages 8-6 to 8-9) of regional evaluation report (DOE/NV, 1997c).

NTS-specific data on longitudinal dispersion were obtained from the three tracer tests conducted at or near the NTS. Estimates from a model are also available in a report by Borg et al. (1976). Other estimates of dispersivity are available from the literature (Gelhar et al., 1992). Longitudinal dispersivities were estimated from the three tracer tests conducted at the NTS and vicinity. The

values were calculated from the tracer data using several methods (IT, 1996g). The results are presented in [Table 3-31](#). Information about the tracer tests was provided in [Table 3-29](#). Borg et al. (1976) estimated longitudinal dispersivities from the calibration of a numerical solute transport models against hydraulic and concentration data. The longitudinal dispersivities reported by Borg et al. (1976) ranged from 11.6 m (38.1 ft) to 91 m (299 ft) for a wide variety of lithologies, ranging from glacial outwash sand and gravel, to basaltic lava, to dolomite and limestone. The dispersivity for a sand and gravel deposit was estimated to be 21.3 m (70 ft). The dispersivity for the Bonanza King Formation near the NTS was estimated to be 15 m (49.2 ft) (Borg et al., 1976). Borg et al. also summarized dispersivity values obtained by calibration of transport models from the literature. Their research showed that longitudinal dispersivity ranges from 11.6 to 91 m (38 to 298 ft), and that horizontal transverse dispersivity ranges from 4.3 to 137 m (14 to 449 ft) (Borg et al., 1976).

Table 3-31
Longitudinal Dispersivity Information Summary from Tracer Tests Conducted
at or Near the Nevada Test Site

Site Location	Test Site HSU	Scale of Test meters (feet)	Analysis Method	Longitudinal Dispersivity (meters)	References
Amargosa Desert, near NTS	LCA	122.8 (403)	Fitting of Grove's curves	15 to 30.5	Leap & Belmonte, 1992
Yucca Flat, NTS	LCA	29.3 (96)	Calculated by Welty & Gelhar's equation	0.6 to 1.4	Winograd & West, 1962 (calculation not included)
Cambric Site, Frenchman Flat, NTS	AA	91.0 (298)	1. Welty & Gelhar Method	9.6	Thompson, 1991b (calculation not included)
			2. Sauty's Method	2.0	Burbey & Wheatcraft, 1986
			3. Sauty's Method	9.1	Travis et al., 1983
			4. Sauty's Method	15.1	Thompson, 1988; Ogard et al., 1988

Source: IT, 1996g.

LCA = Lower Carbonate Aquifer
AA = Alluvial Aquifer

Gelhar et al. (1992) performed a critical review of dispersivity observations from 59 different field sites, domestic and abroad. Gelhar et al. (1992) first evaluated the data for reliability and then analyzed the data to identify the trends. The data were classified into three reliability classes. The

analysis indicated a trend of systematic increase of the longitudinal dispersivity with observation scale, but the trend is much less clear when the reliability of the data is considered. Gelhar et al. (1992) reported longitudinal dispersivities ranging from 10^{-2} to 10^4 m (0.3 to 32,800 ft) for travel distances ranging from 10^{-1} to 10^5 m (0.3 to 330,000 ft), but the largest distance with high-reliability data was only 250 m (820 ft) and the longitudinal dispersivity was only 4 m (13 ft). Fewer data on horizontal transverse dispersivities were available. The two high-reliability points available show that horizontal transverse dispersivity is one order of magnitude less than longitudinal dispersivity. Even fewer vertical transverse dispersivity data were available. Gelhar et al. (1992) found that in all cases where transverse dispersivities were also measured, the values of vertical transverse dispersivity were one to two orders of magnitude less than that of those of the horizontal transverse dispersivity. Gelhar et al. (1992) also concluded from the data that overall dispersivity values did not appear to differ with lithology (porous versus fractured media).

3.4.8.3 Matrix Diffusion Coefficient

This section includes descriptions of the available matrix diffusion data for tritium compiled during the regional evaluation (DOE/NV, 1997c). In addition, a brief summary of data available for matrix diffusion of other constituents is provided. The details may be found in Section 5.0 (pages 5-1 to 5-3) of Volume V of the regional evaluation documentation package (IT, 1996g), and in Section 8.7 (pages 8-9 to 8-10) of the regional evaluation report (DOE/NV, 1997c). Additional information may be found in Section B.2.3 of Appendix B (page B-10) of the VOIA report (IT, 1999c).

Available data on matrix diffusion of tritium into the volcanic rocks of Yucca Mountain have been reported by Triay et al. (1993). A summary of these data is presented in [Table 3-32](#). The effective diffusion coefficient for tritium in the welded-tuff aquifer is on the order of 1.0×10^{-6} to 3.5×10^{-6} square centimeters per second (cm^2/s) (1.1×10^{-9} to 3.8×10^{-9} square feet per second [ft^2/s]).

However, the data summarized in [Table 3-32](#) are limited for several reasons. First, this represents a small set of information for only one HSU. Second, the range of porosity values is narrow compared with all the rock units at the NTS as a whole. Third, these tests were performed on fresh rock surfaces, whereas most *in situ* fractures have some mineral coating, especially in the saturated zone. The testing of fresh surfaces provides the most direct access for tritium to diffuse into the rock matrix. If the fracture surface is coated with mineralization, then the diffusion coefficient could be reduced.

Table 3-32
Diffusion Coefficients for Tritium

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

Source: Triay et al., 1993.

^aWelded-Tuff Aquifer

^bNot available

The small dataset limits the extrapolation of the results to other HSUs at the NTS. This is especially true for the LCA, which will have characteristics that differ significantly from the tuffs at Yucca Mountain.

Selected matrix diffusion data of other constituents available from the literature are provided. Harrison et al. (1992) simulated diffusion of organic contaminants into clay till in Canada. They used effective diffusion coefficient values in the range of $1.5 \times 10^{-6} \text{ cm}^2/\text{s}$ ($1.6 \times 10^{-9} \text{ ft}^2/\text{s}$). In modeling of diffusion of strontium and plutonium in fractured granite, Krishnamoorthy et al. (1992) chose a range of values from 4.8×10^{-7} to $1.9 \times 10^{-6} \text{ cm}^2/\text{s}$ (5.2×10^{-10} to $2.1 \times 10^{-9} \text{ ft}^2/\text{s}$). Feenstra et al. (1984) measured diffusion through intact sandstone cores and obtained a range of values from 3.4×10^{-8} to $3.2 \times 10^{-7} \text{ cm}^2/\text{s}$ (3.7×10^{-11} to $3.4 \times 10^{-10} \text{ ft}^2/\text{s}$) with a mean of $1.5 \times 10^{-7} \text{ cm}^2/\text{s}$ ($1.6 \times 10^{-10} \text{ ft}^2/\text{s}$). In mudstone, Barone et al. (1992) measured a diffusion coefficient of 1.5×10^{-6} to $2.0 \times 10^{-6} \text{ cm}^2/\text{s}$ (1.6×10^{-9} to $2.2 \times 10^{-9} \text{ ft}^2/\text{s}$). Hadermann and Heer (1996) obtained matrix diffusion coefficients of $2.5 \times 10^{-7} \text{ cm}^2/\text{s}$ ($2.7 \times 10^{-10} \text{ ft}^2/\text{s}$).

3.4.8.4 Distribution Coefficients

The distribution coefficient (K_d) is a factor that is used in contaminant transport models to account for a variety of chemical interactions between dissolved contaminants and the solid substrate through which the contaminants are transported. Measured K_d values are typically a function of the

mineralogy of the solid substrate, the chemical composition of the water, and a variety of experimental variables including the water to rock ratio, batch versus column testing, and the particle sizes of the solid substrate. In some cases measured K_d values may reflect processes other than sorption (e.g., precipitation) (Meijer, 1990). No information was gathered on distribution coefficients during the regional evaluation (DOE/NV, 1997c) because the only radionuclide considered at the time was tritium ($K_d = 0$). Thus, a preliminary review of the literature available on K_d s for radionuclides was conducted as part of the Yucca Flat DQO process.

[Table 3-33](#) lists K_d values for selected contaminants that may be of concern at Yucca Flat and Climax Mine as reported by studies of the NTS and Yucca Mountain Project. The wide range of K_d s shown in [Table 3-33](#) is indicative of the site-specific nature of contaminant retardation during subsurface migration. The K_d values in [Table 3-33](#) from Triay et al. (1997) are the data recommended for use in the Yucca Mountain performance assessment. The K_d ranges shown are based on data obtained from studies using both volcanic and carbonate aquifer groundwater. For most of the potential contaminants, Triay et al. (1997) reported K_d ranges for devitrified, vitrified, and zeolitic tuff. For carbon, K_d data were only available for an iron-oxide substrate.

The K_d ranges reported by Meijer (1990) are from Yucca Mountain Project batch sorption experiments on crushed tuff samples ([Table 3-37](#)). The composition of groundwater from the NTS Well J-13, a sodium-potassium-bicarbonate water type ([Section 3.4.6](#)), was used as the reference composition for most of the sorption experiments. Distribution coefficient data reported by Meijer (1990) for experiments that used very fine particles (less than 500 micrometers [μm] diameter) were omitted from [Table 3-33](#). This is because the K_d s derived from these tests are typically unrealistically large due to the higher surface areas associated with small particles.

[Table 3-33](#) also contains K_d data from Borg et al. (1976). Except for tests performed using alluvium, which was from the Central Nevada Test Area, all solids used in the K_d studies were from the NTS. Although the K_d varies by orders of magnitude for a given contaminant, several general observations can be made based on the data presented in [Table 3-33](#), these observations are:

- Iodine does not sorb.
- Carbon and uranium are not greatly sorbed.
- Cesium, lead, plutonium, and strontium sorption is appreciable, regardless of substrate.
- Cesium and strontium sorption is very high in zeolitic tuff.

Table 3-33
Summary of Distribution Coefficient Data

Constituent	Distribution Coefficient (milliliters per gram)		
	Triay et al. (1997)	Meijer (1990)	Borg et al. (1976)
Carbon	iron oxide: ^a 10 - 100	ND ^b	ND
Cesium	devitrified tuff: 20 - 1,000 vitric tuff: 10 - 100 zeolitic tuff: 500 - 5,000	crushed tuff: 123 - 39,000	alluvium: 120 - 3,170 tuff: 1,020 - 17,800 carbonate: 14
Iodine	0	ND	tuff: 1
Lead	devitrified tuff: 100 - 500 vitric tuff: 100 - 500 zeolitic tuff: 100 - 500	ND	ND
Plutonium	devitrified tuff: 50 - 300 vitric tuff: 50 - 300 zeolitic tuff: 30 - 300	crushed tuff: 64 - 4,700	ND
Strontium	devitrified tuff: 10 - 200 vitric tuff: 20 - 50 zeolitic tuff: 2,000 - 50,000	crushed tuff: 22 - 87,000	alluvium: 50 - 2,450 tuff: 260 - 4,300 carbonate: 0.2
Uranium	devitrified tuff: 0 - 5.0 vitric tuff: 0 - 4.0 zeolitic tuff: 5 - 20.0	crushed tuff: 0 - 54	ND

^aIron oxide substrate used as a surrogate for Yucca Mountain waste container; these are the only data available in reviewed literature.

^bNo data

The observation that cesium and strontium sorption appears to be increased in zeolitized units, while lead and plutonium sorption is not, is probably due to differences in the sorption mechanisms of these constituents. For example, cesium and strontium sorption is probably predominantly controlled by cation exchange in zeolitic tuffs, whereas lead and plutonium sorption is not.

3.4.8.5 Colloidal Transport

No information was gathered on colloidal transport during the regional evaluation (DOE/NV, 1997c) because the only radionuclide considered at the time was tritium, which is not subject to colloidal transport. Thus, a preliminary review of the literature available on the colloidal transport of

radionuclides was conducted as part of the Yucca Flat DQO process and is provided in [Section 3.4.8.5](#) of this document.

Colloids are small, less than 1 μm , particles that may facilitate the migration of contaminants in the groundwater flow system. Dissolved contaminants may be removed from solution and attached to colloids by ion exchange or adsorption. Ramsay (1988) described three general cases for colloidal-facilitated contaminant migration: (1) uncharged colloid particles that migrate without retardation; (2) charged colloids that have the same sign as the surface charge of the aquifer medium and are repelled by the medium walls, resulting in a net increase in colloid flow velocity; and (3) the case of colloids and the medium surfaces having opposite charges, which could result in a slowing down of the colloid particles by interaction with the medium. Colloids are comprised of either organic material or inorganic mineral fragments and secondary minerals of the host rock. Oxides and hydroxides of actinide elements (e.g., plutonium) can also form as colloids (Kersting et al., 1998).

Colloids containing radionuclides have been observed in groundwater at Pahute Mesa (DOE/NV, 1999b). The mass concentration of colloids in groundwater from the CHESHIRE location was 10 mg/L in a sample from the cavity region and 4 mg/L in a sample from the formation above the cavity (Buddemeier, 1988). The fraction of total radioactivity associated with colloids varied by radionuclide; some radionuclides were present in groundwater entirely as dissolved species (e.g., tritium), while others were predominantly associated with colloids (e.g., europium) (see [Section 3.4.7](#) of the Pahute Mesa CAIP [DOE/NV, 1999b]).

On three separate occasions in 1996 and 1997, groundwater was sampled near the TYBO test location (Wells ER-20-5 #1 and #3). The samples were analyzed for tritium, gamma emitters, and plutonium isotopes. Radionuclides were found in groundwater samples collected from Well ER-20-5 #1. The data indicated that a large fraction of the total activity of each radionuclide was associated with colloidal material composed of clay, zeolites, cristobalite and minor glass. This mineralogy is consistent with the host-rock lithology. It was initially assumed that the radioactivity found in groundwater at Wells ER-20-5 #1 and #3 was derived from the TYBO test. However, evaluation of the data indicated the source of radionuclides was the BENHAM test, located approximately 1,300 m (4,265 ft) north of the ER-20-5 well. These findings imply that plutonium may migrate an appreciable distance from the nuclear test where it originated (Thompson, 1998; Kersting et al.,

1998). Evaluation of the plutonium migration process in the Yucca Flat near-field environment will be investigated during the CAI (see [Section 6.1](#)).

Additional information on the nature and behavior of colloids in groundwater at the NTS and the Yucca Mountain region are presented in Bryant (1992), Buddemeier and Hunt (1988), Kingston and Whitbeck (1991), Thompson (1998), and Triay et al. (1997). Other colloid research and modeling activities that may be applicable to the Yucca Flat CAIP include Grindrod and Lee (1997), Mills et al. (1991), Penrose et al. (1990), Puls et al. (1991), Toran and Palumbo (1992), and Vilks et al. (1997).

3.5 Contaminants

This section includes descriptions of all known and/or inferred radioactive and hazardous substances present in the Yucca Flat/Climax Mine CAU. In addition, a description of those substances that are considered potential contaminants based on the risks they may pose to human health and the environment is also included. Information on tritium is available in Section 6.0 of Volume V (Pages 6-1 to 6-2) of the regional evaluation documentation package (IT, 1996g), and in Section 8.8 (pages 8-10 to 8-12) of the regional evaluation report (DOE/NV, 1997c). Information on other contaminants of interest may be found in Section B.2.1 of the VOIA report (Page B-9) (IT, 1999c). The measured contaminant concentrations available for Yucca Flat locations are presented in [Section 3.4.7](#) of this document.

3.5.1 Radioactive and Hazardous Substances Present

Three predominant types of substances are associated with the radiologic source term. They are: (1) *in situ* materials or those contained within the device which have not undergone fission or thermonuclear reaction; (2) direct products of the nuclear reactions, such as fission products; and (3) radionuclides produced by activation of the fuel, materials used within the test, and the surrounding environment affected by the test.

[Table 3-34](#) lists materials commonly used in or produced as a result of an underground nuclear test. During a given underground nuclear test, large quantities of materials used to support the test were introduced into the shafts or tunnels. These materials included steel used to support the device, lead and magnetite used as shielding material, and cement and gravel used to backfill the opening. In

addition, nuclear devices commonly contained fissionable or fusionable radioactive elements in the critical mass for detonation. These elements include uranium, plutonium, tritium, and lithium. Small amounts of radiochemical detectors were also used. Incomplete consumption of these radioactive materials during detonation from testing would leave them within the subsurface for potential leaching to groundwater (Bryant and Fabryka-Martin, 1991).

Table 3-34
Materials Involved in Underground Nuclear Testing

Fuels, Detectors, Tracers	Rack/Canister Materials	Organics	Drilling/Stemming Materials
Americium Curium Neptunium Plutonium Tritium Uranium Lithium Yttrium Zirconium Thulium Lutetium	Aluminum Arsenic Barite Beryllium Boron Cadmium Chrome Lignosulfate Chromium Copper Gold Iron Lead ^c Lithium Magnetite ^d Nickel Osmium Potassium Chloride Sodium Hydroxide Tantalum Tungsten Zinc	Alcohol Anionic Polyacrylamide Coal-Tar Epoxy Complex Fluorescing Compounds ^a Galacto-Mannans (C ₆ H ₁₀ O ₅) _n Laser Dyes ^a Liquid Anionic Polyelectrolyte Paraformaldehyde Phenolic Polystyrene Polyvinyl Chloride Two-Part Epoxy	Bentonite Cement Gel Gravel Modified Starch Neoprene [®] Polyethylene Pregelatinized Starch Sand Sepiolite Soda Ash ^b Sodium Polyacrylate Sodium Montmorillonite Surfactant TF Foamer Teflon [™]

Source: Bryant and Fabryka-Martin, 1991

^aFluorescing compounds and laser dyes used in some detector packages may contain potentially hazardous organic constituents.

^bContains the ophylline, ethylenediamine, carbonic acid disodium salt

^cExtensive quantities of lead (57.2 metric tons) are typically used as shielding material for device canisters and racks.

^dMagnetite is naturally occurring iron oxide (Fe₃O₄) containing thorium and other heavy rare earths.

3.5.2 Potential Contaminants for the CAI

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

A comprehensive list of radiological contaminants was established based on knowledge of radionuclides that are residual from underground nuclear testing. The list, shown in [Table 3-35](#), includes 64 radiological contaminants (Smith, 1995b). Fifty-six of the candidate contaminants were naturally-occurring and nuclear weapon-produced radionuclides with half-lives greater than ten years. The other eight candidate contaminants were radionuclides with half-lives of less than ten years. These eight radionuclides were added to the comprehensive list because they are presently encountered in fluids returned from saturated nuclear test cavities (Smith, 1997). The comprehensive list ([Table 3-35](#)) was used to derive a preliminary list of potential contaminants ([Table 3-36](#)) that are relevant to UGTA corrective action activities (Smith, 1997).

Table 3-35
Comprehensive List of Radionuclides Related to Underground Testing

Radionuclides							
Aluminum-26	Carbon-14	Europium-152	Krypton-85	Niobium-92	Plutonium-241	Sodium-22 ^a	Uranium-232
Americium-241	Cesium-134 ^a	Europium-154 ^a	Lead-205	Niobium-93	Plutonium-242	Strontium-90	Uranium-233
Americium-243	Cesium-135	Europium-155 ^a	Lead-210	Niobium-94	Protactinium-231	Technetium-98	Uranium-234
Antimony-125 ^a	Cesium-137	Hafnium-178	Manganese-53	Palladium-107	Rhenium-186	Technetium-99	Uranium-235
Argon-39	Chlorine-36	Holmium-166	Molybdenum-93	Platinum-193	Ruthenium-106 ^a	Thorium-232	Uranium-236
Beryllium-10	Cobalt-60 ^a	Iodine-129	Neptunium-237	Plutonium-238	Samarium-146	Tin-121	Uranium-238
Cadmium-113	Curium-244	Iridium-192	Nickel-59	Plutonium-239	Samarium-151	Tin-126	Zinc-65 ^a
Calcium-41	Europium-150	Krypton-81	Nickel-63	Plutonium-240	Selenium-79	Tritium	Zirconium-93

^aShort-lived radionuclide, half-life less than ten years

Table 3-36
Preliminary List of Potential Radioactive Contaminants for UGTA

Contaminant of Concern	Abbreviation	Half-Life (years)	Criteria
Americium-241	Am-241	432.7	health
Antimony-125	Sb-125	2.758	mobility
Carbon-14	C-14	5,730	production, mobility
Cesium-134	Cs-134	2.065	health
Cesium-137	Cs-137	30.17	production, health
Chlorine-36	Cl-36	3.01×10^5	mobility
Cobalt-60	Co-60	5.27	mobility
Europium-152	Eu-152	13.48	production
Europium-154	Eu-154	8.59	production
Europium-155	Eu-155	4.74	production
Iodine-129	I-129	1.57×10^7	mobility, health
Krypton-85	Kr-85	10.73	mobility
Neptunium-237	Np-237	2.14×10^6	mobility, health
Plutonium-239	Pu-239	2.41×10^4	production, health
Plutonium-240	Pu-240	6.56×10^3	production, health
Ruthenium-106	Ru-106	1.02	mobility
Samarium-151	Sm-151	90	production
Strontium-90	Sr-90	29.1	production, health
Technetium-99	Tc-99	2.13×10^5	mobility
Tritium	H-3	12.3	production, mobility
Uranium-234	U-234	2.46×10^5	production, health
Uranium-238	U-238	4.47×10^9	production, health

Source: Smith, 1997

Note: This table does not contain any classified data.

Three criteria were used in formulating the preliminary list of potential radioactive contaminants shown in [Table 3-36](#): (1) the production of a radionuclide in a nuclear test, (2) the relative mobility of the radionuclide determined from historical field observations, and (3) the health effect of the radionuclide relative to a total body or organ dose. The health effects were obtained from a ranking of radionuclides related to DOE and proposed EPA drinking water standards. The preliminary list reflects an evaluation of each radionuclide against the above criteria. This list ([Table 3-36](#)) represents radionuclides potentially of concern at sites contaminated by underground nuclear testing.

A list of potential contaminants for the 1,000-year CAI time period was derived from the preliminary list ([Table 3-36](#)) by the TWG VOIA Subcommittee. Nine radioactive contaminants were selected based on observed concentrations in groundwater, inventory estimates, health effects, and fate and transport information: ^{14}C , iodine-129 (^{129}I), plutonium-239/240 ($^{239/240}\text{Pu}$), ^{137}Cs , ^{90}Sr , tritium, americium-241 (^{241}Am), neptunium-237 (^{237}Np), and uranium-238 (^{238}U). This group of radionuclides was considered to be the most significant for prediction of the 4-millirem (mrem) contaminant boundary over a 1,000-year time period. For this reason, the nine radionuclides were included in the simulations performed for the Yucca Flat VOIA (IT, 1999c).

In addition to the nine radionuclides discussed above, other radioactive contaminants listed in [Table 3-36](#) may be of potential concern to the Yucca Flat/Climax Mine CAU. The list of potential radioactive contaminants that will be included in simulations of the contaminant boundary for the Yucca Flat/Climax Mine CAU may be modified based on the findings of the CAI.

Lead has also been included in the potential contaminants for the Yucca Flat/Climax Mine CAU because it is known to have been used in significant quantities in underground nuclear tests. In addition, lead has been included because it represents a *Resource Conservation and Recovery Act* (RCRA) contaminant (RCRA, 1996). It was assumed that any volatile or semivolatile organic RCRA constituent would be consumed during the explosion; therefore, only metals could remain as potential contaminants.

[Table 3-37](#) presents estimated concentration ranges for the potential radioactive contaminants evaluated in the Yucca Flat VOIA (IT, 1999c). The concentration ranges were recommended by the TWG VOIA Subcommittee with input from members of the TWG Source Term Subcommittee. The TWG VOIA Subcommittee provided inputs on a generic distribution for radionuclide concentrations within the hydrologic source term. The proposed generic probability distribution is log-normal with a three-order-of-magnitude range. The wide range was selected to reflect the uncertainties associated with the radionuclide concentrations in the hydrologic source term. The concentration ranges for the nine radionuclides of concern ([Table 3-37](#)) were obtained by scaling the generic range by the most probable concentration value for each of the nine radionuclides. The most probable concentration values for these radionuclides were chosen by considering available analytical data ([Section 3.4.7](#)) as well as the unclassified source term estimates for non-Pahute Mesa tests, converted to concentration.

Table 3-37
Estimated Concentration Range of Potential Radioactive Contaminants
in Nuclear Test Cavity Groundwater

Contaminant	Estimated Range of Dissolved Concentrations	
	Minimum	Maximum
	Concentration (pCi/L)	Concentration (pCi/L)
Tritium	1×10^7	1×10^{10}
Carbon-14	1×10^2	1×10^5
Strontium-90	1×10^1	1×10^4
Iodine-129	1.48×10^{-2}	1.48×10^1
Cesium-137	1	1×10^3
Uranium-238	1×10^{-1}	1×10^2
Neptunium-237	1×10^0	1×10^3
Plutonium-239/240	1×10^2	1×10^5
Americium-241	1×10^1	1×10^4

Source: IT, 1999c

If the solubility limit for the radionuclide was lower than the concentration, that value was used instead.

3.6 Conceptual Model of the CAU

The conceptual model for the Yucca Flat/Climax Mine CAU is described in this section. Additional descriptions are provided in [Section A.1.2.1.2](#) of [Appendix A](#).

The conceptual model of a given contaminated site includes descriptions of the release and discharge mechanisms, migration routes, contaminated media, and exposure pathways associated with the contamination. In cases where groundwater is the contaminated medium, as is the case for the Yucca Flat/Climax Mine CAU, an understanding of groundwater flow and contaminant transport within the subsurface is paramount to the conceptual model of the site. Many types of data are usually required to conceptualize groundwater flow and contaminant transport within a given site. They include

precipitation and recharge, topography, surface water, geology, hydrogeology, groundwater chemistry and radiochemistry, transport parameters, and contaminants.

The current conceptual model of the Yucca Flat/Climax Mine CAU was developed during the DQO process described in [Appendix A](#). The groundwater flow and contaminant transport component of the Yucca Flat/Climax Mine conceptual model was adapted from the regional model (IT, 1996c through h; IT, 1997b and c; DOE/NV, 1997c) and developed for the Yucca Flat/Climax Mine VOIA (IT, 1999c). Specific sources of data for the conceptual model of the Yucca Flat/Climax Mine CAU used in the VOIA (IT, 1999c) are presented in [Table 3-38](#). A visualization of the Yucca Flat/Climax Mine conceptual model of groundwater flow and transport including the predicted extent of contamination is provided in [Appendix A](#) ([Figure A-5](#) and [Figure A-6](#)). The remainder of this section provides descriptions of the release and discharge mechanisms, migration routes, contaminated media, and exposure pathways associated with the underground nuclear testing.

3.6.1 Release and Discharge Mechanisms

The release mechanisms of contaminants from underground nuclear tests to the subsurface, including groundwater, are described in this section. A brief description of potential contaminant discharge to the environment from the Yucca Flat/Climax Mine subsurface, via groundwater, is also included.

3.6.1.1 Release Mechanisms

Radionuclides and other contaminants enter the groundwater system through a variety of mechanisms starting with the explosion of the nuclear device. [Figure 3-27](#) is a schematic diagram of the processes whereby radionuclides can enter the groundwater flow system as a result of underground nuclear testing.

To support the understanding of release mechanisms associated with underground nuclear tests, this section includes a generalized description of nuclear explosion phenomenology prepared by Pawloski (1998). Phenomenology describes the effects of the nuclear explosion on the surrounding medium. Actions that occur during the time period from the explosion to when the cavity void grows to its full size and then rebounds are referred to as early-time phenomenology. Actions that occur after the cavity has reached its full size are referred to as late-time phenomenology and consist mainly of

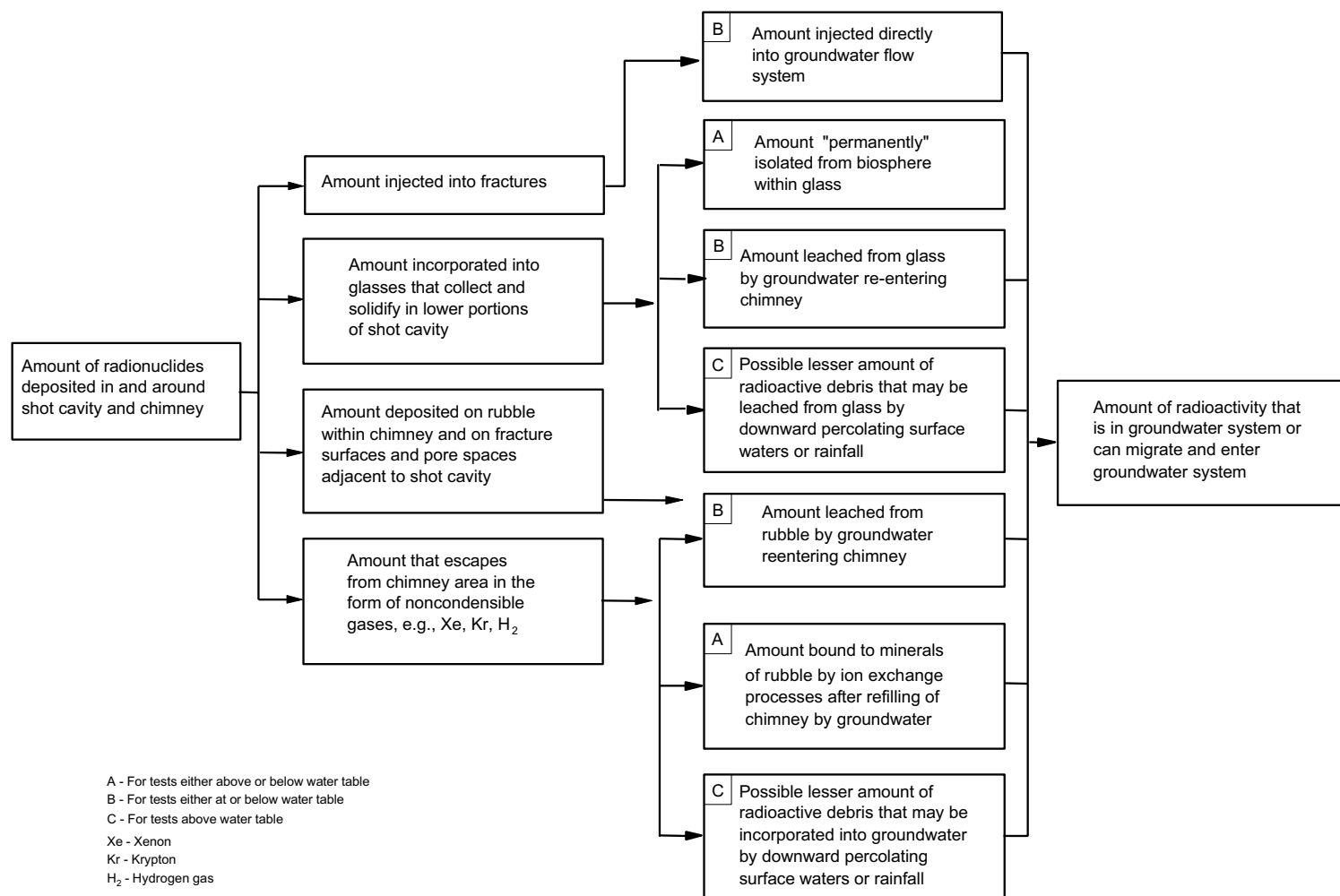
Table 3-38
Sources of Information for Yucca Flat/Climax Mine Conceptual Model of
Groundwater Flow and Contaminant Transport

Data Type	Reference within CAIP	Reference within Regional Evaluation Documentation Package	Reference within Regional Model Report and VOIA Report
Precipitation	Sect. 3.4.1 (pg. 63)	Sect. 3.0 through 11.00 (pg. 3-1 to 11-6); Specific to precipitation: Sect. 7.3.1 (pg. 7-5 to 7-12) of Volume III (IT, 1996c)	Sect. 5.7.1.2.1 (pg. 5-24 to 5-25) of the regional evaluation report (DOE/NV, 1997c)
Topography	Sect. 3.4.2 (pg. 66)	Map F20 in Appendix F of Volume I (IT, 1996f)	Sect. 2.2 (pg. 2-1 to 2-4) of the regional evaluation report (DOE/NV, 1997c)
Surface Water	Sect. 3.4.3 (pg. 67)	Sect. 5.0 (pg. 5-1 to 5-2), Sect. 8.0 (pg. 8-1 to 8-7), and Appendix A (pg. A-1 to A-26) of Volume III (IT, 1996c)	Sect. 5.7.2.1 (pg. 5-30 to 5-37) of the regional evaluation report (DOE/NV, 1997c)
Geology	Sect. 3.4.4 (pg. 68)	Appendices C5 through C9 (pg. C5-1 to C9-15), and C15 (pg. C15-1 to C15-10) of Volume I (IT, 1996f); and Appendix B of Volume II (pg. B-1 to B-73) (IT, 1996e)	Sect. 4.0 (pg. 4-1 to 4-15) of the regional evaluation report (DOE/NV, 1997c)
Hydrostratigraphy	Sect. 3.4.5.1.1 (pg. 83) and Sect. 3.4.5.2.1 (pg. 91)	Appendices C5 through C9 (pg. C5-1 to C9-15), C15 (pg. C15-1 to C15-10), E2, and F of Volume I (IT, 1996f)	Sect. 4.0 (pg. 4-1 to 4-15), and Sect. 6.2.1 (pg. 6-2 to 6-11) of the regional evaluation report (DOE/NV, 1997c)
Hydraulic Conductivity	Sect. 3.4.5.1.1 (pg. 83) and Sect. 3.4.5.2.1 (pg. 91)	Sect. 3.0 to 8.0 (pg. 3-1 to 8-3), Appendices A and C of Volume IV (IT, 1996d)	Sect. 5.5 (pg. 5-4 to 5-12) of the regional evaluation report (DOE/NV, 1997c)
Hydraulic Conductivity Versus Depth	Sect. 3.4.5.1.2 (pg. 87) and Sect. 3.4.5.2.2 (pg. 98)	Sect. 6.2 (pg. 6-3 to 6-12) of Volume IV (IT, 1996d)	Sect. 5.5.1.5 (pg. 5-9 to 5-12) of the regional evaluation report (DOE/NV, 1997c)
Water Levels	Sect. 3.4.5.1.2 (pg. 87) and Sect. 3.4.5.2.2 (pg. 98)	Sect. 3.0 through 10.0 (pg. 3-1 to 10-4), Appendix A (pg. A-1 to A-69), and Appendix C (pg. C-1 to C-54) of Volumes II (IT, 1996e)	Sect. 5.6 (pg. 5-15 to 5-21) of the regional evaluation report (DOE/NV, 1997c)
Recharge	Sect. 3.4.5.1.2 (pg. 87) and Sect. 3.4.5.2.2 (pg. 98)	Sect. 3.0 through 11.00 (pg. 3-1 through 11-6) of Volume III (IT, 1996c) - Recharge-specific discussion in Sect. 7.3.2 (pg. 7-12 to 7-18)	Sect. 5.7.1 (pg. 5-22 to 5-30) of the regional evaluation report (DOE/NV, 1997c)
Groundwater Flow	Sect. 3.4.5.1.2 (pg. 87) and Sect. 3.4.5.2.2 (pg. 98)	Sect. 9.3.2 (pg. 9-6 to 9-8) of Volumes II (IT, 1996e), and Volume VI of the regional evaluation (IT, 1997b)	Sect. 6.2.2 (pg. 6-12 to 6-32), Sect. 7.0 (pg. 7-1 to 7-99), Appendix B, and Appendix C of the regional evaluation report (DOE/NV, 1997c)
Porosity	Sect. 3.4.8.1 (pg. 149)	Sect. 3.0 (pg. 3-1 to 3-12), Appendix A, Appendix B, and Appendix C of Volume V (IT, 1996g)	Sect. 8.5 (pg. 8-3 to 8-6) of regional evaluation report (DOE/NV, 1997c); and Sect. B.2.2 of Appendix B (pg. B-9 to B-10) of the VOIA report (IT, 1999c)
Dispersion Coefficient	Sect. 3.4.8.2 (pg. 152)	Sect. 4.0 (pg. 4-1 to 4-22) of Volume V (IT, 1996g)	Sect. 8.6 (pg. 8-6 to 8-9) of regional evaluation report (DOE/NV, 1997c)
Matrix Diffusion Coefficient	Sect. 3.4.8.3 (pg. 154)	Sect. 5.0 (pg. 5-1 to 5-3) of Volume V (IT, 1996g)	Sect. 8.7 (pg. 8-9 to 8-10) of regional evaluation report (DOE/NV, 1997c); and Sect. B.2.3 of Appendix B (pg. B-10) of the VOIA report (IT, 1999c)
Contaminants	Sect. 3.5 (pg. 159)	Sect. 6.0 of Volume V (pg. 6-1 to 6-2) (IT, 1996g)	Sect. 8.8 (pg. 8-10 to 8-12) of regional evaluation report (DOE/NV, 1997c); Sect. B.2.1 of the VOIA report (pg. B-9) (IT, 1999c)
Contaminant Transport	Sect. 3.4.7 (pg. 122)	Volume VI of the regional evaluation (IT, 1996h)	Sect. 9.0 (pg. 9-1 to 9-54) of regional report (DOE/NV, 1997c); Sect. 3.5.1 (pg. 3-13 to 3-15), Sect. B.1.2 through B.3.0 (pg. B-2 to B-13) in Appendix B, and Table F-2 (pg. F-4) in Appendix F of the VOIA report (IT, 1999c)

Sect. = Section(s)

pg. = page(s)

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Source: Modified from Borg et al. (1976)

Figure 3-27
Introduction or Distribution of Radionuclides from Underground Tests to
Hydrologic Source Term and Groundwater Flow System
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thermally-induced mechanisms that lead to the eventual collapse of the cavity. A discussion of the distribution of materials introduced into the subsurface during nuclear testing and their availability for transport in groundwater is also included.

Early Time Phenomenology

Sufficient energy is released when an underground nuclear device is exploded to instantaneously vaporize the experiment canister and the rock surrounding the experiment. Within microseconds of the detonation, initial temperatures rise to several million degrees Kelvin, and pressures of about 1 megabar are created. As a result, a compressive shock wave is generated that imparts momentum on the rock. Additional rock is crushed and cracked within milliseconds. In tenths of seconds, the energy passes elastically through the outlying material to the ground surface (Pawloski, 1998).

Rock material surrounding the explosion is vaporized and melted, and pore water is vaporized. The cavity void continues to grow radially as the expanding shock wave imparts outward momentum on the surrounding media. Cavity growth is dependent on the strength of the overlying rock. Depending on the yield of the explosion, the cavity reaches its largest size within 80 to 500 milliseconds when the elastic strains within the rock attempt to recover. The material rebounds radially due to elastic unloading and tries to return to its original position. A compressive tangential hoop stress is formed when the stress field in the rebounded rock is greater than the cavity pressure. This compressive or residual hoop stress closes radial fractures that were opened during cavity expansion. The final size and shape of the cavity are dependent on the yield of the explosion, the overburden stresses, and the strength of the surrounding rock (Pawloski, 1998).

As the shock wave moves outward, cavity growth slows. At about one third of the distance from the detonation point to the ground surface, the shock wave becomes elastic, travels at elastic speeds, and reaches the surface within about 100-500 milliseconds. Rock failure can be brittle or plastic, depending on the stress conditions and the strength properties of the geologic materials. Upward acceleration of material from the detonation point to the ground surface can cause surface bulges of about 1 to 3 m (3 to 9 ft) (Pawloski, 1998).

Final cavity pressure is not dependent on overburden pressure, but rather on the strength of the overlying rock. Frequently, cavity growth ceases when ambient hydrostatic overpressure is greater

than cavity pressure. The cavity stabilizes and dynamic motion ceases within a few seconds of the explosion (Pawloski, 1998).

Late Time Phenomenology

Rock vapor begins to condense and forms a puddle of melted material at the bottom of the cavity after the shock and elastic waves have dissipated. Water vapor and noncondensable gases, such as carbon dioxide and hydrogen, are still present in the cavity. Energy in the gas is radiated and high thermal gradients are created within the cavity walls via thermal conduction, causing ablation and spalling of wall material. This activity occurs within minutes to hours of the explosion. Flaked wall material of various sizes enhances cooling and mixes with puddle glass. Some material becomes incorporated in the melt and larger pieces survive as rubble within the glass. The repeated ablation and mixing reduces cavity pressure until it is only a few pounds per square inch. Cavity collapse starts within minutes or hours of the explosion and progresses quickly, usually within tens of minutes. If the overlying rock is not strong enough to support the cavity roof span, collapse propagates upwards forming a rubble chimney. If the material strength of the overlying rock is insufficient and the bulking factor is small, collapse proceeds to the surface and a subsidence crater is formed (Pawloski, 1998).

Other Phenomena

Other phenomena related to underground nuclear testing have occurred, including hydrofracturing, prompt injection of radionuclides, groundwater effects (such as mounding and pressurization), reflections off of impedance layers caused by material property differences (such as rock strength or air void content, bedding planes, or faults), and movement on preexisting structural features (such as faults). These phenomena may affect cavity growth, residual stress, collapse, and crater formation (Pawloski, 1998).

Distribution and Release of Materials Related to Testing

The nuclear explosion phenomenology described above is responsible for the observed distribution of materials that were introduced into the subsurface during testing. Radioactive elements are not uniformly distributed in the chimney/cavity region, but are partitioned based on their physical and chemical characteristics.

Smith (1993) indicates that the partitioning can be described in terms of a three-stage condensation process. The refractory radionuclides (e.g., actinides), whose melting points are significantly greater than the melting temperature of the adjacent geologic media, are scavenged by the molten material that lines the cavity. These nuclides are volumetrically deposited within the puddle glass. Further condensation occurs as cavity gas moves into the crushed rubble and fractured material surrounding the working point. During this stage, the radioisotopes of intermediate volatility, often with gaseous precursors (e.g., ^{137}Cs), condense and deposit on rubble and fracture surfaces. Final condensation occurs as residual gas ascends toward the ground surface. Condensation during this stage also occurs on surfaces. The above process leads to a distribution of radionuclides that is fractionated, with heavier refractory nuclides concentrated within the glass and lighter and volatile nuclides concentrated higher in the chimney (Smith, 1993). Tritium initially is distributed in the gas phase and later as molecular tritium oxide in steam (Smith, 1995a).

During tests conducted at or below the water table, groundwater is evacuated from the test cavity and then slowly seeps back into the cavity after the detonation (Borg et al., 1976). Where detonations are near or below the static water level, groundwater is impacted due to the prompt injection of radionuclides into surrounding fractures or the leaching of radionuclides as water seeps back into the test cavity and rubble chimney (Figure 3-27).

The distribution of radionuclides in the cavity/chimney region greatly influences the availability of potential contaminants for transport by groundwater. Radionuclides volumetrically incorporated in the melt glass matrix are accessible to groundwater only through slow processes such as glass dissolution. Other radionuclides are predominantly associated with surfaces and are accessible to groundwater through relatively fast processes such as ion exchange (Smith, 1995b).

In addition, metals, drilling mud, and other organic material may be left within, or in close proximity of the chimney or test cavity due to reentry operations. Nonradiological contaminants from these sources can also be leached into groundwater and potentially transported to environmental receptors.

3.6.1.2 Discharge Mechanisms

Contaminants resulting from underground nuclear testing at Yucca Flat and Climax Mine may potentially be discharged to the surface by groundwater. No groundwater discharge occurs within the

Yucca Flat/Climax Mine area and vicinity. Therefore, access to groundwater in these areas is only through open boreholes and water-supply wells. However, groundwater flows through the nuclear testing areas of Yucca Flat and Climax Mine past the southern boundary of the NTS and eventually discharges to the surface from springs at Franklin Lake Playa and Death Valley (DOE/NV, 1997c).

3.6.2 Migration Routes

In order for human receptors to be exposed to radionuclides leached or injected into groundwater near underground nuclear test locations, a transport or migration mechanism must be present. For contaminants generated from underground testing at Yucca Flat and Climax Mine, the most probable potential migration pathway is via transport in the regional groundwater-flow system. A summary of the current understanding of the groundwater flow paths, and the contaminant concentrations and travel times is presented in this section.

3.6.2.1 Groundwater Flow Paths

During the 200-year simulation period used in the regional modeling (DOE/NV, 1997c), groundwater flow paths passing through the Yucca Flat and Climax Mine underground nuclear tests are predicted to cross the NTS area south of Yucca Flat, cross the southern NTS boundary, and enter the Amargosa Desert ([Figure 3-28](#)). Based on particle-tracking simulations conducted during the VOIA (IT, 1999c) and within a simulation period of 1,000 years, most groundwater flow paths reach the AA of the Amargosa Desert on their way to the Death Valley discharge area ([Figure 3-29](#)). A few pathlines take a southerly turn towards Franklin Lake Playa ([Figure 3-29](#)). All of these groundwater paths eventually end up at Franklin Lake Playa or the Death Valley discharge area.

During the simulations, an imaginary particle was started at the water table below the PILE DRIVER test in the Climax Stock at the northern end of Yucca Flat. This particle started in the intrusive, passed through a small amount of UCCU, and entered the LCA beneath northern Yucca Flat. It traveled along the upper part of the LCA, passing beneath Massachusetts Mountain which separates Yucca Flat from Frenchman Flat. Moving beneath the northwestern part of Frenchman Flat in the LCA, the particle moved down Rock Valley and entered the AA near Skeleton Hills. The particle continued to move southwestward to discharge at the Amargosa River discharge area (IT, 1997c).

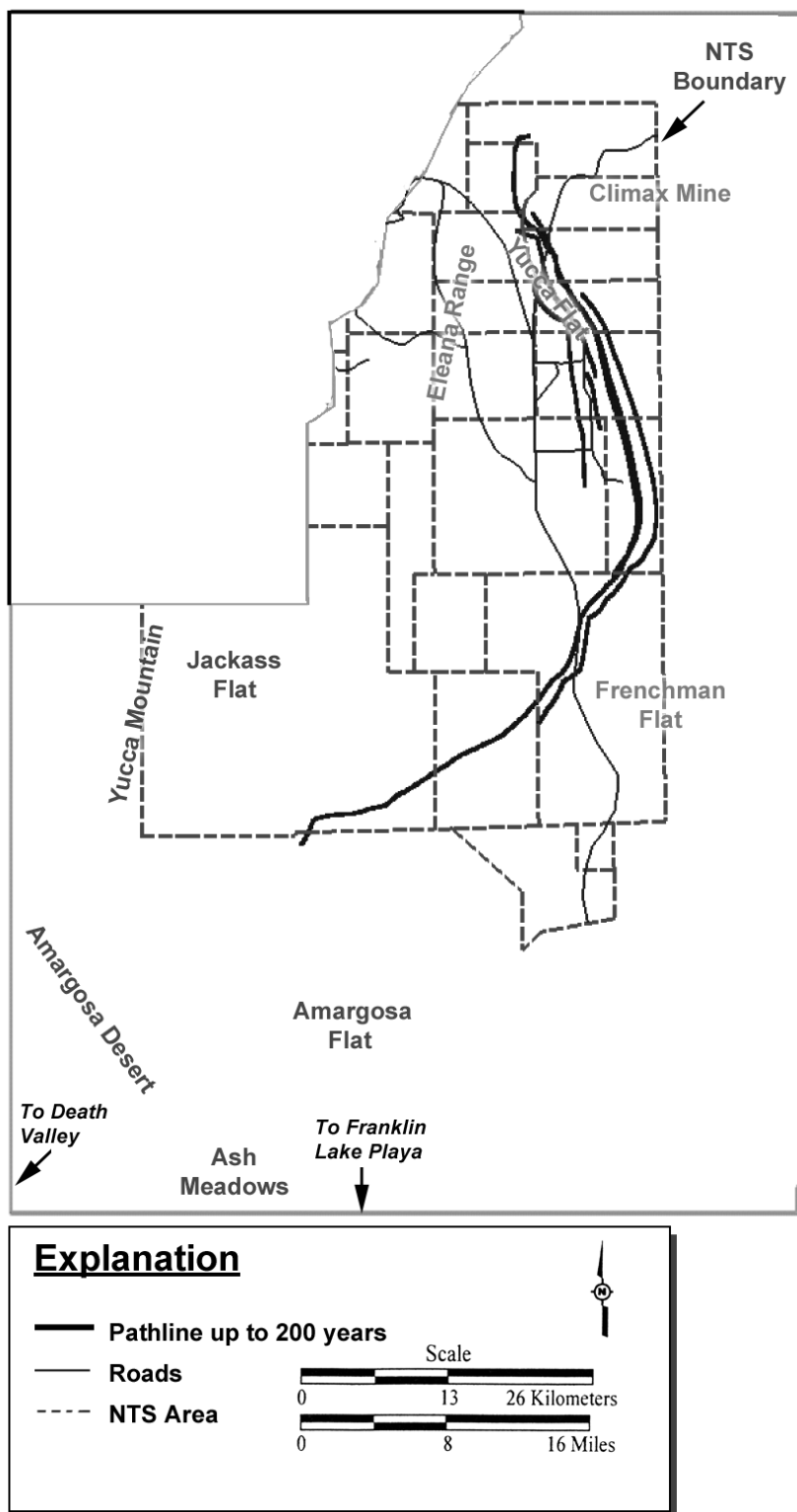


Figure 3-28
Simulated Groundwater Pathlines from Yucca Flat and Climax Mine
Nuclear Test Locations for a 200-Year Period Based on Regional Model Results
 (Modified from DOE/NV, 1997c)
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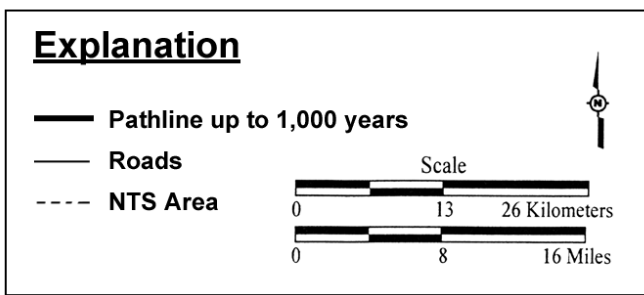
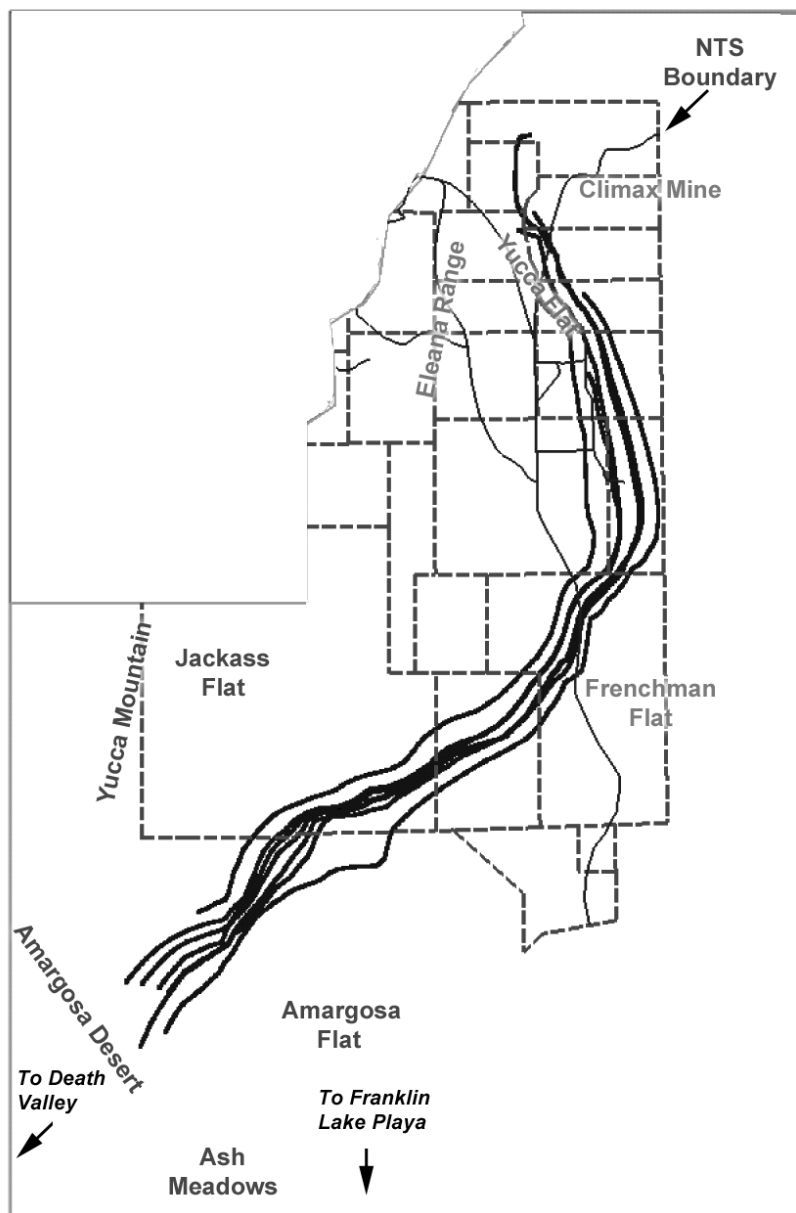


Figure 3-29
Simulated Groundwater Pathlines from Yucca Flat and Climax Mine
Nuclear Test Locations for a 1,000-Year Period

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Five particles were started in Yucca Flat. COULOMMIERS and CORDUROY originated in the VCU and LCA, respectively, and had similar flowpaths to the PILE DRIVER particle, discharging from the AA at the Amargosa River discharge area. BOURBON also started within the LCA, but migrated southward farther to the east than the previous two particles, discharging in the AA at the Franklin Lake discharge area. The final two particles, STRAIT and CUMARIN, began in the VCU on the western side of Yucca Flat. Both particles traveled in the LCA into the Amargosa Desert, but were not captured by the Amargosa River discharge area. Instead, they moved from the AA back into LCA and TSDV and discharged in Death Valley (IT, 1997b).

3.6.2.2 Contaminant Concentrations and Travel Times

Tritium transport simulations were performed along one pathline relating to the BOURBON test in Yucca Flat ([Figure 3-30](#)) using the regional contaminant transport model (DOE/NV, 1997c; IT, 1996h). This nuclear test was selected to represent Yucca Flat because it has the greatest simulated downgradient advective travel distances. Other factors such as the geology of the nuclear test location and/or the degree to which the tests are representative of the Yucca Flat flow area were also considered. Transport simulations of other radionuclides were also performed in support of the VOIA (IT, 1999c) using the regional model (DOE/NV, 1997c). Simulations were limited to a generic pathline, the BOURBON pathline, but included the transport of the major potential radionuclides listed in [Section 3.5.2](#) (IT, 1999c).

Underground nuclear tests located on the same pathline as BOURBON (KANKAKEE and MICKEY/TORRIDO) were accounted for in the contaminant transport simulations to evaluate the effects of multiple sources on the extent of migration. The BOURBON pathline originates at the KANKAKEE test and passes through the BOURBON and MICKEY/TORRIDO tests ([Figure 3-30](#)). The transport of tritium was simulated as part of the regional transport model (IT, 1996h and DOE/NV, 1997c). The sources of contamination originating from the tests were assumed to correspond to finite volumes of tritiated groundwater occupying spherical volumes spanning two cavity radii. Average initial tritium concentrations based on unclassified data were assumed for these sources. The simulations included the effects of parameter uncertainty via a Monte Carlo approach. Parameters that were varied during the Monte Carlo simulations include groundwater flux, effective

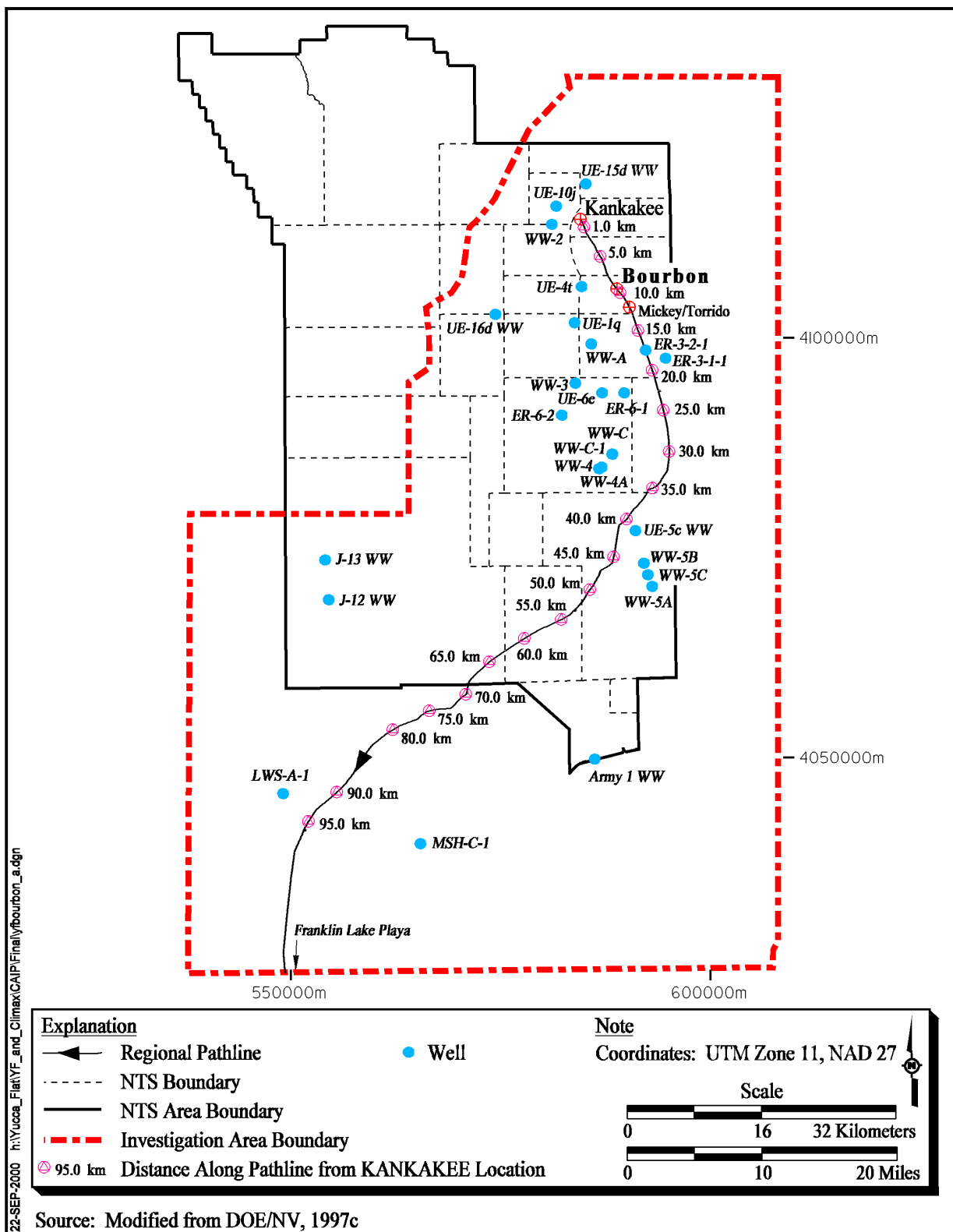


Figure 3-30
Simulated Groundwater Pathline Through BOURBON Nuclear Test

porosity, dispersion coefficient, matrix diffusion, and initial tritium concentration at the source (IT, 1996h).

Simulation results indicate that at the 50 percent level, the distance to the 20,000 pCi/L contour is approximately 20 km (12.4 mi) from KANKAKEE or 10.5 km (6.5 mi) downgradient from the BOURBON test. At the larger levels, such as 95 percent, the amount of downgradient movement as represented by the 20,000 pCi/L line is greater than at the 50 percent level, but less than 40 km (24.9 mi). For reference, the 36 km (22.9 mi) distance is a point at the northern edge of Frenchman Flat, well within the boundaries of the NTS. The 20,000 pCi/L contour reaches its maximum extent in approximately 25 years and then begins to recede gradually over the next 125 years (IT, 1996h). The maximum downgradient migration distances were primarily a function of the groundwater flux (how much water was moving) and the matrix diffusion parameters. Matrix diffusion removes contaminants from the more rapid flow regime in the fractures and stores them temporarily in the relatively immobile matrix. The larger the matrix diffusion coefficient, or the larger the matrix porosity, the more contaminants were removed from the rapid flow regime.

Transport simulations were also performed during the VOIA (IT, 1999c). All radionuclides of concern listed in [Table 3-37](#) were initially considered, however, only three of them were found to contribute to the prediction of the location of the contaminant boundary. They are tritium, ^{14}C , and $^{239/240}\text{Pu}$. The distance of the 4-mrem/yr dose at 50 percent confidence within 1,000 years along the generic pathline is 58 km ([Figure A-6 in Appendix A](#)) (IT, 1999c). The distance calculated at the 95 percent confidence level is not representative of reality because it was assumed that the generic pathline would continue moving through the LCA all the way to Death Valley. In reality, pathlines originating from tests in Yucca Flat and Climax Mine enter and traverse the AA of the Amargosa Desert before reaching the Death Valley discharge area.

The results of the transport simulations performed during the VOIA (IT, 1999c) were further extrapolated to selected underground nuclear tests to estimate the expected distance from the source of the 4-mrem/yr dose within a 1,000-year period. The corresponding distances are depicted in [Figure A-5 in Appendix A](#).

3.6.3 Contaminated Media

Contaminated media are subsurface soils and groundwater within the unsaturated and the saturated zones. Contamination within the unsaturated zone may be transported downward with infiltrated water from precipitation. This vertical movement is, however, extremely slow and is not within the scope of this investigation. Contamination within the saturated zone is subject to much more rapid transport in groundwater and is the focus of this CAI.

Groundwater contamination occurs within the nuclear test cavities, their vicinity, and potentially downgradient of the Yucca Flat/Climax Mine CAU. The portion of the groundwater flow system that may potentially be contaminated downgradient of the underground test areas, includes all groundwater below the water table within a region stretching from Climax Mine and Yucca Flat, southward towards the Amargosa Desert. The region encompasses the Yucca Flat/Climax Mine area, Frenchman Flat, southern NTS, and the Amargosa Desert. Geologic units within this area include alluvium, bedded tuffs, fractured welded tuffs and lava flows, fractured Paleozoic carbonates, and clastic-confining units as described in [Section 3.0](#). The details about the geology and hydrogeology of the area of interest are provided in [Sections 3.4.4](#) and [3.4.5](#) of this document. The groundwater chemistry and radiochemistry are described in [Sections 3.4.6](#) and [3.4.7](#).

Lateral and vertical extent of groundwater contamination were estimated using the regional model (DOE/NV, 1997c). Laterally, the contaminants are currently located within the vicinity of the test cavities and downgradient of the test locations in Yucca Flat and Climax Mine. Within the 1,000-year timeframe of interest, the contamination may extend from a few hundred meters away from an underground test location to (in extreme cases) as far as the Amargosa Desert. Vertically, the potential contaminants may extend from the maximum water table elevation 1,048 m amsl (3,437 ft amsl) to as low as the deepest nuclear test, 490 m amsl (1,607 ft amsl). Therefore, as much as 558 m (1,830 ft) or more of the thickness of the groundwater flow system may be impacted by the potential contaminants. A detailed description of the contaminants is provided in [Section 3.5](#) of this CAIP. The contaminant transport processes are described in [Section 3.4.8](#).

3.6.4 Exposure Pathways

Yucca Flat and Climax Mine are reserved as nuclear test zones. The Nellis Air Force Range complex land potentially affected by contamination from the Yucca Flat/Climax Mine CAU is used for military training, and BLM lands surrounding the Nellis Air Force Range complex and NTS are used for grazing, mining, and recreation.

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

3.6.5 Uncertainties

The current conceptual model of the Yucca Flat/Climax Mine CAU has several areas of uncertainties, which are as follows:

- A lack of subsurface geologic characterization for the entire Yucca Flat/Climax Mine area, and a lack of hydrologic characterization in specific areas
- Insufficient characterization of the hydrochemical framework of the Yucca Flat/Climax Mine region
- Limited knowledge of the contaminant transport processes and associated parameters
- Limited understanding of the contamination sources

3.7 Preliminary Corrective Action Levels

Regulatory and health-based preliminary action levels (PAL) for the potential contaminants are provided in this section. The PALs are provided for groundwater only because the investigation will include sampling of groundwater only.

A PAL is the concentration of a contaminant in drinking water that will result in a member of the public receiving an ingestion dose limit from that contaminant. The PALs for the potential contaminants evaluated in the Yucca Flat/Climax Mine VOIA are presented in [Table 3-39](#).

Preliminary action levels for ^{14}C , ^{129}I , $^{239/240}\text{Pu}$, ^{237}Np , ^{241}Am , and ^{238}U were calculated using two methodologies: *40 Code of Federal Regulations (CFR) Part 141.16* (CFR, 1999e) and *10 CFR Part 20 Subpart E* (CFR, 1999a). The most restrictive PAL value was then used in this CAIP ([Table 3-39](#)). The preliminary actions levels for tritium and ^{90}Sr were obtained from *40 CFR Part 141.16* (CFR, 1999e). These values represent average annual concentrations assumed to produce a total body or organ dose of 4 mrem/yr. The preliminary action level for lead was obtained from *40 CFR Part 141.80* (CFR, 1999f).

Table 3-39
Preliminary Action Levels for Potential Contaminants

Contaminant	Preliminary Action Level	Regulatory Source for PAL
Tritium	2E+04 pCi/L	40 CFR 141.16 (CFR, 1999b)
Cesium-137	5E+01 pCi/L	40 CFR 141.16 (CFR, 1999b)
Plutonium-239/240	1.6E+00 pCi/L	10 CFR 20 Part E (CFR, 1992a)
Carbon-14	2E+03 pCi/L	40 CFR 141.16 (CFR, 1999b)
Americium-241	1.5E+00 pCi/L	40 CFR 141.16 (CFR, 1999b)
Neptunium-237	1.2E+00 pCi/L	40 CFR 141.16 (CFR, 1999b)
Strontium-90	8E+00 pCi/L	40 CFR 141.16 (CFR, 1999b)
Uranium-238	2.2E+01 pCi/L	10 CFR 20 Part E (CFR, 1992a)
Iodine-129	5E-01 pCi/L	40 CFR 141.16 (CFR, 1999b)
Lead	1.5E+01 µg/L	40 CFR 141.80 (CFR, 1999f)

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

µg/L = Micrograms per liter

4.0 Summary of Data Quality Objectives

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

4.1 Data Quality Objectives Approach

The purpose of the DQO process is to define the environmental problem to be solved, identify the information needed to resolve the problem, and then identify an investigation program to gather the missing information. The approach to the definition of the DQOs used for the Yucca Flat/Climax Mine CAU was a logical, orderly progression that resulted in a clear definition of the data needed and corresponding work activities needed to achieve the ultimate objective of the Yucca Flat CAI. As stated in [Section 1.1](#), this objective is the prediction of a contaminant boundary at an acceptable level of uncertainty. A VOIA was conducted in support of the DQO process (IT, 1999c). The VOIA focused on the assessment of activities that could be undertaken to reduce the uncertainty in the prediction of a contaminant boundary for the Yucca Flat/Climax Mine CAU. The regional model (DOE/NV, 1997c) and the FFACO (1996) were also used to support the DQO process (see [Section A.1.1](#) of [Appendix A](#)).

The DQO approach used includes three major steps that are consistent with the three-step method (EPA, 1987). The approach also compares relatively well to the seven-step method (EPA, 1993 and 1994). The VOIA (IT, 1999c) was conducted to fulfill several substeps of the DQO process. A comparison of the method used and its relationship with the EPA methods is presented in [Figure 4-1](#).

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

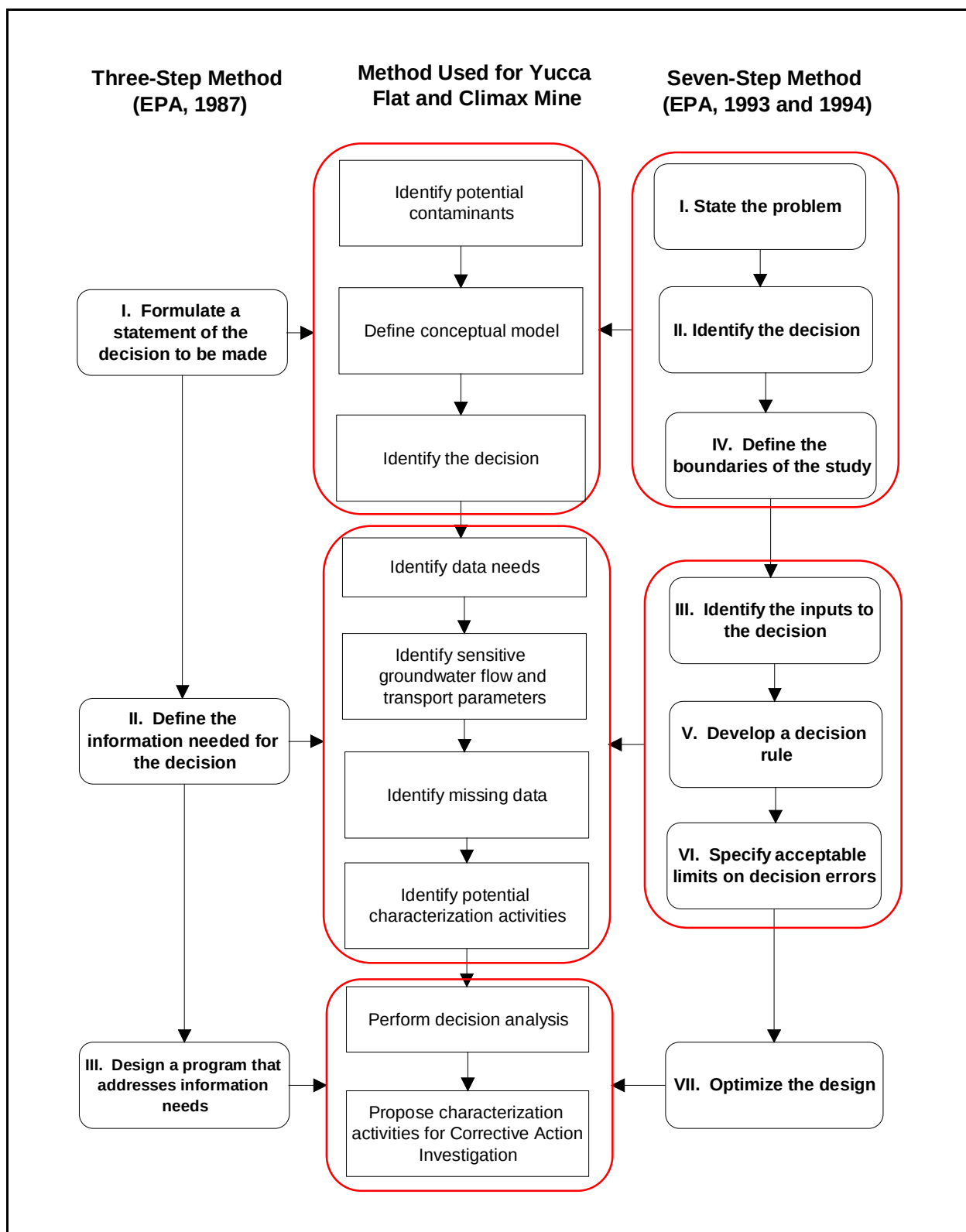


Figure 4-1
Comparison of DQO Method Used for the
Yucca Flat CAI to the EPA Methods

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

The third and last step of the process is the *design of a program that addresses information needs*. This step corresponds to the seventh step of the seven-step process which is to optimize the design by selecting the best candidate characterization activities to be conducted in the Corrective Action Investigation.

4.2 Data Quality Objectives Process Results

The DQO process included several steps which were conducted to plan the CAI for the Yucca Flat/Climax Mine CAU. The results of each step are provided in this section.

4.2.1 Formulation of a Statement of the Decision to be Made

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

- A list of the major potential contaminants is provided in [Table A-2 \(Appendix A\)](#).
- The current conceptual model is based on the regional model (DOE/NV, 1997c) and the VOIA (IT, 1999c), and is described in [Section 3.6](#) of this document and in [Appendix A](#). Supporting information are presented in [Sections 3.3, 3.4, and 3.5](#) of this document.

As discussed in [Appendix A](#), the current CAU conceptual model has several areas of uncertainties which are as follows:

- A lack of subsurface geologic characterization for the entire Yucca Flat area, and a lack of hydrologic characterization in specific areas
- Insufficient characterization of the hydrochemical framework of the Yucca Flat region
- Limited knowledge of the contaminant transport processes and associated parameters
- Limited understanding of the contamination sources

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

4.2.2 Definition of the Information Needed for the Decision

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

The information needed for the decision is that necessary to develop a groundwater flow and contaminant transport model of the problem area that represents reality at an acceptable level of uncertainty. This information consists of geologic data, groundwater data including contamination sources and concentrations in groundwater, and an understanding of the processes that control contaminant migration in groundwater. As stated before, such information was gathered during the regional evaluation (DOE/NV, 1997c) and the Yucca Flat VOIA (IT, 1999c), and used to define the current conceptual model described in the first step of the DQOs. The areas of uncertainty that exist in this conceptual model correspond to data or information gaps identified during the regional evaluation (DOE/NV, 1997c). These include data gaps in uncharacterized portions of the area of interest, and an insufficient understanding of the sources of contamination and the contaminant transport processes at work. Based on these areas of uncertainty, it was determined that an acceptable groundwater flow and transport model could not be formulated for the Yucca Flat groundwater flow system using the existing data only. Additional data were deemed necessary to address the areas of uncertainty.

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

The results indicate that the most sensitive parameters are matrix diffusion in the LCA, hydrologic source term, effective porosity in the LCA, slope multiplier across the VCU to the LCA, and groundwater flux from the north. These parameters are described in [Table A-4 \(Appendix A\)](#). Based

on the conceptual model uncertainties previously described in this section, and the sensitive parameters, the following priority information needs were identified:

- TCU extent and mineralogy
- Structure of basin structures and structures within the basin
- Hydrogeologic data and groundwater chemistry data for the area located in the vicinity of Wells ER-6-1 and ER-6-2
- Verification of the origin and flow paths of groundwater and estimates of travel times from the Yucca Flat area to the discharge areas
- Estimates of transport parameters, including effective porosity, dispersivity, matrix diffusion, adsorption and colloidal transport
- Improved phenomenological models

A VOIA was performed to determine what characterization options would be best-suited to improve the conceptual model of the Yucca Flat area. Characterization options included individual activities and groups of activities designed to reduce uncertainty in sensitive parameters. A list of the individual activities is provided in [Section A-5 \(Appendix A\)](#). All characterization options are described in detail in the VOIA report (IT, 1999c).

All data collected during these activities for purposes of improving the CAU model of the Yucca Flat and Climax Mine areas must be collected using stringent quality assurance (QA) procedures specified in a Quality Assurance Project Plan (QAPP).

4.2.3 Design of a Program that Addresses Information Needs

Further analyses conducted during the VOIA (IT, 1999c) and the results of the regional evaluation (DOE/NV, 1997c) were then used as tools to design a program that addresses the information needs.

During the VOIA (IT, 1999c), the characterization options identified in the second step of the DQO process were evaluated and compared with respect to their cost and potential to reduce uncertainty associated with the contaminant boundary. During this analysis, the execution costs of the characterization options were compared with their usefulness in reducing uncertainty, and the options were ranked.

Characterization activities were selected for inclusion in the Yucca Flat Corrective Action Investigation based on the results of the VOIA (IT, 1999c) and other DOE concerns and responsibilities. All characterization data collected during these activities for purposes of developing the CAU model of Yucca Flat/Climax Mine area will be in compliance with the QAPP (DOE/NV, 2000). The selected characterization activities are listed in [Section A-6 \(Appendix A\)](#) and described in [Section 6.1](#). Brief summary descriptions of the activities are as follows:

Characterization Activity 1: Mineralogy Study of the Tuff Confining Unit

The purpose of this activity is to define the extent, and physical and mineralogic nature of the VCU. The determination of the extent and physical nature of the VCU will be used to construct the hydrostratigraphic model for the Yucca Flat area. The determination of the mineralogic properties of the VCU will help in the assessment the retardation capacity of the TCU.

Characterization Activity 2: Geophysical Interpretation of the Paleozoic Framework

The purpose of this activity is to investigate the geologic structure and stratigraphy of the Paleozoic framework in the Yucca Flat area. The new information will be used to develop the CAU-scale hydrostratigraphic model.

Characterization Activity 3: Analysis of Existing Seismic Data

The purpose of this activity is to provide a better definition of key structural features such as fault locations and HSU pinchouts or juxtapositions that may influence groundwater flow and contaminant transport in the Yucca Flat area. The information will be used to construct the CAU-scale hydrostratigraphic model.

Characterization Activity 4: Hydrogeologic Investigation of Wells ER-6-1 and ER-6-2

The purpose of this activity is to investigate the hydrology and chemistry of two existing wells: ER-6-1 and ER-6-2. The hydrologic and geochemical information will be used in the development of the CAU-scale groundwater flow model. Any applicable radiochemical information will be used in the development of the CAU-scale contaminant transport model.

Characterization Option 5: Isotopic and Geochemistry-Based Investigation

The purpose of this investigation is the verification of groundwater flow paths at the Yucca Flat and Climax Mine underground test areas using geochemical data, and the estimation of travel times using ^{14}C data. The results of this activity will be used to verify the results of the CAU-scale groundwater flow and contaminant transport model.

Characterization Activity 6: Analysis of Existing Tracer Test Data

The purpose of this activity is to measure transport parameters such as effective porosity, dispersivity, and matrix diffusion for representative HSUs of the Yucca Flat groundwater flow system. The results will be used to develop the CAU-scale contaminant transport model.

Characterization Activity 7: Laboratory Studies of Transport Processes

The purpose of this activity is to obtain laboratory estimates of radionuclide transport parameters such as matrix diffusion, dispersion, sorption, and estimates of parameters describing colloid transport processes. The results of these experiments will be used in the CAU-scale contaminant transport model.

Characterization Activity 8: Rainier Mesa Colloid Studies

The purpose of this activity is to develop a better understanding of the geochemical and radiochemical controls on the movement of radionuclides under ambient flow conditions. The activity will be focussed on colloid-facilitated radionuclide transport. The results of this activity will be used to develop more credible contaminant transport models.

Characterization Activity 9: Analysis of Data for Phenomenological Models

The purpose of this task is to improve the current conceptual phenomenological models. The activity includes the evaluation of the measured dynamics of nuclear tests and pretest calculations to better understand potential radionuclide transport mechanisms (i.e., prompt injection); and factors affecting pathways (i.e., slow collapse, chimneys, tensile fracturing distances), and radionuclide deposition (i.e., bedding planes, fractures, faults). This information will be used to help define the hydrologic source term appropriate for use in the near-field models.

4.3 Relationship Between Data Collection Activities and Conceptual Model

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

The first three characterization activities will address the major uncertainties that exist within the geologic framework of the area covering the Yucca Flat area and vicinity. Characterization of the TCU is extremely important because most migration routes from the underground test areas are expected to cross the TCU which is believed to significantly retard contaminant transport. Therefore, knowledge of its extent and nature are paramount to making credible predictions of the location of the contaminant boundary. Characterization of the structure of the area will help in the construction of a more realistic groundwater flow model, which will provide a better definition of the migration routes.

Characterization Activity 4 will allow refinement of the estimates of hydraulic and geochemical information about the groundwater flow system in the vicinity of the testing areas. Better estimates of hydraulic and geochemical information will be used in the development of the CAU-scale groundwater flow model. They will provide better definitions of the migration pathlines and estimates of the groundwater flux, an essential parameter in the determination of the migration rate and the ultimate location of the contaminant boundary. This activity may also provide radiochemical data that may be useful in the development of the contaminant transport model.

Characterization Activities 5, 6, 7, and 8 will provide site-specific information on essential transport processes and associated parameters, namely advective transport, dispersion, matrix diffusion, and colloidal transport. These processes control the contaminant rates of migration. Advective transport is the basis of contaminant transport. Without it contaminant movement does not occur. Advective transport is controlled by the rate of water movement (or groundwater flux) and the effective porosity of the geologic media. Therefore, estimates of site-specific effective porosity are extremely

important in simulating contaminant transport rates. Matrix diffusion was found to be one of the most important processes in the simulation of the rate of contaminant migration and, therefore, the location of the contaminant boundary. Colloidal transport is an important transport process because it has the potential to cause accelerated migration of contaminants that would otherwise be immobile. The proposed activities will help understand and quantify this process.

Characterization Activity 9 is designed to improve the current understanding of the contamination release mechanisms from the source term into groundwater. This activity will reduce some of the uncertainties associated with the sources of contamination. The phenomenological models will provide better descriptions of the near-field environment, leading to a better definition of the source term in the near-field models.

5.0 Corrective Action Investigation

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

5.1 Groundwater Flow and Contaminant Transport Model

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

5.1.1 Overview of Modeling Process

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

The objectives of the Yucca Flat/Climax Mine CAU model are as follows:

- Develop a CAU model that integrates a wide variety of data into a mass conservative description of contaminant migration in groundwater from underground nuclear test locations in a CAU.
- Simulate, as output, the concentration of individual contaminants downgradient of underground test locations over a time period of 1,000 years. These concentrations will be used to define a contaminant boundary based on a 4 mrem/yr composite dose.
- Quantify the uncertainty in concentrations and contaminant boundary location.

- Serve as a tool to evaluate impacts of future flow system changes on the migration of contaminants in the CAU.

As shown in [Figure 5-1](#), the major tasks in the modeling process for the Yucca Flat/Climax Mine CAU are data acquisition, data assessment, model (or code) selection, hydrostratigraphic framework model development, groundwater flow model development, contaminant transport model development, sensitivity analyses, uncertainty analysis, model validation, and contaminant boundary prediction.

The end of each modeling step corresponds to a major decision point during the modeling process. The findings of each modeling step are documented in a product which is either a technical report (or portion of a report), a plan, or an FFACO document ([Table 5-1](#)). These products are then reviewed by the DOE/NV UGTA Project Manager, NDEP, modeling experts, and representatives of the TWG, as appropriate. The decisions are then made by the DOE/NV UGTA Project Manager based on the results of the product review for each modeling step. A schedule for the Yucca Flat/Climax Mine CAI will be prepared in the future. The Yucca Flat/Climax Mine CAI work will not be initiated until the CAI activities currently underway at Frenchman Flat and Pahute Mesa are completed. The DOE/NV will provide NDEP with the schedule at that time, and will keep NDEP informed of the progress of all CAI activities.

The data acquisition step includes several studies designed to obtain new data needed to fill the information gaps identified for the Yucca Flat/Climax Mine CAU during the DQO process described in [Section 4.0](#) and [Appendix A](#). The field and laboratory data collected during these activities will be assessed along with the existing data as described in the following text. Additional details on the field and laboratory studies are provided in [Section 6.1](#).

The data assessment task consists of compiling and evaluating relevant data for use in the CAU model ([Figure 5-2](#)). The specific data required for the CAU model are presented in [Sections 5.1.3.2.1](#) and [5.1.3.3.1](#). The relevant data for the CAU model will come from the following sources:

- Data used to prepare this CAIP ([Section 3.0](#)) including data from relevant wells and springs are shown in [Figure 3-1](#)

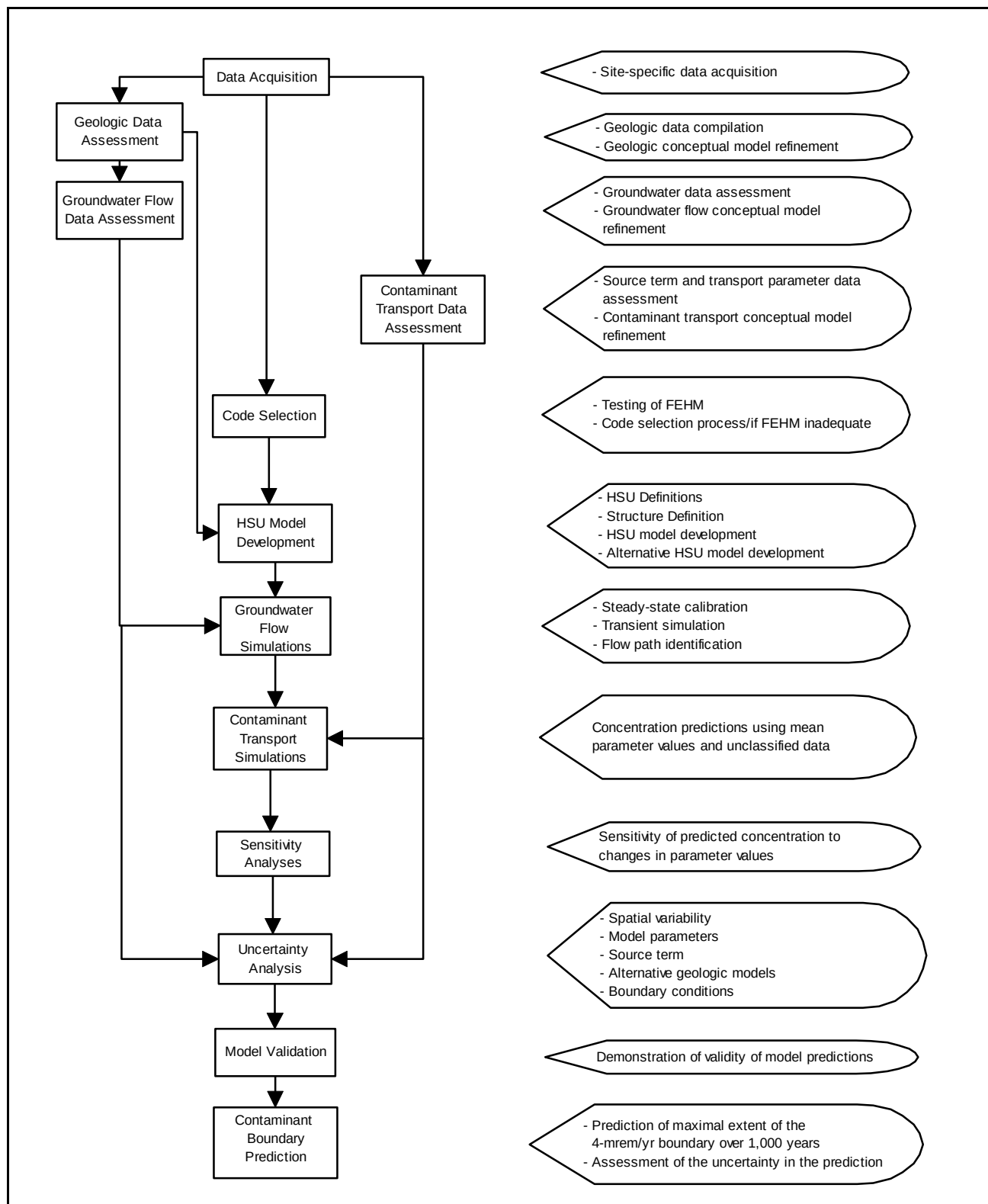


Figure 5-1
Modeling Process for the Yucca Flat/Climax Mine CAU

**Table 5-1
Modeling Products**

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

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

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

Following data gathering and compilation, the data will be screened for quality. The screening process includes data documentation evaluation and data quality evaluation. The data documentation evaluation is described in [Section 7.0](#). The method of data quality evaluation varies with the criteria

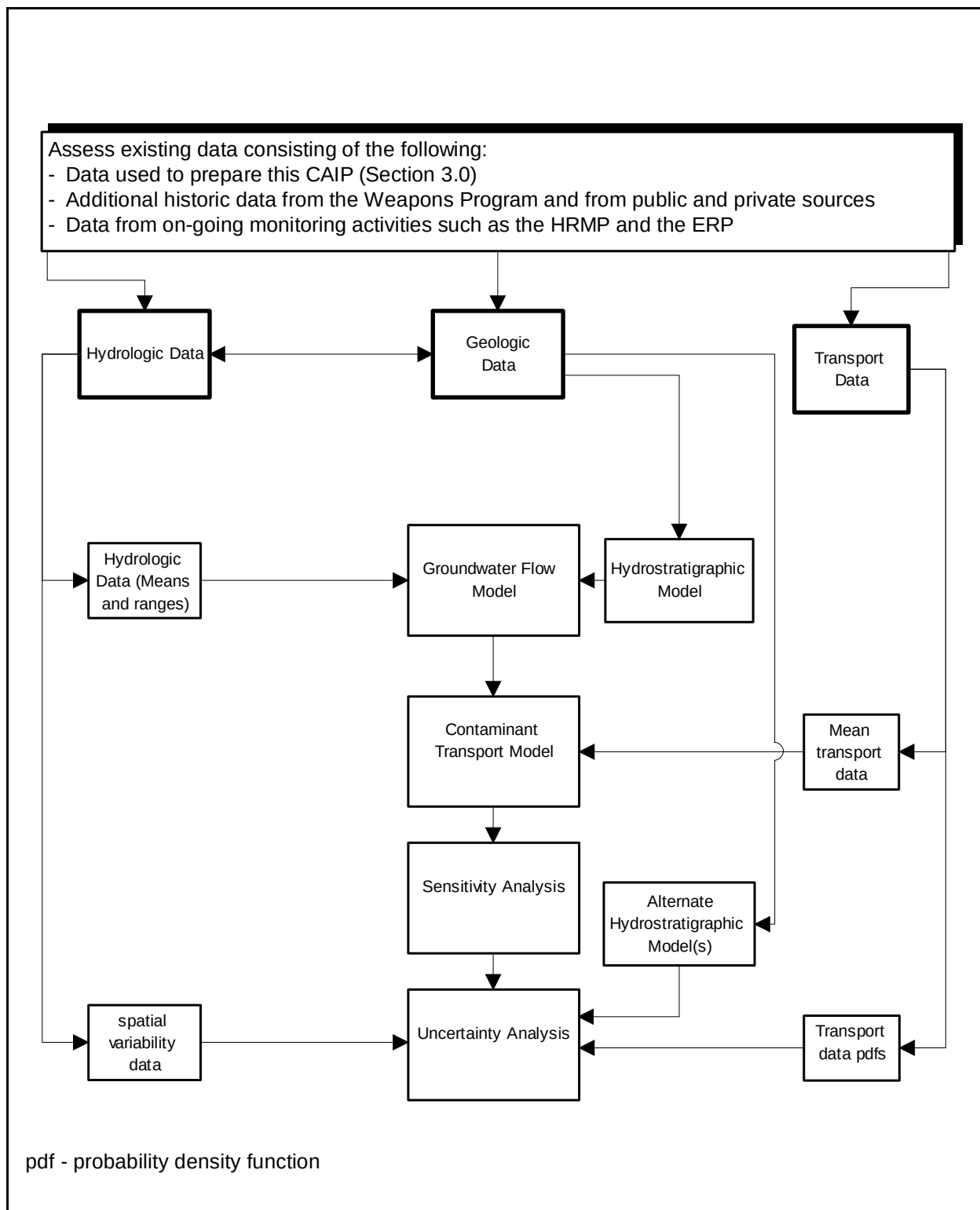


Figure 5-2
Data Utilization During the CAU-Modeling Process

for the data and the intended use of the data. Thus, a variety of criteria will be used to evaluate data quality. As a result of this evaluation procedure, one or more flags will be assigned to each record compiled in the database, indicating the data quality or suitability of the individual data record for a specific intended use.

Descriptions of the specific data types needed for the groundwater flow model and the contaminant transport model and their utilization during the modeling process are presented in [Sections 5.1.3.2.1](#) and [5.1.3.3.1](#). A detailed discussion of the data assessment process will be presented in the documentation packages which will explain the findings of the Yucca Flat/Climax Mine CAI. The interface between the data and the model includes attributes such as scale of measurement and uncertainty. Some of these attributes will be addressed in the data documentation and other attributes will be presented in the model documentation.

Code selection is the process used to identify the computer code that will be used to simulate contaminant migration at the CAU-scale. Code selection is conducted in parallel with the data acquisition and assessment processes ([Figure 5-2](#)). The Yucca Flat/Climax Mine code selection process will depend on the assessment of the application of the code FEHM (Zyvoloski et al., 1997b) to the Pahute Mesa CAUs. If the FEHM application to Pahute Mesa is acceptable, FEHM will be tested with an example problem designed to represent conditions in the Yucca Flat/Climax Mine area. If the test is successful, then FEHM will be chosen as the code for the simulation of groundwater flow and radionuclide transport in the Yucca Flat/Climax Mine area and code selection will be completed. If FEHM is not acceptable, then the code selection process will move into a second phase by defining a set of required and desirable code attributes, identifying a set of available codes, and selecting three of these codes for further evaluation. The second phase continues by defining a set of testing criteria and testing the three selected codes. The final code selection is based on the results of the testing. Details on the code selection process for the Yucca Flat/Climax Mine CAU is described in [Section 5.1.2](#).

Following completion of the data assessment process and the final code selection, the groundwater flow model and the contaminant transport models are constructed. Both the groundwater flow model and the contaminant transport model constructions include model setup and model calibration. Model setup consists of preparing the relevant data for input to the CAU model. Model calibration is

the process of adjusting input parameters until the model results match the observed behavior of the groundwater flow system within predefined limits of acceptability. The construction of the two components of the CAU model are described in [Sections 5.1.3.2.2, 5.1.3.2.3, 5.1.3.3.2, and 5.1.3.3.3.](#)

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

Uncertainty analyses will follow the sensitivity analyses. The purpose of these analyses is to quantify the level of uncertainty associated with the CAU-modeling results. The uncertainty of the predicted contaminant concentrations and the location of the contaminant boundary is caused by the uncertainties in the data used to build the CAU model. Model result uncertainties caused by uncertainties in the CAU hydrostratigraphic model, source term, parameter values, and boundary conditions will be evaluated as described in [Section 5.1.3.5.](#) Alternative hydrostratigraphic and conceptual hydrologic models will be evaluated as part of the uncertainty analyses.

During the validation process, DOE/NV, NDEP, and a panel of peers will review the modeling approach and results following completion of the CAU model. If DOE/NV and NDEP do not provide written justification for rejecting the CAU model, a plan for verifying the CAU model will be developed, sent to NDEP for approval, and executed. The model validation process is detailed in [Section 5.1.4.](#)

Once the CAU model is validated to DOE/NV's and NDEP's satisfaction, the location of the contaminant boundary will be calculated. The maximal extent of the 4-mrem/yr boundary over 1,000 years and the uncertainty in the prediction will be calculated using the concentrations simulated by the CAU model as explained in [Section 5.1.5.](#)

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

5.1.2 Model Selection

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

The selection process will follow one of two tracks depending on the acceptability of the code FEHM, which was chosen to simulate the Pahute Mesa groundwater flow system (DOE/NV, 1999b).

[Figure 5-3](#) outlines the code selection process for the Yucca Flat/Climax Mine area. The first step (in the upper left hand corner of [Figure 5-3](#)) is an assessment of how well FEHM performed in the simulation of radionuclide transport in groundwater of the Pahute Mesa CAUs. If the FEHM performance is deemed acceptable, then an example problem representing conditions in the Yucca Flat/Climax Mine area will be created to test FEHM for applicability to the Yucca Flat/Climax Mine CAU. If the test is successful, then FEHM will be chosen as the code for simulating the flow and transport in the Yucca Flat/Climax Mine area. However, if FEHM is deemed unacceptable, then the code selection process will move into a second phase with the identification of candidate codes and the selection of the three best-qualified codes based on the set of code attributes identified in [Section 5.1.2.2](#). These three codes will then be tested by application to an example problem designed to simulate conditions in the Yucca Flat/Climax Mine area and the final code selection will be made.

5.1.2.1 Assessment of FEHM Acceptability

As presented in the Pahute Mesa CAIP (DOE/NV, 1999b), the code FEHM (Zyvoloski et al., 1997b) was chosen to simulate the groundwater flow and radionuclide transport for the Pahute Mesa CAUs. The processes of interest for the Yucca Flat/Climax Mine area are the same as those for the Pahute

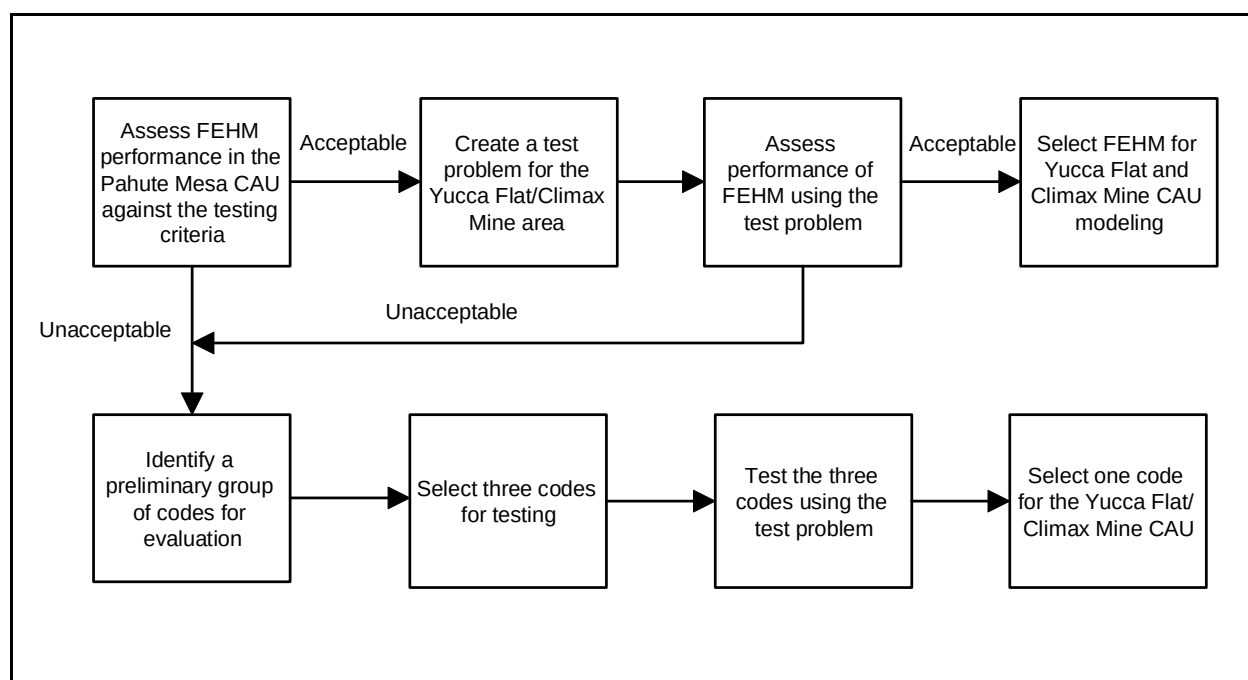


Figure 5-3
Code Selection Process for the Yucca Flat/Climax Mine CAU Model

Mesa area. Therefore, it is expected that if FEHM is acceptable for the Pahute Mesa CAUs, it will be acceptable for the Yucca Flat/Climax Mine CAU also.

It is anticipated that application and assessment of FEHM to the Pahute Mesa CAUs will be available before the Yucca Flat/Climax Mine code selection is completed. The first step is to evaluate the application of FEHM to the Pahute Mesa CAUs to determine if the application is acceptable. Acceptability will be defined by comparison to code testing criteria (defined in [Section 5.1.2.4.1](#)), with particular emphasis on the ability to represent CAU hydrogeology and speed of simulation. If FEHM is acceptable, then a test problem will be created to represent the unique features of the Yucca Flat/Climax Mine area. FEHM will be run with the test problem to determine if there are any operational constraints that were unnoticed in the Pahute Mesa Application. If the application of FEHM to the Yucca Flat/Climax Mine test problem is deemed acceptable, then FEHM will be the code chosen for the Yucca Flat/Climax Mine CAU modeling and code evaluation will halt.

If the FEHM is found to be unacceptable for application to the Yucca Flat/Climax Mine area, the code selection moves into a second phase where the process identified below will be initiated. The code attributes identified in [Section 5.1.2.2](#) will be used to screen a list of candidate codes and to rank the

codes in order of preference. The list of candidate codes will not be presented at this time because the code selection is planned for the future and advances in existing codes and development of new codes may make any current list obsolete at the time the code evaluation is performed.

5.1.2.2 Code Attributes

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

5.1.2.2.1 General Attributes

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

Fully Three-Dimensional

The groundwater flow system is controlled by the distribution of geologic units as well as the location of sources and sinks of water. Additionally, transport properties including source location and strength, porosity, and diffusion may vary in space. The 3-D nature of the groundwater flow system

requires that the CAU model be 3-D to adequately simulate migration of the potential contaminants within the CAU-model area.

Table 5-2
Required Hydrologic Code Attributes^a

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

^aOrder of attributes does not indicate order of importance.

Large Numbers of Nodes Capability

The greater the number of nodes in the CAU model, the greater the detail that can be included. Given the anticipated large geographic area of the Yucca Flat/Climax Mine CAU model (to as far south as the Amargosa Desert), the ability of the CAU model to simulate many nodes will control the amount of detail that can be included and reduce errors caused by source dilution.

Multiple Boundary Condition Options

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

Transient Capability

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

Efficient Solver

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

Acceptable Numerical Accuracy

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

Minimal Numerical Dispersion

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

Acceptable Verification and Validation

The degree of computer code verification and validation varies widely depending on the code being considered. The extent to which this process has been documented for a particular code varies even

more. Thoroughly documented testing is required to ensure that the code satisfies requirements specified for its options and features.

Access to Source Code

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

5.1.2.2.2 Groundwater Flow Model Attributes

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

Saturated Groundwater Flow

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

Heterogeneous and Anisotropic Hydraulic Conductivity

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

Point and Distributed Sources and Sinks of Water

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

Temperature Dependence

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

Simulate Complex Geology

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

5.1.2.2.3 Transport Model Attributes

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

Advection, Dispersion, Sorption, and Matrix Diffusion

The primary processes of interest in the Yucca Flat/Climax Mine groundwater flow system that are expected to influence the concentration of radionuclides in groundwater are listed in this section. The

regional contaminant transport model (IT, 1996h) simulations and the VOIA (IT, 1998c and IT, 1999c) showed that advection (via the groundwater flux) and matrix diffusion were the primary factors influencing tritium transport in fractured media. It is expected that sorption will also be important for reactive contaminants, but this may not be the dominant contributor to the location of the contaminant boundary. Longitudinal dispersion was not shown to be of primary importance in the regional simulations, but is included here because it may be more important at smaller scales.

Radioactive Decay

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

Transport of Colloids

The movement of colloids may enhance the movement of otherwise immobile contaminants. As discussed in [Section 3.0](#), colloids are submicron size particles to which radionuclides or other solutes sorb. The colloids are then transported via the groundwater flow, and the sorbed solutes move with the colloids. Currently, FEHM is the only contaminant transport code known to explicitly simulate the transport of colloids while meeting all of the code attributes.

5.1.2.2.4 Desirable Attributes

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

Finite Element Formulation

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

Steady-State Capability

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

Double-Porosity/Double Permeability Formulation

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

Multiple Solutes

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

Daughter Products

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

Established Pre- and Postprocessors

Pre- and postprocessors are computer codes used to facilitate the data manipulations that are made before and after a given numerical model is used. Preprocessors are used to transform the input data into a form that is required by the model. Postprocessors are used to aid in the interpretation of the model output. Typically, postprocessors are used to create graphic images of some simulated

variables such as hydraulic heads or solute concentrations. Pre- and postprocessors generally speed up the modeling task. If the processors are not available, then the appropriate processors would be developed.

5.1.2.3 Code Identification and Preliminary Selection

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

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

5.1.2.4 Testing of the Codes and Final Code Selection

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

5.1.2.4.1 Testing Criteria

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

Portability

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

QA Evaluation

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

Ease of Use

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

Ability to Represent the CAU Hydrogeology

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

Speed of Simulation

The time required for a solution is also of importance to the evaluation of the codes. The faster the code, the shorter the time to complete each model run. As calibration normally requires many (often greater than 100) model runs, the simulation time becomes a problem if it is too long. For the purposes of the CAU model, simulation times less than six hours for a steady-state flow simulation are acceptable. This length of simulation time will allow for two or three runs per day, which provides sufficient time to perform the calibration assuming up to 200 runs to calibrate.

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

5.1.2.4.2 Test Problem

A test problem will be created to evaluate the acceptability of FEHM to simulate groundwater in the Yucca Flat/Climax Mine flow system. In the case that FEHM is not acceptable, this problem will be used to test candidate codes. This testing of the code is in addition to documented code validation and verification where the code is compared with existing solutions to test its accuracy. The test problem goes beyond code evaluation to assess the applicability of the code to the specific situation in the Yucca Flat/Climax Mine area. The goal of the test problem is to identify deficiencies, quirks, or other features of a code that may cause difficulties in applying the code to the Yucca Flat/Climax Mine CAU. The features of the test problem will be chosen to mimic the conditions expected in the Yucca Flat/Climax Mine model area. By doing so, the effort to set up and run the problem could be evaluated as well as the assessment of the run times of the model. The features to be included in the

test problem include: complex geology such as lithologic and structural features, temperature-dependent flow, radionuclide migration from a cavity, and matrix diffusion.

The test problem will be designed to mimic the expected level of complexity anticipated for the Yucca Flat/Climax Mine area. A portion of the Yucca Flat/Climax Mine CAU hydrostratigraphic model, large enough to be representative of the CAU, will be selected for the comparison. The test model area will have the same boundary conditions along all sides as anticipated for the CAU model. The hydraulic heads along the boundaries will be obtained from observed data where available or from the regional groundwater flow model. The HSU model for the test problem will include all the hydrostratigraphic layers in the Yucca Flat/Climax Mine hydrostratigraphic model, as well as many of the faults. Each of the HSUs will be assigned a hydraulic conductivity consistent with values obtained from the regional flow model (IT, 1997b).

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

5.1.3 Model Discussion/Documentation/Data Availability

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

5.1.3.1 Description of the Candidate Code

Based on current information, the only code identified for use in the Yucca Flat/Climax Mine CAU model is FEHM (Zyvoloski et al., 1997b). If FEHM is deemed unacceptable, three codes will be selected from a larger number of possible codes by a review of the literature and discussions with members of the TWG Modeling Subcommittee (TWG/MS). Candidate codes will be selected because of their ability to meet most or all of the code selection attributes described in [Section 5.1.2.2](#). The other five testing criteria (i.e. portability, level of QA testing, ease of use, ability

to represent CAU Hydrogeology, and speed of simulation) will be assessed during the creation and execution of the test problem. If FEHM is deemed acceptable for the Pahute Mesa CAUs, it will be tested by simulating a Yucca Flat/Climax Mine example problem. If FEHM is deemed unacceptable, three candidate codes will be selected for testing and evaluated against the testing criteria in [Section 5.1.2.4.1](#). One of the three codes will be recommended to DOE/NV as the code for the Yucca Flat/Climax Mine CAU modeling.

The FEHM code (Zyvoloski et al., 1997b), developed by Los Alamos National Laboratory, simulates 3-D, time-dependent, multiphase, multicomponent, nonisothermal, reactive groundwater flow through porous and fractured media. FEHM's finite element formulation provides an accurate representation of complex 3-D geologic media and structures and their effects on subsurface flow and transport. Specific capabilities include:

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

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

5.1.3.2 Groundwater Flow Model Development

This section describes the groundwater flow model development process. The discussion of the modeling process is generic in the sense that the final code selection has not been made. The process outlined will apply to any codes. The goal of the groundwater flow model is to simulate the movement of water in and around the Yucca Flat/Climax Mine CAU. The groundwater flow model

will define the pathways from the underground test locations and provide the flux input to the transport model which will be used to simulate the concentration of contaminants in the groundwater system. The model development process includes data assessment, model setup, and model calibration.

5.1.3.2.1 Groundwater Flow Data Assessment

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

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

Geologic Data

A hydrostratigraphic model of the Yucca Flat/Climax Mine region will be constructed to define the framework of the groundwater flow system. The methodology to be used consists of geologic data compilation, conceptual hydrogeologic model development, and digital HSU model development. A process similar to the one used to create the regional HSU model (IT, 1996f) will be used to create the Yucca Flat/Climax Mine CAU-scale HSU model. Some process changes will be made, particularly with respect to the model platform (ERMA versus EarthVision), but the selection of HSUs and interpretation of the geology will remain largely the same. Existing and newly-acquired geologic

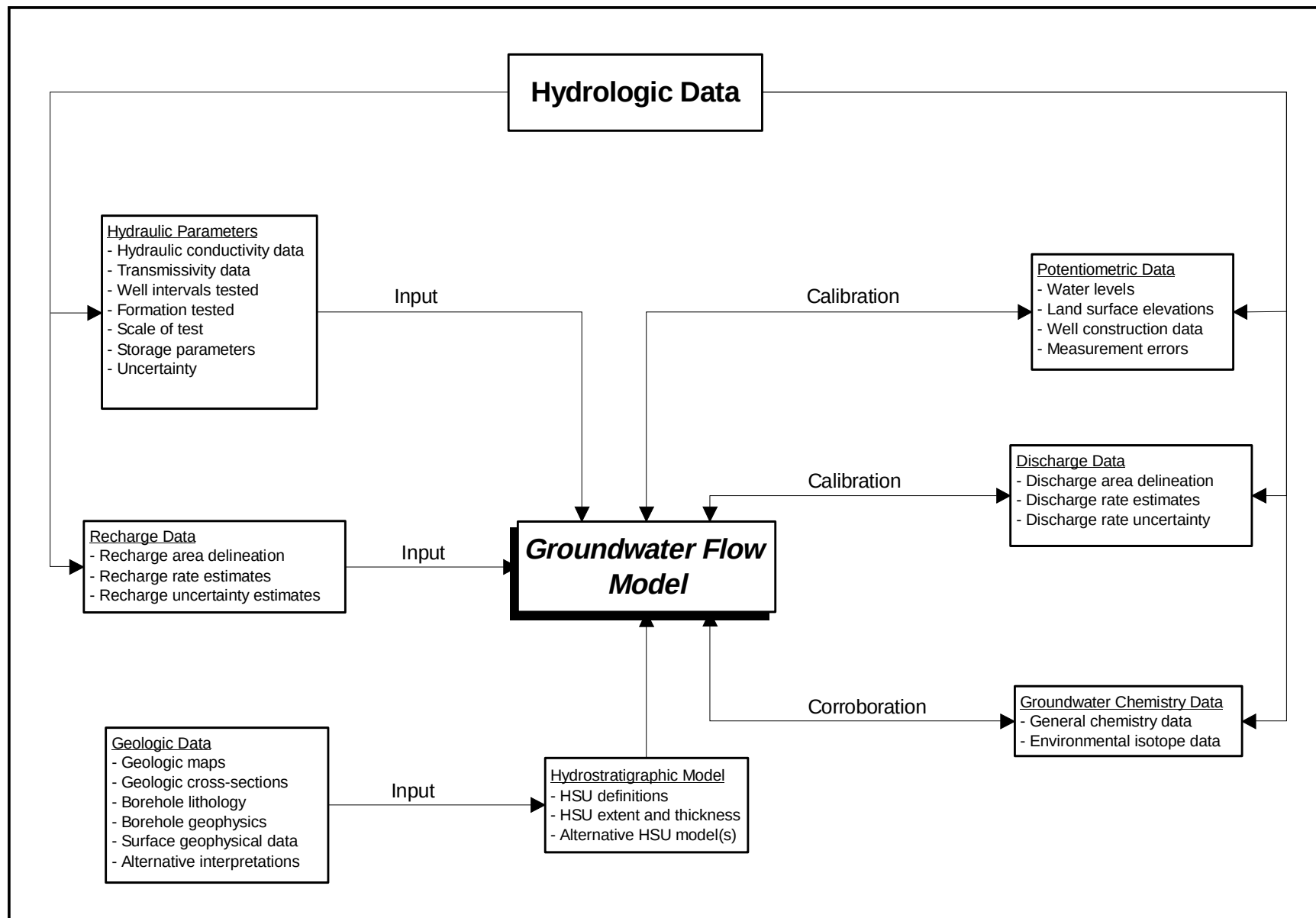


Figure 5-4
Data Types and Utilization in the Groundwater Flow Model
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data will be compiled and evaluated. To develop the conceptual hydrostratigraphic model, detailed structural cross sections will be drawn to depict structural and stratigraphic features and will then be simplified to focus on HSU relationships. To construct these HSU cross sections, hydrologically similar geologic units will be combined into HSUs, and only the HSUs and hydrologically significant structures will be depicted. The geologic data and digitized HSU cross sections will be integrated into a 3-D digital HSU model. The HSU model will provide HSU thicknesses to be used in the design of the groundwater flow model layers. During this process, alternative HSU framework models will be defined to account for the range in possible framework interpretations. These alternative framework models will be used to assess uncertainty in CAU model predictions resulting from uncertainty in HSU areal extent, thickness, structural relationships, and material properties.

Hydraulic Heads

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

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

The calibration process involves modifying input parameters such as recharge and hydraulic conductivity until the calculated hydraulic head matches the observed head, within prespecified limits. For the steady-state calibration, a set of observed average hydraulic heads will be determined

from the dataset by selecting an appropriate range in which the measurements appear to be stable and approximately consistent with expected prepumping and pretesting conditions. This is the same process that was followed for the determination of target hydraulic heads for the regional groundwater flow model calibration (IT, 1997b).

After the steady-state model is calibrated, additional simulations will be performed to examine transient effects. In the transient simulations, the pumpage from water supply wells will be included and hydraulic head changes, with time, will be simulated. The simulated hydraulic heads changes will be compared with the measured hydraulic head changes over time.

Boundary Fluxes and Recharge

There are two sources of water entering the Yucca Flat/Climax Mine CAU model area. The first is flow across the CAU-model boundary from neighboring regions, and the second is recharge from local precipitation.

The amount of flow across the CAU model boundary will be bounded using the regional groundwater flow model. The regional model will provide the best approximation of boundary conditions for the CAU model because it integrates the entire flow system into a mass-conservative representation. However, the regional model is uncertain; therefore, the fluxes from the regional model are uncertain. To define the boundary conditions of the Yucca Flat/Climax Mine CAU-model domain, uncertainty analyses will be conducted with the regional model to define the range of boundary fluxes across each boundary face of the CAU model.

The current estimate of areal recharge distribution for the NTS area is derived from the regional model using a modification of the Maxey-Eakin method (Maxey and Eakin, 1949). During the Yucca Flat/Climax Mine data assessment process, this recharge distribution will be considered along with others resulting from studies of groundwater recharge. The findings of these studies may lead to refinements or modifications to the recharge distribution derived from the regional model. Recharge estimation procedures being developed for the Yucca Mountain Project (Flint et al., 1999) will also be considered during the development of a groundwater recharge distribution for the Yucca Flat/Climax Mine area. Additional new work may include precipitation measurements in the uplands surrounding

the Yucca Flat/Climax Mine area and flow monitoring in selected drainages accompanied by neutron probe investigations.

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

Boundary Fluxes and Discharge

Groundwater discharge occurs as either outflow across the CAU-model boundary, discharge to the land surface, or discharge to wells. The flow across the CAU-model boundary will be handled via the determination of boundary conditions using the regional flow model as was described for recharge. Regionally, the discharge to the land surface occurs in the Amargosa Desert, Ash Meadows, and Death Valley. The current discharge estimates are uncertain, but in Ash Meadows and Oasis Valley the discharge estimates have been improved by evapotranspiration measurements conducted by the USGS. The refined discharge measurements will be included in the recalibration of the regional flow model to improve the discharge fluxes. For the CAU model, the discharge from wells will be included in transient simulations even though such discharge is expected to be a minor component of the flow system.

Hydraulic Parameters

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

In the regional flow model (IT, 1997b), the calibrated values were shown to fall within the range of measured values. During the CAU-model calibration, the hydraulic conductivity data will again be used to define a range of possible values. The hydraulic conductivity will not be calibrated on a cell-by-cell basis, but rather will be defined on larger zones that represent similar hydrogeologic conditions. Measured hydraulic conductivity within the zones (which are not yet defined) will be used to place bounds on the range of values. As presented in [Section 3.4.5.2.1](#), the hydraulic conductivity data from Yucca Flat is limited to 14 single well tests. Of those, 10 are in carbonate rocks, two in alluvium or volcanics, and two in confining units. The range of values in the carbonates covers nearly five orders of magnitude. The range of values for the other HSUs is nearly two orders of magnitude, but because of the small number of samples, the actual range is probably larger. The hydraulic conductivity assessment for the regional model (IT, 1997b) presented more than four orders of magnitude variability for the volcanic and alluvium HSUs. The available data represents relatively small scale measurements of hydraulic conductivity, yet the CAU and local models use averaged values of hydraulic conductivity appropriate for larger spatial areas. Vanmarcke (1983, page 382) has shown that the variability of averaged parameters is often much less than the variability in the small scale values. This scale dependent variability will be examined as part of the data analysis and used to limit the range of variability in the hydraulic conductivity values in the local and CAU models.

The Frenchman Flat External Peer Review Report (IT, 1999b) identified the uncertainty in transport predictions resulting from random field simulations to be of second order importance compared with other sources of uncertainty. For example, the external peer reviewers expected that uncertainty in the geologic framework model would be more important than small-scale spatial variability. Nonetheless, some effort will be made to examine the impact of spatial variability on the uncertainty in contaminant boundary predictions.

During the uncertainty analyses, a number of possible hydraulic conductivity fields may be created by DRI to represent possible small-scale distributions of that parameter. These possible random fields will be conditioned on observed values. This means that where measured values are recorded, the generated random field will match the observed value within a specified error range. The random field analyses will be limited to near-field simulations where small-scale variability is most important. Larger-scale variability, characterized by alternative conceptual hydrostratigraphic framework models, will be simulated via the creation of alternative framework models.

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

Geochemistry Data

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

5.1.3.2.2 Model Setup

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

Model Grid

The model grid itself cannot be specified at this time because it will depend on the code that is chosen. However, several guidelines are presented that will be followed after the CAU model is selected.

The scale of the CAU model will be on the order of the Yucca Flat/Climax Mine CAU, and the downgradient area in which the contaminant boundary is likely to occur. The size of the CAU model

will be the minimum necessary to simulate the flow paths of concern. As discussed in [Section 1.2](#), the potential CAU-model area includes the Yucca Flat/Climax Mine CAU, Northwestern Frenchman Flat, CP Basin, Rock Valley, and the Amargosa Desert ([Figure 1-2](#)). Grid cell sizes will vary over the CAU-model area. In the vicinity of the underground tests, the horizontal and vertical spacing will be smaller than on the boundaries of the model. Specific grid spacing dimensions will be defined only after the CAU model is selected.

The Yucca Flat/Climax Mine area offers some unique challenges ranging in scale from small to very large. Such challenges include the source term, flow along faults, and potential long distances of contaminant transport in the regional aquifer (LCA). To address all the issues of concern in the Yucca Flat/Climax Mine area, more than one model will need to be developed to simulate processes at different scales.

For the purposes of this discussion, four modeling scales are proposed: small scale, intermediate scale, large scale, and very large scale. Small-scale models, also called near-field models, refer to simulations of processes in a portion of the groundwater flow system up to 1 km (3 to 5 cavity radii) around an underground nuclear test. Typically the near-field models will be used to simulate the hydrologic system in the vicinity of the underground tests. The local models will address specific processes at scales up to about 10 km. These models will address questions of flow system interaction such as the influence of faults or the impact of the high pressure zone. One large-scale model, the CAU model, will be designed to simulate groundwater flow and contaminant migration of all the underground tests in Yucca Flat and Climax Mine. This model will be at least as large as Yucca Flat hydrographic basin and may extend downgradient as far as the location of the contaminant boundary. The largest scale model is the regional model. The regional model provides the regional context of the CAU flow system. The regional model will be used to provide boundary condition constraints on the CAU flow system.

Early flow simulations will focus on local models to assess local features such as fault effects, high pressure zones, or flow through confining units. Later, the CAU model will simulate the flow at the CAU scale to provide the prediction of the contaminant boundary.

It is expected that a finite-element code will be selected for the CAU model. The finite-element mesh will be a function of the particular features of each CAU. Features such as the lateral and vertical

distribution of geologic layering and faults are included in the hydrostratigraphic model. To the extent possible, the physical location of layers and faults will be honored by the finite-element mesh. This will provide the maximum level of accuracy regarding contaminant movement near potentially important geologic boundaries.

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

- The external boundary of the CAU model will correspond to appropriate cell boundaries within the regional groundwater flow model. In this way, the boundary conditions from the regional groundwater flow model will be applied to the appropriate CAU-model boundary.
- Grids will be placed as close as practical at each underground test location as well as at specific well locations.
- Grids will be placed along faults that are identified as being important to the distribution of HSUs or impact the flow system.
- The grid density will be greatest in the vicinity of the underground tests, faults (if hydrologically significant), and discharge wells, but will decrease in density at the CAU-model boundaries. The CAU model grid spacing will be no larger than the regional groundwater flow model grid.
- For a finite-element model only, nodes will be preferentially placed along HSU contacts to more precisely incorporate the hydrostratigraphic model structure in the simulations.

Local Models

Several local models may need to be developed to address specific questions in the Yucca Flat/Climax Mine area. For example, a key question to be addressed is the possibility of radionuclide pathways from the AA, VA and VCU into the LCA. The majority of the radionuclides are in the units above the LCA, which because of porosity, hydraulic conductivity, and chemical interaction properties are expected to have slower rates of radionuclide migration than for the LCA. Simulations on the scale of several to 10 km (6 mi) on a side will need to be performed to address pathways into the LCA via faults, holes in confining units, or pathways created by structural displacement. These simulations will be performed to quantify the water flux into the LCA from overlying units.

Another local model of groundwater flow in the central portion of Yucca Flat will be performed to assess the origin and significance of a region of greater than normal fluid pressures. The elevated pressures may reflect HSU consolidation due to underground testing. This may have resulted in reductions in hydraulic conductivity and enhancement of the ability of the units to limit migration of radionuclides because of the reduced groundwater fluxes. The local models will be as complex as necessary to address specific questions or processes. In some cases, these local models may be one or two dimensional and of small areal extent.

After the local models are completed, the CAU model will be developed. The CAU flow model will link the regional model flow system and the local flow system into an integrated flow system at the scale of the Yucca Flat/Climax Mine CAU.

Near-Field Models

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

Boundary Conditions

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

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

It is expected that most of the CAU model boundaries will be defined via specified-head conditions. Without boundary flux constraints, this can lead to unrealistic scenarios because there are no limitations on the amount of water that can cross the model boundary. The regional groundwater flow model will be used to set bounds on the amount of water that can enter the CAU model. First, one or more sets of CAU model boundaries will be defined. Sensitivity analyses of the regional model will be performed to define the parameters that impact fluxes across CAU model boundaries or regional discharge fluxes such as at Ash Meadows or Death Valley. For the sensitive parameters, ranges of values and probability distributions will be defined to encompass a wide range of uncertainty. Monte Carlo simulations with the regional model will be performed and boundary fluxes saved for each realization. The realizations will be screened to remove those that yield physically unrealistic results. For the remaining realizations, the boundary flux statistics will be calculated and will form one estimate of the bounds on the CAU model boundary fluxes. Additional uncertainty in the regional model comes from alternative HSU and hydrologic conceptual models. These may be as simple as increased or decreased recharge or as complex and modifications to the regional HSU model to represent alternative interpretations. Selected alternatives will be included in the regional model boundary flux uncertainty analyses along with the Monte Carlo analyses. In this manner the regional model provides bounds on the CAU model while allowing flexibility in alternative conceptualizations within the CAU model.

The bottom of the CAU model will be no deeper than the regional model (4,000 m [13,120 ft] below sea level). If the bottom is the same as the regional model, then the bottom of the CAU model will be treated as “no flow” as was the case in the regional model. Recent evaluations of the regional groundwater flow model have shown that little flow occurs deep in the model because of the small

values of hydraulic conductivity. As noted in the regional groundwater flow model documentation (IT, 1997b) and the Physical Setting Section ([Section 3.4](#)), the measured hydraulic conductivity data show a trend of decreasing values with depth. The deepest underground test conducted in the Yucca Flat/Climax Mine area has a working point elevation of about 490 m (1,600 ft) above sea level. The CAU-model bottom may be significantly shallower than 4,000 m (13,120 ft) below sea level if it can be shown that very little flow occurs at the larger depths. If so, the regional flow model will be used to define bounds on the fluxes through the bottom of the CAU model.

Finally, the recharge will be initially defined as in the regional groundwater flow model with the option of modifying it to account for increased spatial resolution on recharge provided by ongoing work such as the investigation of recharge being performed by DRI on the NTS.

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

Initial Flow Conditions

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

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

5.1.3.2.3 Groundwater Flow Model Calibration

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

During the model calibration, input parameters will be adjusted until the flow simulation results match site-specific information such as measured water levels and discharge fluxes within predetermined ranges. Input parameters will be adjusted within their known ranges based on data, if sufficient data exist, or based on accepted estimated ranges if data do not exist or are scarce. In accordance with American Society for Testing and Materials (ASTM) Standard Method D-5981-96 (ASTM, 1996a), the range of values for the calibration parameters will be presented in the data documentation packages. The calibration will produce quantitative and qualitative measures of the degree of correspondence between the simulation and site-specific information related to the physical hydrogeologic system. The degree of correspondence between the simulation and the physical hydrogeologic system can then be compared to that for previous simulations to ascertain the success of calibration efforts and, if needed, to identify potentially beneficial directions for further calibration efforts. Quantitative measures of correspondence will be developed based on the analysis of hydraulic head data. This will parallel the same effort that was undertaken for the regional groundwater flow modeling (IT, 1997b).

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

After the above steady-state calibration process is completed, a verification of the calibration will be implemented to verify the steady-state results. In the verification, the drawdown from pumping wells

and other hydraulic transients will be simulated. The effectiveness of the model verification will, however, depend on the accuracy of the groundwater discharge data. It is intended that the transient calibration will serve as the verification of the steady-state groundwater flow model.

The groundwater flow model for the Yucca Flat/Climax Mine area will be calibrated using ASTM standard guidance for calibrating groundwater models. The *Standard Guide for Calibrating a Ground-Water Flow Model Application* (D-5981) (ASTM, 1996a) is a guide for calibrating porous medium (continuum) groundwater flow models. The method can be adjusted to use on other types of groundwater models such as multiphase models, noncontinuum (karst or fracture flow) models, or mass transport models.

The ASTM standard procedures that will be used to implement the guidance cover the use of site-specific information (D-5490) (ASTM, 1994a), applying modeling to site-specific problems (D-5447) (ASTM, 1993), defining boundary (D-5609) (ASTM, 1994c) and initial (D-5610) (ASTM, 1995a) conditions, performing sensitivity analyses (D-5611) (ASTM, 1994b), and documenting groundwater flow model applications (D-5718) (ASTM, 1995b).

5.1.3.3 Contaminant Transport Model Development

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

Transport will be simulated for each of the flow models developed. The near-field models simulate radionuclide release from the melt glass and cavity exchange volume and simulate complex chemical interactions, including aqueous complexation, surface complexation, ion exchange, precipitation and dissolutions reactions along the flow path from the point of release to several cavity radii outside the

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

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

5.1.3.3.1 Contaminant Transport Data Assessment

A wide variety of data types are required to simulate contaminant transport in the groundwater system. As discussed in [Section 5.1.1](#) and shown in [Figure 5-2](#), relevant existing and newly acquired

contaminant transport data will be gathered and compiled into a comprehensive database. The existing and newly acquired CAU-specific data will have the highest priority. However, non-CAU specific data may be included in the development of the conceptual model, particularly to provide additional constraints on parameter uncertainty.

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

Initial Source-Term Conditions

Two source-term datasets will be defined for the Yucca Flat/Climax Mine CAU Model. One source term will be based on unclassified data and will be extrapolated to all underground tests in Yucca Flat and Climax Mine. Later, a classified dataset, based on classified information will be used to calculate the final location of the contaminant boundary.

For the unclassified data, the initial concentration data will be derived from the work conducted by LLNL. Several of the data collection tasks, described in detail in [Section 6.0](#) of this report, may directly or indirectly contribute to improvements in the hydrologic source term. These studies are: (1) Mineralogy Study of the TCU ([Section 6.1.1](#)); (2) Isotope/Geochemistry Mass-Balance Studies ([Section 6.1.5](#)); (3) Laboratory Radionuclide Transport Studies ([Section 6.1.7](#)); and (4) Analysis of Data for Phenomenological Models ([Section 6.1.9](#)). The source term calculated by LLNL is anticipated to provide estimates of the following source term components:

- The spatial distribution of the source term in and near an average test cavity

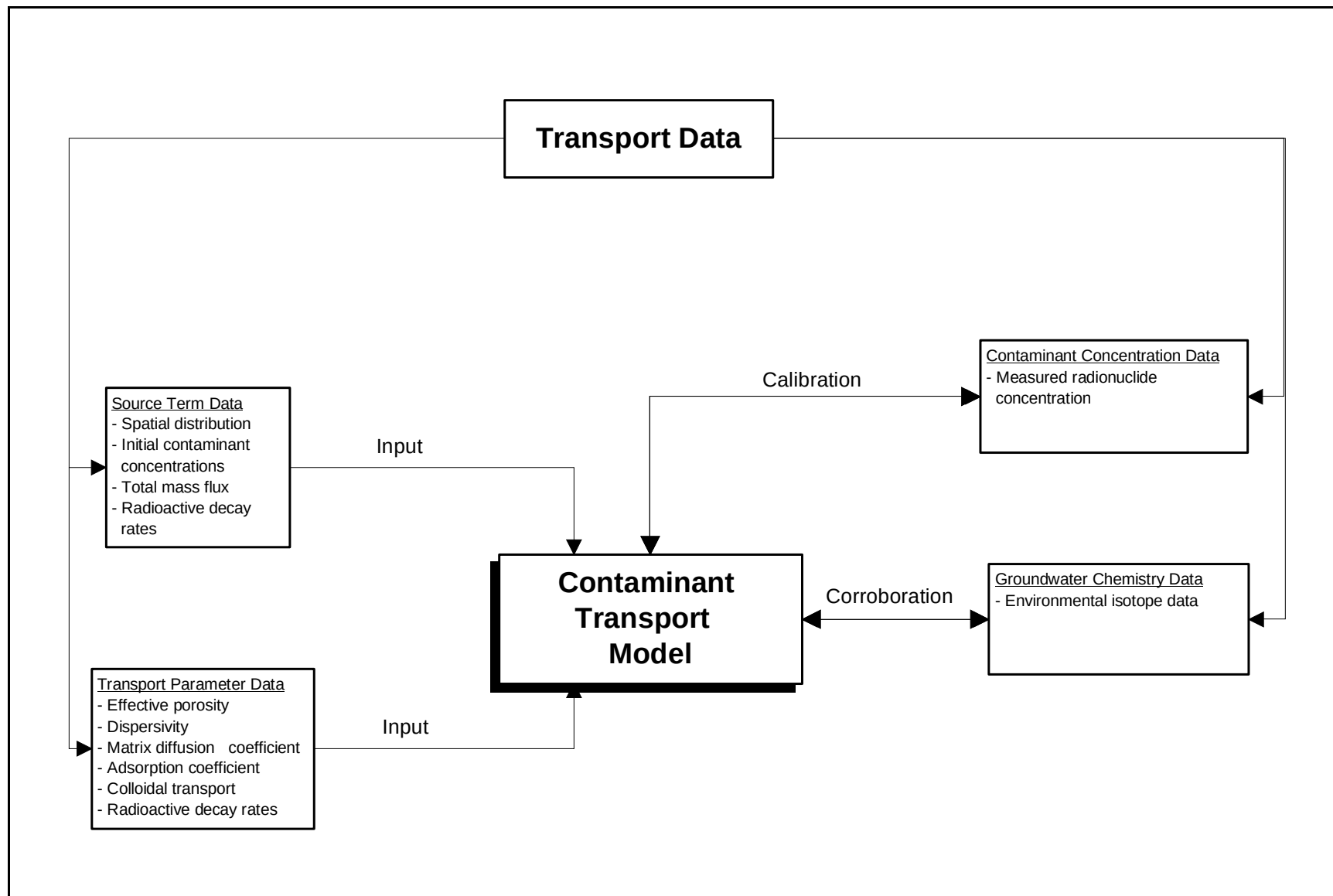


Figure 5-5
Data Types and Utilization in the Contaminant Transport Model

- The concentration of radionuclides dissolved in the groundwater for an average test cavity
- The leach rate for radionuclides currently incorporated into the melt glass
- The release rate of sorbed radionuclides in the rubble

The mobility of radionuclides in the cavity, fracture zone, and the near-field undisturbed zone

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

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

Effective Porosity

The advective velocity of a contaminant (assuming no chemical or diffusion interactions) is the same as the mean water velocity. The water velocity is defined as the groundwater flux (from the flow model) divided by the effective porosity which is a measure of the interconnected pore space through which water and solutes migrate. The effective porosity values for the Yucca Flat/Climax Mine CAU model will come from several sources. First, the data from the BULLION forced-gradient tracer experiment (IT, 1996a, b, and 1998b) will be of primary importance for the fractured VA. Additional supplemental data will come from fracture porosity estimates and an application of the cubic law to fracture data obtained from several studies of fracture characteristics in boreholes and core. The fracture data are available for the LCA from wells ER-6-1 and ER-6-2 (IT, 1996i); the TCU from UE-7f, UE7az, UE7ba, and UE7bc (Prothro, 1998); and for selected volcanic units on Pahute Mesa from holes UE-19x, UE-18t, UE-18r, UE-20e#1, UE-20bh#1, U-20c, UE-20c, UE-20f, ER-20-5#1, and ER-20-2#1 (Drellack et al., 1997). For the LCA, limited additional fracture porosity data are

available from tracer tests in wells WW-C and WW-C-1 as well as from the Amargosa Tracer Test Site (IT, 1996d). Expert elicitation as part of the Yucca Flat/Climax Mine VOIA (IT, 1999c) analyses provides an estimate of the range of effective porosity values for the fractured LCA and fractured VAs. For the porous units such as the AA and the VCU, the core and geophysical log data summarized in reports by Burkhard (1989) and IT (1996g) will be used to estimate effective porosity values. Other sources of information, including Howard (1985) will be examined to compile the final data sets. It is expected that a mean value and uncertainty range will be established for each of the HSUs. For the porous units, the uncertainty ranges will be relatively narrow and well constrained by data. For fractured units, the ranges are expected to be much larger and only poorly constrained.

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

Radioactive Decay Coefficients

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

Distribution Coefficients

The distribution coefficients for each of the potential contaminants will be obtained from published reports of laboratory experiments. Published distribution coefficient values are typically quite

variable (Triay et al., 1993) and, therefore, have a wide range of uncertainty. For the transport simulations, an expected value for each radionuclide will be chosen from the published ranges. Typically, the expected value will be chosen to be conservative (i.e., closer to the low side of the range of values). Although these values are quite uncertain, it is not expected that this will significantly impact the predicted contaminant boundary location. As observed in the Yucca Flat/Climax Mine VOIA (IT, 1999c), the location of the contaminant boundary over a period of 1,000 years was dominated by the most mobile radionuclides. Unless the sorbed radionuclides have a small distribution coefficient, they will lag behind the more mobile radionuclides and contribute significantly to the leading edge of the contaminant boundary.

Matrix Diffusion Coefficients

Based on the regional contaminant transport modeling (IT, 1996h) and the VOIA (IT, 1999c), it is expected that matrix diffusion will be an important mechanism controlling the rate of radionuclide migration and, therefore, the location of the contaminant boundary, particularly in the LCA. The matrix diffusion coefficient controls, in part, the rate at which a contaminant will diffuse from a fracture into the surrounding rock matrix. All things being equal, the faster the diffusion, the slower the contaminant will appear to move relative to the movement of the groundwater. Matrix diffusion coefficient estimates for volcanic units will be available from the BULLION tracer experiment (IT, 1998b). Additional data for volcanic units are available from Reimus et al. (1999). New work in the Yucca Flat/Climax Mine area will provide laboratory measured diffusion data for carbonate rock (described in [Section 6.0](#)). Other measurements of the diffusion coefficient are available from the literature and will be evaluated to assess the range of uncertainty in the matrix diffusion coefficient values. The limited diffusion data available will lead to large uncertainty ranges for the diffusion coefficient.

Matrix Porosity

The matrix porosity defines the volume of water in the matrix into which contaminants can diffuse. The larger the volume, the more contaminant that can diffuse into the matrix and be stored there. Numerous matrix porosity values are available for the geologic units of the Yucca Flat/Climax Mine area. Many of these data are available from core and geophysical logs. The matrix porosity values are uncertain, but the range is typically much smaller than for many of the other parameters. More

data are available for the shallower volcanic units than for the deep LCA. Matrix porosity will be included in the uncertainty analyses, but it is not expected to be one of the dominant parameters.

Description of the Fracture Geometry

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

Colloid-Facilitated Transport

The transport of contaminants via colloids may be an important consideration in fractured HSUs. In previous discussions, it was stated that sorbing nuclides are not likely to impact the determination of the location of the maximum extent of the contaminant boundary because they will travel at a slower rate than non-sorbing nuclides. However, if these sorbing contaminants attach to colloidal-size particles, they can be transported much more rapidly than would otherwise be expected. Research at LANL is being conducted to define a way to measure and simulate colloid transport in groundwater flow systems. If colloid-facilitated transport is deemed an important process, it will be described in the Yucca Flat/Climax Mine CAU model report . Additionally, some of the work described in [Section 6.0](#) will also contribute to an assessment of the role and parameterization of colloids in fractured rock.

Contaminants

Measurements of radionuclide concentrations in water samples may be useful in evaluating the CAU-model predictions. Evidence of radionuclide migration away from test locations, if available, may be compared with the range of simulated results of the CAU model and local models. Additionally, time series of radionuclide concentrations from cavity samples may be of sufficient quality to compare with simulated concentration declines at the same locations. These data will be evaluated to provide further confidence in the simulations. The data presented in [Section 3.4.7.1](#) appear to be sufficient to serve as preliminary comparisons to model results. However, the observed data is incomplete and may not provide complete evaluation of the model predictions.

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

5.1.3.3.2 Transport Model Setup

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

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

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

5.1.3.3.3 *Transport Model Calibration*

Any known groundwater radionuclide concentration data will be evaluated as additional calibration targets. The amount of concentration data is generally quite limited and may not be at an appropriate scale, but every attempt will be made to include existing data. A particular difficulty in calibrating concentration data is that the actual source term for any test is classified. Therefore any comparisons that are made will involve one of two situations: (1) the source term is a generic term not representative of the test and, therefore, not appropriate for calibration or (2) the simulations and comparisons are performed in a classified environment. It is expected that the distance of

radionuclide migration from any cavity at the present time is small compared with the scale of the CAU. Therefore, comparisons of model predictions to observed radionuclide concentrations would be most likely take place at the source term or local scale. It is not expected that meaningful comparisons could be made with the CAU model.

5.1.3.4 Sensitivity Analyses

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

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

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

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

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

5.1.3.5 Assessment of Uncertainty

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

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

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

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

will be identified by the interaction of the CAU modelers with the source-term modeling group from LLNL.

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

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

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

The small-scale spatial variability can be described statistically via 3-D random fields (Pohlmann and Andricevic, 1994; Shirley et al., 1996). Using borehole, core, and geophysical log data, a statistical description of these random fields can be estimated. The DRI uses this statistical description to generate equiprobable alternative random fields that honor measured data but create a series of possible values away from the measured data. These possible values (called realizations) describe the uncertainty in the spatial variation of the hydraulic conductivity. These random fields can be used to

asses the impact of random fields on the range of effective models parameters appropriate for the local or CAU scale modeling. These effective parameters will be described by probability functions representing the range of uncertainty.

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

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

Assessment of sources of uncertainty that cannot be described via a probability distribution will be included in a different manner. The alternative interpretations of the HSU or conceptual hydrologic models, for example, will be described by a limited number of interpretations, not by a probability

distribution. In these cases, the simulation of contaminant concentrations for each alternative provides a quantitative change in a measure (e.g. contaminant concentration contours), but does not provide a probabilistic assessment like the Monte Carlo approach does. The amount of change in the contaminant concentration contours from an alternative HSU model will be compared with the Monte Carlo results to identify the comparable change due to parameter uncertainty. For example, if an alternative hydrostratigraphic model resulted in a 500 m (1,640 ft) change in the location of the contaminant concentration contours, this change would be compared with the change in the location of the contaminant concentration contours in the Monte Carlo analysis. If the 500 m (1,640 ft) change corresponded to 55 percent confidence level, then it would appear the uncertainty in the contaminant concentration contours due to that alternative geologic interpretation is small. If the 500 m (1,640 ft) change corresponded to a 90 percent confidence level, then the alternative geologic interpretation would be considered more important.

5.1.4 Model Validation

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

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

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

5.1.4.1 Model Purpose and Objectives

The objectives of a given model guide the level of detail and accuracy required of the model. The CAU-scale model will be used to integrate a wide variety of data into a mass conservative description of contaminant migration in groundwater from underground nuclear test locations in a CAU. This CAU model is then used as a decision-making tool for that CAU during the CAI. In the terms of the *Standard Guide for Subsurface Flow and Transport Modeling* (ASTM, 1995c), a hydrologic model can be termed an aquifer simulator. This means that the model is used to assess the value of unknowns at specific locations and times, which requires a high degree of correspondence between the simulations and the physical hydrogeologic system. To the extent practicable, the model is designed to honor observed data to a specified degree of confidence by following a calibration process.

The model objectives can be summarized as follows:

- Develop a CAU model that has the ability to represent the physical and chemical features of the CAU groundwater flow system important to contamination migration, using the existing and newly-collected data.
- Simulate the concentration of individual contaminants downgradient of underground test locations over a time period of 1,000 years. These concentrations will be used to define a contaminant boundary based on a 4-mrem/yr composite dose.
- Use the CAU model as a tool to evaluate impacts of future flow system changes on the migration of contaminants in the CAU.

5.1.4.2 Conceptual Model

The conceptual model of interest to the CAU model includes the groundwater flow system and contaminant transport. The conceptual model of groundwater flow defines the characteristics and dynamics of the hydrogeologic system. The elements of a groundwater flow system conceptual model are defined in ASTM D-5979, *Standard Guide of Conceptualization and Characterization of Ground-Water Systems* (ASTM, 1996b). The contaminant transport conceptual model defines the sources of groundwater contamination and the mechanisms of contaminant migration in groundwater. The data used to construct the current conceptual model of groundwater flow and contaminant transport are presented in [Sections 3.1](#) through [3.5](#) of this document. This conceptual model will be

refined during the data assessment phase of the CAI as described in [Sections 5.1.1, 5.1.3.2.1, and 5.1.3.3.1](#). Non-CAU specific data may be included in the development of the conceptual model, particularly to provide additional constraints on parameter uncertainty.

5.1.4.3 Selection of a Computer Code and Code Verification

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

5.1.4.4 Model Design

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

5.1.4.5 Model Calibration

As defined in ASTM D-5981, *Standard Guide for Calibrating a Ground-Water Flow Model Application* (ASTM, 1996a), model calibration is the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater system. The model calibration process has been defined in [Sections 5.1.3.2.3 and 5.1.3.3.3](#).

For the CAU model, it is expected that most of the calibration will focus on water levels because the groundwater discharge locations will fall outside the boundaries of the CAU model and therefore,

will not be direct calibration targets of the CAU model. However, because the modeling process includes the regional groundwater flow model, the constraints imposed by distant groundwater discharge calibration targets in the regional model will become indirect calibration targets at the CAU scale via the boundary conditions. The hydraulic head calibration targets of the CAU model are expected to be refined (more restrictive) than for the regional model. Specific calibration target ranges for the CAU model will be documented as part of the calibration analysis.

Additional calibration targets based on ranges of regional groundwater flow model derived boundary fluxes may also be imposed if specified head boundaries are utilized. These will be combined with the hydraulic head targets and will utilize constraints placed on hydraulic conductivity by observed data. This whole process may be automated via a parameter estimation approach such as the one available in the PEST code, a commercially available computer code from Westmark Computing (1998).

5.1.4.6 Sensitivity and Uncertainty Analyses

The sensitivity and uncertainty analyses are quantitative methods of determining the effect of variations in the parameter and boundary conditions (input parameters) on model predictions (output parameters). These analyses will follow ASTM D-5611, *Standard Guide for Conducting a Sensitivity Analysis for a Ground Water Flow Model Application* (ASTM, 1994b). The planned sensitivity and uncertainty analyses are presented in [Sections 5.1.3.4](#) and [5.1.3.5](#) of this document. The resulting uncertainty in model predictions will be summarized in several forms and will include the contaminant boundary location and particle pathlines for conservative contaminants. The uncertainty analyses will include bounding calculations that are intended to capture 90 percent of the uncertainty by choosing uncertainty ranges for input parameters that extend from the 5 percent to 95 percent levels.

5.1.4.7 Model Review

A thorough review of the model will be performed to verify the modeling approach and to determine if the modeling process can move forward to the verification phase. The model will be reviewed by four groups: (1) an internal group made up of the UGTA TWG/MS Subcommittee, (2) DOE/NV management, (3) an external peer review group whose members will be prominent members of the

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

5.1.4.8 Model Verification

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

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

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

If the data significantly modifies the pdf, or if it falls outside of the 5 percent and 95 percent ranges, the model will not have been verified. In this case, DOE/NV and NDEP will initiate discussions to identify the appropriate path forward.

5.1.4.9 Predictive Simulations

The stated purpose of the CAU model is to provide predictive simulations of radionuclide migration away from underground test cavities for a period of 1,000 years. For each contaminant, the model will predict the concentration in the model at selected time steps from 0 to 1,000 years. These data will be processed to calculate a contaminant boundary location. The contaminant boundary is defined as the maximum extent of the 4 mrem/yr composite dose which is made up of the sum of the doses from each of the contaminants. The results will be presented as a median location of the contaminant boundary along with 5 percent and 95 percent locations of the boundary based upon the uncertainty analyses. Additional discussion of the predictive simulations is given in [Section 5.1.5](#) of this document.

5.1.4.10 Presentation of Model Results

The model and results will be presented in the same level of detail as in the previous regional model documentation packages (IT, 1997b and 1996h). The regional model documentation package included descriptions of the numerical model, the model grid, boundary conditions, aquifer parameter assignments, model calibration, sensitivity analyses and presentation of results. For the CAU model, the same information will be presented for the groundwater flow model. Additional information will be added for the transport simulations. This additional information will include the transport parameters, unclassified source term, and results which will be presented in terms of the location of

the 4 mrem/yr composite dose contaminant boundary based on the classified source term. The results will be presented as a median location of the contaminant boundary along with 5 percent and 95 percent locations of the boundary based upon the uncertainty analyses. Additional results showing contaminant concentrations and the location of the contaminant boundary at selected times will also be presented. These times may include the verification period, the end of the five-year proof-of-concept period, as well as other times that are of specific interest.

5.1.4.11 Postaudit

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

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

5.1.5 Contamination Boundary Prediction

As specified in [Section 2.1.2.2.1](#), the contaminant boundary is defined as the maximum extent of contamination corresponding to a human dose of 4 mrem/yr for radionuclides, or a concentration equal to drinking water standards (maximum contaminant levels) for other contaminants, at the 50 percent confidence level within 1,000 years. The 50 percent level will be calculated from the median of the Monte Carlo simulations. The 4-mrem/yr dose is calculated as the sum of the doses from each of the radionuclides simulated. In the most general case, this would require a full set of Monte Carlo runs for each nuclide and then a summation of the 50 percent level doses to determine the contaminant boundary.

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

5.2 Other Models Supporting the Yucca Flat/Climax Mine CAU Model

In the preceding discussion, several models have been identified as providing input to the Yucca Flat/Climax Mine CAU model. Other models will be run in support of the CAU model: the regional flow model, the DRI random field generator, and the LLNL hydrologic source-term model, and local models to address the high pressure region and possibly the impact of faults. The regional flow model provides the boundary conditions necessary to ensure that the CAU model is consistent with the regional flow system. The DRI random field generator creates realizations of spatially variable parameters that will aid in assessing uncertainty in the near-field model and will provide a tool to define effective parameters. The near-field hydrologic source-term model provides the spatial distribution, release rates, and near-source mobility of a variety of radionuclides. In addition, there may be one or more local models developed to address specific questions or processes. These models may address the role of faults in groundwater flow or the consequences of the high pressure region in the volcanic units of central Yucca Flat.

5.2.1 Regional Groundwater Flow Model

The regional groundwater flow model (IT, 1997b) was created to provide the necessary regional framework within which the CAU model operates. The regional model balances groundwater inflows and outflows on a regional scale to ensure that a large scale model flow is consistent with measured water levels, inflows, and outflows. For the CAU-model results to be considered valid, the groundwater flow through the CAU model must be in balance with the regional model predictions.

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

5.2.2 Random Field Generator

The purpose and methodology of the DRI random field generator are described in this section. The descriptions are based on a personal communication from Shirley (1998). The Frenchman Flat External Peer Review Report (IT, 1999b) identified the random field simulations as a second order process. It is expected that uncertainty in the HSU framework model will be more important than spatial variability. Historically, spatial variability of hydraulic conductivity has been lumped into larger dispersion coefficient terms for large scale simulations. Therefore, there are approximate methods to incorporate spatial variability. Nonetheless, some effort will be made to examine the impact of spatial variability on the uncertainty in contaminant boundary prediction, particularly for near-field simulations.

5.2.2.1 Purpose

Heterogeneity, at some scale, occurs in all geologic media (Davis, 1986), including those of the Yucca Flat/Climax Mine area.

In modeling groundwater flow and contaminant transport, decisions of how to address this heterogeneity are critical. The spatial distribution of attributes such as hydraulic conductivity and porosity are the primary controls on the paths that groundwater follows and the velocity with which it moves along those paths. The direction and velocity of flow and transport is controlled by connected volumes of rock characterized by higher and lower-than-average values of these attributes. Continuous bodies of high and low hydraulic conductivity act respectively as conduits with greater-than-average flow and barriers with less-than-average flow. Both conduits and barriers can change the direction of flow and associated transport. Naff et al. (1998a and b) conclude a high-resolution Monte Carlo study by emphasizing the need to include heterogeneity in modeling flow through porous geologic media. Radionuclide transport at higher-than-anticipated velocity can occur when a region of concentration, such as a test cavity, intercepts a high conductivity conduit.

To incorporate the uncertainties associated with the geologic media heterogeneities, particularly those at sub-CAU scales, researchers at DRI (Pohlmann and Andricevic, 1994; Shirley et al., 1996) have developed a methodology to create maps of a specified attribute (e.g., hydraulic conductivity) using observed data and geophysical logs. Each map represents one possible distribution of the specified

attribute. This methodology for including random fields in small-scale models is discussed in the following text.

5.2.2.2 Methodology

Geologic media are known to be highly heterogeneous, but are not considered wholly random (Dagan, 1986). Much of geology is concerned with elucidating the systematic departure from randomness. This study combines the results of two types of stochastic simulations to yield both equiprobable spatial distributions of both hydrogeological classes (or states) and specific hydrologic attributes (Goovaerts, 1996). These classes are roughly equivalent to informal HSUs, being characterized by porosity and permeability (Seaber, 1988). However, hydrogeologic classes are defined in a more quantitative fashion. The probability of occurrence of all classes within the model domain is specified, as are the orientation, anisotropy, and correlation length of transitions from any one class to any other class. Spatial distributions of specific attributes (e.g., 3-D maps of hydraulic conductivity) make use of the hydrogeologic class maps. The mean, variance, orientation, anisotropy and correlation length of an attribute are specified for each hydrogeologic class (Rubin and Journel, 1991). Spatial distributions of the attribute for each class are generated which approximate and, in the ensemble, reproduce these statistics. The hydrogeologic class at each point in the model domain is used to select the appropriate attribute value. This method allows for abrupt lithologic contrasts without requiring an unsupported assumption of continuity.

The 3-D maps are conditioned on all available data. Locations where an attribute is considered known (i.e., hard data such as a packer test) are given the same value for that attribute in each map generated. At locations distant from known values, the assigned values will vary from map to map. The variance at that point within the complete set of equiprobable maps represents the uncertainty. The lack of data between sample locations inevitably leads to uncertainty in any model. The methods used for this study explicitly recognize this uncertainty and present it as the differences between the equally likely realizations (i.e., the equiprobable 3-D maps).

One of the challenges of stochastic modeling of geologic media is producing geologically plausible models. Traditional stochastic simulation methods have allowed generation of statistically valid, but geologically implausible, representations. Some volcanic rocks, such as simple cooling units within ashflow tuffs, have systematic internal variations, leading to the concentration of groundwater flow

within a portion of the lithology (Rosenbaum, 1993). Transition probability modeling, a recent innovation in stochastic modeling methods, can capture known geologic features such as vertical juxtaposition of lithologies as well as systematic variation within lithologies (Carle and Fogg, 1996; Carle, 1997). The reproduction of hydrogeologic class geometry typically found in a specific geologic environment is an important benefit of the method.

5.2.3 Near-Field Groundwater Flow and Transport Model

The purpose and methodology used in the near-field groundwater flow and transport investigation, described in [Section 6.1.7](#), are presented in this section.

5.2.3.1 Purpose

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

5.2.3.2 Methodology

The methodology used to perform the geochemical modeling and the hydrologic modeling in support of the Frenchman Flat CAU model (LLNL, 1999) will also be used in support of the Yucca Flat/Climax Mine CAU model. A summary of this methodology is provided in this section.

Geochemical Modeling

One-dimensional reactive transport simulations of radionuclide migration through puddle glass, cavity region, chimney region, and volcanic rocks will need to be made using a code(s) such as GIMRT or OS3D (Steeffel and Yabusaki, 1996) or other similar application to evaluate the efficacy and controls of migration and retardation. The code(s) will need to simulate multicomponent mass transport in porous and fractured media. The code(s) must provide for aqueous speciation assuming

homogeneous equilibrium, kinetically controlled mineral dissolution and precipitation, and surface complexation. Geochemical models require the use of thermodynamic data for aqueous species, gases, and solids. GEMBOCHS (Johnson and Lundeen, 1997) is an example of such a thermodynamic database.

Hydrologic Flow and Transport Modeling

A 3-D flow model must be developed to understand the flow system in the near-field area, and integrate reactive transport and glass dissolution from the geochemical modeling. Spatial resolution must permit smaller-scale variabilities of material properties such as hydraulic conductivity, porosity, or mineral abundance to be considered, as well as a refined representation of radionuclide inventories or other chemical distributions. The spatial resolution must allow for numerical dispersion effects produced by coarser grids to be minimized, and permit more defensible simulations of real processes to be made.

An evaluation of 3-D groundwater flow and transport codes will be undertaken for the Yucca Flat/Climax Mine CAU to identify the code which best simulates the existing environment. The Yucca Flat/Climax Mine near-field model may require a fractured flow system application for some locations and a porous-media-equivalent code such as ParFlow (Ashby, 1996) for locations in porous HSUs. Numerous groundwater flow and contaminant transport codes were evaluated by the UGTA TWG/MS. It is possible that the appropriate code for the near-field model will be selected from the list evaluated by this group.

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

5.2.4 Local Models

A number of local models may be developed to address specific questions or issues that may impact the transport of contaminants within the local groundwater system. Two examples are: (1) local

groundwater flow and transport model, perhaps 10 km (6 mi) in length on a side, that is designed to assess the migration of radionuclides along faults from the volcanic units to the underlying LCA, and (2) a model to assess the impact of the high pressure zone in central Yucca Flat.

The local groundwater flow and transport models will not be linked directly to the CAU model, but rather they will be used to investigate a process or phenomenon that may influence radionuclide migration in the Yucca Flat/Climax Mine area. These models will be much smaller in size than the CAU model and will not necessarily require 3-D formulations. Each local model will have a specific goal. For example, the fault modeling will have as a goal the quantification of the range of mass flux of radionuclides in the LCA. This range would then be used to bound the mass flux into the LCA in the CAU model. As necessary, the local models will be bounded by existing data. In the case of the role of faults, known potentiometric surface differences between the volcanics and alluvium will be honored as various scenarios are investigated.

The pressurized-zone model will be developed by LANL to assess the origin and significance on radionuclide transport of a region of high hydraulic pressures in the volcanic units of central Yucca Flat. The high pressure may represent compaction caused by underground testing. By understanding the compaction process and the perturbation in fluid pressures, a better understanding of the hydraulic characteristics of the VCUs will be obtained. It seems likely that the high pressure zone is now a very effective hydraulic barrier.

The high-pressure zone model will use the code FEHM to simulate the compaction process and simultaneous rise in fluid pressures. It is not expected that the Yucca Flat/Climax Mine CAU model will need to use the compaction options of FEHM. Rather, this intermediate-scale model will provide hydraulic properties and ranges of fluxes into the LCA from the overlying units.

6.0 Field Activities

This section includes a discussion of the characterization activities for the Yucca Flat CAI. The activities were designed to collect information in support of the groundwater flow and contaminant transport model described in [Section 5.0](#) of this CAIP. The process to be followed for proposing any necessary additional characterization activities is also outlined. Descriptions of related support activities involved in the Yucca Flat CAI are also provided. The UGTA strategy is currently under revision. Any data-collection activities that may be proposed as a result of these revisions will be described in an addendum to this CAIP.

6.1 Investigation Activities

The Yucca Flat CAI includes nine major characterization activities. They are as follows:

- Mineralogy Study of the TCU
- Geophysical Interpretation of the Paleozoic Framework
- Analysis of Existing Seismic Data
- Hydrologic Investigation of Wells ER-6-1 and ER-6-2
- Isotope/Geochemistry Mass-Balance Studies
- Analysis of Existing Tracer Test Data
- Laboratory Radionuclide Transport Studies
- Rainier Mesa Colloid Transport Studies
- Analysis of Data for Phenomenological Models

These activities are discussed in more detail in the following subsections.

6.1.1 Mineralogy Study of the Tuff Confining Unit

This study is designed to refine knowledge of the nature and extent of the TCU in Yucca Flat. It is a joint study between BN, LANL, and LLNL. The study began in fiscal year (FY) 1999 and is planned to be completed in FY 2001. A progress report of the study for FY 1999 has been produced (Prothro et al., 1999). Further progress will be reported in subsequent reports. The significance of the TCU in contaminant transport in the groundwater flow system of the Yucca Flat area is explained. This discussion is followed by the objectives and the details of the study.

6.1.1.1 Significance of the Tuff Confining Unit

The TCU is believed to play an important role in the transport of contaminants in the groundwater flow system of the Yucca Flat area. The TCU is believed to form an extensive physical barrier to contaminant transport from the upper aquifers to the LCA, because of its confining characteristics. In addition, the TCU is also believed to significantly retard the transport of radionuclides because of its sorbing abilities.

The TCU is widespread beneath Yucca Flat and lies partially to completely below the water table in the central portion of the Yucca Flat basin. The TCU separates the AA and the VA from the LCA, which is believed to be the main potential migration route for contaminants from Yucca Flat and Climax Mine to areas located outside of the NTS. Most underground nuclear tests in the Yucca Flat CAU were conducted within or above the TCU. The TCU may have the ability to partition or seal the LCA from the overlying contaminated volcanic tuff aquifers because of its positioning between the nuclear test points and the LCA. Therefore, knowledge of the lateral continuity and hydraulic characteristics of the TCU will aid in assessing this ability.

Also of importance are the type and distribution of alteration minerals in the composition of the TCU. The alteration minerals, which can retard contaminant transport within the TCU, possess a significant range in sorption capacity for radionuclides. Recent work by LLNL in Frenchman Flat has identified the significance of zeolites and clays in retarding radionuclides through the processes of sorption and ion exchange within the TCU of the area of interest (LLNL, 1999).

6.1.1.2 Objectives

The purpose of this study is to collect geologic and mineralogic information to characterize the TCU in the Yucca Flat area physically and mineralogically.

Specific objectives of this characterization activity are:

- Estimation of the lateral continuity and hydraulic characteristics of the TCU
- Determination of the geochemistry of the alteration minerals
- Quantification of the alteration minerals
- Definition of the spatial variability of the alteration minerals
- Determination of the extent of hydrothermal alteration

The first objective will help in the physical characterization of the TCU. Knowledge of the extent and hydraulic characteristics of the TCU will supplement the existing geologic information. The additional data will help in the development of the hydrostratigraphic model of the Yucca Flat and Climax Mine CAUs. The other objectives support the mineralogic characterization of the TCU. Identification of the type, quantity, and distribution of alteration minerals within the TCU will allow modelers to more accurately simulate influences of alteration minerals on the groundwater flow system, calculate hydrologic source terms, simulate radionuclide transport, and predict contaminant boundaries.

6.1.1.3 Existing Data Assessment

Work on evaluating the nature and extent of the TCU began in FY 1999 and was documented by Prothro et al. (1999). The work included:

- Compiling and evaluating existing data
- Establishing a system for managing the data
- Preliminary analysis of the existing data to identify heterogeneities within the VCU, particularly with regard to alteration minerals
- Constructing preliminary maps of alteration zones to define their general extent
- Identifying boreholes from which to acquire additional samples for analysis

Work performed in FY 1999 included compiling and evaluating existing data on the TCU, and reviewing the literature. Most of the compiled data are from boreholes in Yucca Flat, including geophysical logs, published and unpublished lithologic logs, and results of laboratory analyses. The laboratory procedures used included mineralogic analyses by X-ray diffraction (XRD) and petrography, and chemical analyses. All compiled data were placed in a database. Data generated in the future as part of this activity will be incorporated into this database.

Available information on distribution of fractures within the TCU and mineralogy of fracture filling minerals will be compiled in the future. However, no additional investigation on fractures or detailed fracture analyses are planned.

6.1.1.4 Field and Laboratories Activities

Additional volcanic rock samples from existing boreholes will be acquired in the future. The focus of the effort will be on collection of samples from alteration zones within the TCU for analysis of mineralogic content and distribution. Silicate samples of the TCU will be analyzed for strontium-87/strontium-86 ($^{87}\text{Sr}/^{86}\text{Sr}$) and oxygen-18/oxygen-16 ($^{18}\text{O}/^{16}\text{O}$) isotopic ratios to determine the extent of hydrothermal alteration affecting this unit.

6.1.1.5 Data Analysis

All of the data collected during this study will be evaluated and interpreted, and the findings will be included in a final report. The report will include maps depicting the content and distribution of alteration minerals in Yucca Flat. Preliminary versions of the maps will be produced for review. The data analysis activities conducted for mineralogic and physical characterization of the TCU are described.

Mineralogic Characterization

Preliminary analysis indicated that the TCU in Yucca Flat is heterogeneous. The various types and distribution of alteration minerals within the TCU probably represent the most significant heterogeneity of relevance to groundwater flow and contaminant transport in the Yucca Flat area. Three alteration zones have been identified: (1) a zone of quartzo-feldspathic alteration, (2) a zone of zeolitization, and (3) a zone of pervasive argillic alteration. Minerals filling the fractures contribute to the alteration minerals within the TCU. Mineral-filled fractures also play an important role in the heterogeneity of the TCU. Emphasis of future sampling and analysis will be placed on identification and quantification of the alteration mineral assemblages in the zone of quartzo-feldspathic alteration to adequately characterize and map it. Future sampling and analysis are expected also to produce a better understanding of the occurrences of zeolites and other alteration minerals in the zone of zeolitization. The zone of pervasive argillic alteration has distinguishing characteristics that are easily observed macroscopically in lithologic samples and with geophysical logs. This permitted a more extensive preliminary analysis, and determination of distribution of this alteration zone than for the other two zones. Consequently, there is no need for extensive additional sampling of the zone of pervasive argillic alteration. The available information on the mineralogy of fracture filling minerals

will be analyzed and interpreted in the future as part of this activity. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{18}\text{O}/^{16}\text{O}$ isotope signatures will be compared against unaltered magmatic isotope signatures to derive quantitative isotope shifts indicative of water/rock reactions.

Physical Characterization

The TCU beneath Yucca Flat is lithologically heterogeneous. The TCU consists of three generalized lithologic units: ash-flow tuff, bedded tuff, and paleocolluvium. Since most of the units of the TCU are zeolitic and have similar hydraulic properties, the lithologic differences could be considered unimportant with respect to regional-scale groundwater-flow modeling. However, for a smaller scale model, such as at the CAU model, the lithologic differences may have a significant impact on groundwater flow patterns. Units of ash-flow tuff, paleocolluvium, and the occurrence of fractures are of particular interest.

Samples of Red Rock Valley Tuff, consisting of ash-flow tuff near the base of the TCU in Well UE-7bc in Yucca Flat, indicate that this tuff is considerably different both lithologically and hydraulically from the surrounding zeolitic bedded tuffs. Thus, the nature, extent, and hydraulic significance of the Redrock Valley Tuff and the other older ash-flow tuffs will be investigated as part of this activity. Paleocolluvium and other sedimentary rocks occur at the base of the Tertiary volcanic section. It appears that these sedimentary rocks have not been widely characterized in Yucca Flat. Their nature, extent, and hydraulic significance will also be investigated as part of this activity. Available information on distribution of fractures within the TCU will be compiled in the future. Hydraulic properties of the TCU will be investigated subsequent to the evaluation of the mineralogic heterogeneities described above.

6.1.2 Geophysical Interpretation of the Paleozoic Framework

An understanding of the subsurface is necessary to accurately construct a hydrostratigraphic model and simulate groundwater flow and contaminant transport beneath Yucca Flat and adjacent to Climax Mine. Because of implications to the regional groundwater flow system, it is particularly important to define the structure and distribution of the Paleozoic rocks beneath Yucca Flat and Climax Mine. Distinct sedimentary units of the Paleozoic section form the major regional aquifer and aquitards (Winograd and Thordarson, 1975; Laczniaik et al., 1996), and form the lower boundary of the regional

groundwater flow system (DOE/NV, 1997c). Because the Paleozoic rocks are not exposed at the surface of Yucca Flat, their distribution must be determined from lithologic logs, geophysical borehole logs, or less direct geophysical methods. A study of depth and structure of the Paleozoic rocks in the Yucca Flat area has been initiated by BN in cooperation with the USGS.

6.1.2.1 Objectives

The purpose of this activity is to contribute the geologic information necessary to better understand the Paleozoic framework, configuration of Mesozoic intrusive rocks, and provide increased definition in the hydrostratigraphic model for the Yucca Flat CAU.

Specific objectives of the Paleozoic framework characterization project are:

- Determine depths to the Paleozoic rocks beneath Yucca Flat through a new and refined inversion based on gravity and borehole data.
- Produce a modified gravity map that represents separately the gravity field of the Paleozoic rocks.
- Produce new cross sections of the Paleozoic rocks.
- Characterize the 3-D configuration of the Climax Mine and Gold Meadows Stocks.

6.1.2.2 Data Compilation

The compilation of existing data that are relevant to this activity was completed by the USGS in FY 1999. Relevant data include geologic, gravity, and magnetic data.

Primary sources of geologic data included a digital geologic database developed by the USGS (Wahl et al., 1997) and an unpublished database of well information for the NTS. The unpublished database contains borehole information for the 1,205 NTS wells of which 992 are in Yucca Flat. This database also contains borehole gravity information for 21 wells located in the NTS and 9 of these are in Yucca Flat (Phelps et al., 1999).

Surface gravity data were obtained from a dataset for gravity stations on the NTS (Harris et al., 1989). There are 9,883 gravity stations within the Yucca Flat study area; 401 stations are on the basement rock surrounding Yucca Flat, approximately 7,300 stations are on basin fill in Yucca Flat, and the

remainder are on basin fill surrounding Yucca Flat. Of the 9,883 gravity stations, 261 were deleted because of apparently anomalous values at those data points (Phelps et al., 1999).

Magnetic data were obtained from high resolution surveys combined with regional surveys (McCafferty and Grauch, 1997). The data for Yucca Flat was processed with USGS software and separated into four datasets according to relative depth below surface.

6.1.2.3 Data Interpretation

In FY 1999, the USGS produced preliminary reports on an updated interpretation of the Paleozoic framework, and a characterization of the 3-D configuration of the intrusives. The interpretation was based on a new and refined inversion of the depth to Paleozoic rocks, which was based on gravity, magnetic, and borehole data. After reevaluation of the available gravity and magnetic data for Yucca Flat, the USGS produced preliminary reports on thickness of the basin fill (Phelps et al., 1999), high-angle basement faults (Phelps and McKee, 1999), structure of the Paleozoic basement (Phelps and McKee, 1999), and structure of the Mesozoic granitic intrusives (Jachens, 1999).

A 3-D inversion technique was used to analyze the Yucca Flat gravity data (Phelps et al., 1999). The analysis yielded a 3-D gravity model representative of the topography of the top surface of the LCA in Yucca Flat. In addition to gravity data, this method of analysis also required the compilation and use of density log data and stratigraphic information from existing boreholes. Density data were used to estimate the density of the Paleozoic rocks and the density contrast between the Paleozoic rocks and the overlying rocks (Quaternary and Tertiary). Stratigraphic information from existing wells and the proposed wells were used to help reduce the uncertainty of this analysis.

This existing aeromagnetic dataset was analyzed to infer the subsurface shapes of the Climax Stock and the Gold Meadows Stock, and to examine their relationships to each other and to the Twinridge Granitic Stock within the subsurface. The spatial distribution of the granitic Climax Stock and Gold Meadows Stock inferred from the magnetic data suggested that these two stocks represent cupolas joined by a saddle, protruding upward from a larger body. The depth of this large intrusion was estimated at 4 km (2.5 mi) or more below the surface. The large intrusion was not interpreted to extend as far east as the Twinridge Stock, except possibly at depths below 6 km (Jachens, 1999).

The USGS will work in conjunction with ITLV, BN, LANL, and LLNL to incorporate the results of the USGS analyses into the Yucca Flat HSU model. Revision of the USGS reports is anticipated as the results are integrated into the HSU model. After satisfactory integration of the new geologic and geophysical information into the HSU model, the preliminary USGS reports will be published as a series of open file reports.

6.1.3 Analysis of Existing Seismic Data

The description of this activity is based on a personal communication with Pawloski (1999). Two-dimensional seismic data have been collected in Yucca Flat in support of weapons testing. In addition, ground motion data have been collected from underground nuclear tests. The two-dimensional seismic data and aftershock mapping data will be evaluated to refine current structural interpretations in Yucca Flat. The results of this activity will be used to develop the HSU model for the Yucca Flat area.

6.1.3.1 Objectives

The objective of this activity is to conduct a comprehensive reinterpretation of existing two-dimensional seismic data incorporating current structural understanding to provide at basin wide scale an investigation of key features such as fault locations and HSU pinchouts or juxtapositions that may influence flow and transport. The analysis would also allow for imaging to depths below those previously considered. In addition, the use of seismic data obtained from local arrays and from regional seismological stations during underground nuclear tests will be evaluated for its contribution to understanding of geologic structure in Yucca Flat.

6.1.3.2 Data Compilation

Extensive seismic reflection and refraction investigations have been conducted by LLNL and LANL in Yucca Flat in support of weapons testing site characterization activities. For example, LLNL data consists of approximately 35 lines of data collected over a period of 8 years. Previous analyses have been piecemeal, separated in time, and considered only the area around one or a few tests at a time. This existing seismic data have not been comprehensively evaluated for possible contribution to the interpretation of the geologic structure and stratigraphy of Yucca Flat.

Seismic data have been collected during underground nuclear tests from local arrays deployed in the vicinity of specific tests and from regional seismic monitoring stations. The data from local arrays may be available from the more recent tests in digital format. However, availability and quality are uncertain. Data were collected during tests by seismic monitoring stations that are part of the Great Basin Digital Seismic Network operated by the University of Nevada, Reno Seismological Laboratory.

6.1.3.3 Data Interpretation

Data interpretation activities include the reinterpretation of existing seismic lines, reprocessing of existing seismic lines, and aftershock mapping.

Reinterpretation of Existing Seismic Lines

Utilizing current structural understanding of the Yucca Flat basin formation and velocity and depth control from existing boreholes, the seismic data would be comprehensively reevaluated for applications to groundwater transport models. Areal extent of and discontinuities between HSUs would be evaluated. Expected contributions to the interpretation of geologic structure and stratigraphy would be:

- Defining the top of Paleozoic aquifer and TCUs
- Identifying the structure in the Paleozoic and overlying tuff
- Determining the areal extent of aquifer and confining units
- Possibly identifying the extent of the Tuff Aquifer in southern Yucca Flat and the margin of the confining unit in western Yucca Flat

Reprocessing of Existing Seismic Lines

New techniques in seismic data processing have emerged since the seismic reflection and refraction investigations were conducted in Yucca Flat. Lawrence Livermore National Laboratory investigated the possible benefit of reprocessing these data using prestack processing techniques to bring out currently unimaged reflection events. Their appraisal suggested that reprocessing may enhance the data and be useful, particularly in locating structure in important confining units in western Yucca

Flat. The two primary techniques recommended are Dip-Move-Out correction and prestack migration. To better evaluate the potential contribution of reprocessing, a small subset of the seismic lines will be reprocessed as a test case to determine the value in reprocessing all or part of the data.

Aftershock Mapping

Investigation of geologic features of hydrologic importance through interpretation of aftershock data is speculative. The interpretation of structure from stress field effects is not straightforward. Difficulties are expected with data availability, data quality, and interpretation. A limited investigation will be conducted as a trial to determine if this approach can offer a significant contribution to the objectives of this activity.

6.1.4 Hydrologic Investigation of Wells ER-6-1 and ER-6-2

The Yucca Flat CAI includes the completion of three of the four Environmental Restoration (ER) wells drilled in Area 6 in 1992 and 1993. These four wells include: Well ER-6-1, ER-6-1 Satellite Hole #1, Well ER-6-2, and ER-6-2 Satellite Hole #1. These wells are located in the southern part of Yucca Flat, on the east and west sides of the basin. Wells ER-6-1 and ER-6-1 Satellite Hole #1 are located in the northeastern corner of Area 6, and Wells ER-6-2 and ER-6-2 Satellite Hole #1 are located in the southwestern portion of Yucca Flat in the central part of Area 6 ([Figure 6-1](#)). Well ER-6-2 Satellite Hole will not be completed because it was abandoned. [Table 6-1](#) provides summary information for the wells to be completed.

These three wells were initially drilled in 1992 and 1993, respectively; were subsequently deepened by coring in 1994 to collect LCA core for analysis; and were then left open pending specification of completion objectives.

6.1.4.1 Well Histories

These wells were drilled to provide subsurface information in southern Yucca Flat. Well ER-6-1 was drilled to provide hydrogeologic data to help characterize the LCA beneath southern Yucca Flat. The ER-6-1 Satellite Hole #1 was later drilled on the same pad to provide additional hydrogeologic data and to permit well-to-well hydrologic studies. Well ER-6-2 was drilled to assess the geologic and hydrologic conditions of Paleozoic sedimentary rocks in a potentially downgradient position from

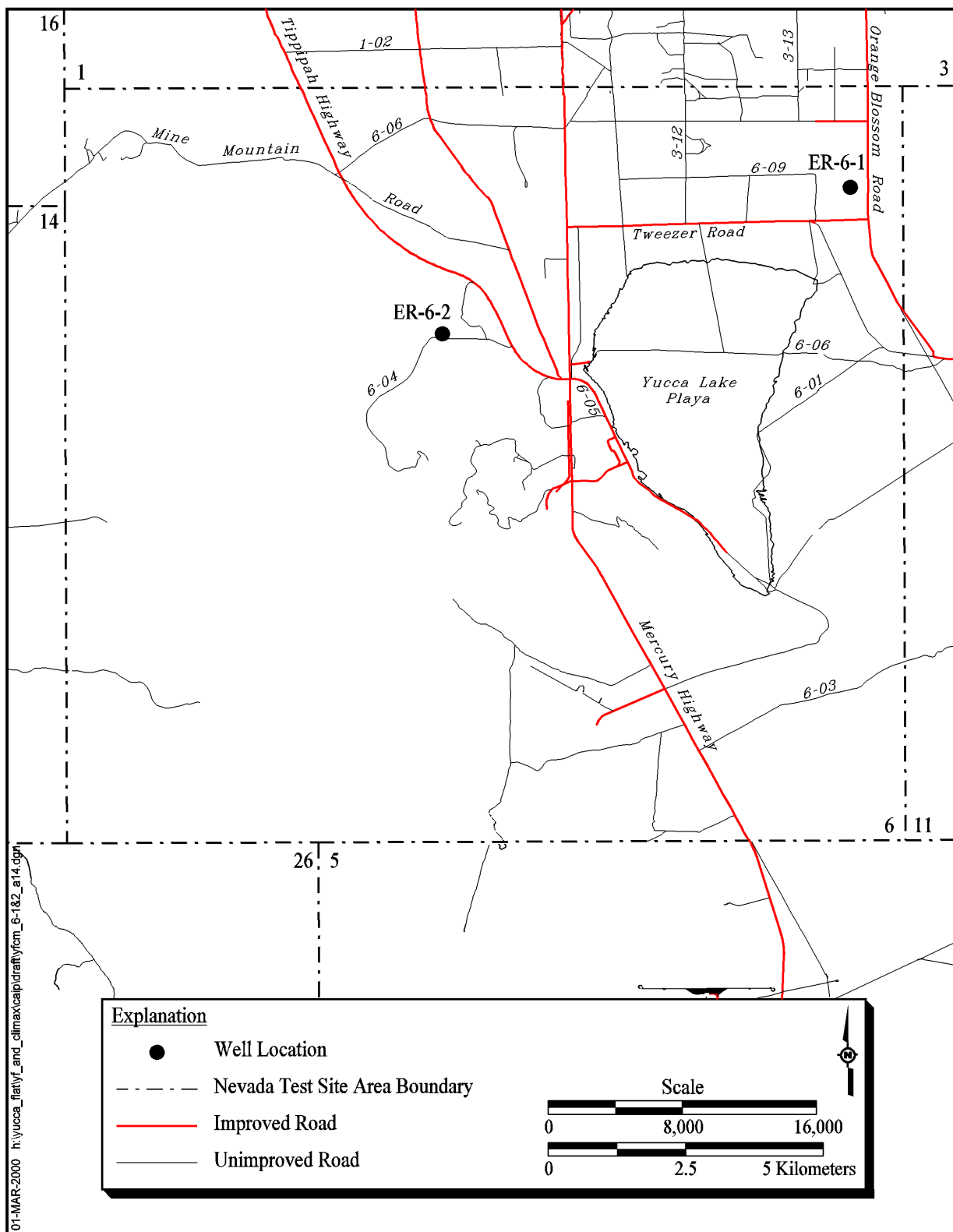


Figure 6-1
Location of Wells ER-6-1 and ER-6-2

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Table 6-1
Location of ER-6-1 and ER-6-2 Wellsites

Well	Nevada State Plane Coordinates (ft)	Universal Transverse Mercator Zone 11 Coordinates (m)	Surface Elevation m (ft)
ER-6-1	N 814,003.9 E 696,799.6	N 4,093,419.1 E 589,633.0	1,199.4 (3,934.9)
ER-6-1 Satellite Hole #1	N 813,951.0 E 696,808.0	N 4,093,402.4 E 589,635.2	1,199.4 (3,934.9)
ER-6-2	N 805,313.6 E 672,494.0	N 4,090,744.7 E 582,235.7	1,289.6 (4,230.9)

expended underground test sites in northern and central Yucca Flat. The following subsections provide detailed information on the histories of these wells.

Well ER-6-1

Rotary drilling at Well ER-6-1 began on June 30, 1992. The drilling was halted at a depth of 639.2 m (2,097 ft) for coring operations. During drilling, sloughing was the primary problem. The coring operations extended the borehole to a temporary total depth (TD) of 648.9 m (2,129 ft) on August 5, 1992. The static water level in the tertiary volcanic section was measured on July 21, 1992, at 449.3 m (1,474 ft) below ground level or 751.6 m (2,466 ft) mean sea level. Drilling was completed on September 4, 1992. On September 7, 1992, open hole water-level measurements were taken in Paleozoic rocks at 470.9 m (1,545 ft). Subsequent water-level measurements taken on June 7, 1996, were the same as the previous measurements. No radionuclides were detected in the borehole.

Operations to deepen Well ER-6-1 by conventional coring began on August 17, 1994. On October 16, 1994, a TD of 977.3 m (3,206.4 ft) was reached. The coring operations were stopped at this TD because of operational problems. However, a gyroscopic survey revealed that the borehole remained fairly straight and vertical during the drilling and coring operations. Coring was completed on November 1, 1994. The well was left as an open borehole pending later completion. In the interim, bridge plugs were placed at depths of 683.7 to 684.0 m (2,243 to 2,244 feet) and 746.8 to 747.1 m (2,450 to 2,451 feet) to prevent vertical groundwater flow between the upper and lower part of the borehole.

ER-6-1 Satellite Hole #1

Rotary drilling at this site began on July 7, 1993, and ended when TD was reached on July 9, 1993, at a depth of 635.5 m (2,028 ft). There were no apparent problems during drilling operations. An access tube was installed for water-level measurements. A static, open-hole water-level measurement was taken at 462.4 m (1,517 ft) on July 12, 1993. No radionuclides were detected in the borehole.

Well ER-6-2

The Well ER-6-2 borehole was also drilled in two stages. The two stages consisted of rotary drilling and coring. Drilling began on December 3, 1992, and ended on January 26, 1993, when TD was reached at 611.4 m (2,006 ft). A static, open-hole water-level measurement was taken on at 543.2 m (1,782 ft) on January 28, 1993. Tritium was not detected above background levels.

Coring operations at Well ER-6-2 began on June 8, 1994, and ended on July 21, 1994, when TD was reached at 1,045.5 m (3,430 ft). A static, open-hole water-level measurement was taken at 544.4 m (1,786 ft) on July 22, 1994. Tritium was not detected above background levels.

ER-6-2 Satellite Hole #1

Well ER-6-2 Satellite Hole #1 is located approximately 15.2 m (50 ft) north of Well ER-6-2 on the same pad. The ER-6-2 Satellite Hole #1 was drilled to a TD of 399 m (1,309 ft) when the hole sloughed and circulation was lost. The drill string became stuck and twisted off. Subsequently, the hole was abandoned and cemented to the surface.

6.1.4.2 Objectives

The objectives for completion of both wells, ER-6-1 and ER-6-2, are to provide for long-term water quality monitoring of the uppermost part of the LCA, and to provide for multi-level head monitoring. Water quality monitoring in the upper part of the LCA is intended to detect the presence of radionuclides transported in groundwater. The majority of nuclear tests in Yucca Flat were conducted above the LCA, with only a few in the uppermost LCA. Monitoring for radionuclides in the uppermost LCA is the most likely detection scenario for radionuclides entering the LCA beneath

Yucca Flat or leaving the basin in the LCA. Multi-level head monitoring will provide both HSU head information and vertical gradient information.

6.1.4.3 Completion Activities

These wells will have completions installed to fulfill the objectives listed above. The completion designs will be developed to meet operational requirements, and will be described in criteria documents for the field activities.

6.1.4.4 Testing and Analysis Activities

Following completion of these wells, measurements and samples will be collected and analyzed to meet the scientific objectives of these wells.

6.1.5 Isotope/Geochemistry Mass Balance Studies

The isotope/geochemistry mass-balance studies include field and laboratory activities, compilation of existing geochemistry data, and data interpretation including geochemical modeling. These studies are a combined effort of ITLV, LANL, LLNL, DRI, and Harry Reid Center for Environmental Services to investigate the Yucca Flat and Climax Mine CAUs.

6.1.5.1 Objectives

The purpose of these studies is to independently verify the origin and groundwater flow paths through the Yucca Flat groundwater flow system, and to provide estimates of the age and travel time for groundwater flow from Yucca Flat to the discharge area.

The specific objectives of these studies are as follows:

- Development of a consistent and complete set of groundwater chemistry data for the Yucca Flat groundwater flow system
- Mineralogical characterization of fracture-coating phases from boreholes
- Characterization of trace element leaching rates

- Micrographic characterization of the mineralogy of fracture-coating phases in support of the fracture diffusion experiments conducted by LANL

6.1.5.2 Field and Laboratory Activities

Field and laboratory activities related to the isotope/geochemistry mass-balance studies include groundwater sampling, mineralogical characterization of fracture-coating phases from boreholes, trace element leaching experiments, and micrographic characterization of the mineralogy of fracture-coating phases. Each of these activities has the potential to produce new data that can be incorporated into the modeling effort to provide an independent verification of groundwater flow paths, travel times, and groundwater budgets for the Yucca Flat groundwater flow system.

Groundwater Sampling and Analysis

Groundwater samples will be collected from approximately 20 well or spring locations upgradient of Yucca Flat, and approximately 10 groundwater samples will be collected from wells within Yucca Flat. At each of these sites, a variety of field parameters will be measured including water temperature, pH, specific conductance, dissolved oxygen, and alkalinity. The groundwater samples will be analyzed for the following constituents:

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

Groundwater samples will be collected either from a discrete interval sampler or at the ground surface from a discharge port, if a well contains a dedicated pump. For wells that contain pumps, groundwater temperature, conductivity, and pH will be monitored during pumping, and stabilization of these parameters will indicate that purging is complete. Flow logging will be performed to identify flow zones in wells without dedicated pumps.

Mineralogical Characterization of Fracture-Coating Phases from Boreholes

IT Corporation, in conjunction with LLNL, will select 20 fractured core samples from existing boreholes for characterization and analysis based on geochemical significance and hydrostratigraphic setting. The selected samples will undergo micrographic, isotopic, and trace element analysis. Specifically, splits will be collected from archived core samples located at the USGS core library in Mercury, Nevada. From these splits, mounts will be prepared for scanning electron microscopy (SEM) analysis, and thin sections across fracture surfaces will be prepared for electron microprobe analysis of fracture-coating mineral phases. X-ray diffraction analysis will also be performed on selected carbonate, clay, oxyhydroxide, or zeolite phases that cannot be adequately characterized using SEM or microprobe. The micrographic analyses will be conducted in collaboration with LANL, using their analytical facilities. Selected carbonate samples will be analyzed for $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and ^{14}C values.

Trace Element Leaching Experiments

The trace element leaching experiments will continue to develop the hydrogeologic and geochemical framework for the interpretation of trace element data at the NTS and specifically for the Yucca Flat groundwater flow system.

Trace element data have previously been obtained for groundwater in the Yucca Flat investigation area. However, unlike major and minor groundwater constituents, the geochemistry of trace elements in the NTS groundwater environment is presently not well understood. This has limited the usefulness of the trace element data for delineating water sources and flow paths in geochemical studies of the NTS UGTA CAUs. This task will provide a hydrogeologic and geochemical basis for the interpretation of trace element data from the Yucca Flat area.

Specifically, eight samples that are representative of the Yucca Flat flow system will be identified for leaching analysis. After collection of the samples, the whole-rock trace element concentration of the samples will be determined. Once the whole-rock trace element concentrations of the samples are determined, the trace element leaching experiments will be conducted with the aquifer solids. In addition to the laboratory work, a literature review will be performed to obtain additional information on the behavior of trace elements in the groundwater environment. The leaching test data will then be

synthesized with the previously generated data and information found during the literature search to develop a hydrogeologic and geochemical basis for the interpretation of trace element data in the Yucca Flat flow system. The lead organization for this activity will be Harry Reid Center for Environmental Science (HRCES), which will be responsible for the trace element leaching experiments. The ITLV staff will support the design of the experiments and the selection of the aquifer samples. In addition, ITLV (in combination with HRCES and other organizations) will adapt the framework for the interpretation of trace element data developed for Pahute Mesa to the more diverse hydrogeologic environment found at Yucca Flat and vicinity.

Micrographic Characterization of the Mineralogy of Fracture-Coating Phases

Mineral-phase assemblage, texture, size distribution, and relative coverage data will be generated to support the measurement and assessment of radionuclide transport properties of various hydrogeologic and HSUs from Yucca Flat. The principal emphasis of this activity is to provide detailed fracture surface characterization that will support the determination of the amount of diffusion that can be expected in various fractured rock types and the influence of fracture-coating phases on diffusive solute transport. The results will provide input for solute transport modeling of the Yucca Flat area at all scales, and may also assist in the refinement of groundwater age and travel time estimates derived from ^{14}C analyses.

IT Corporation in conjunction with LANL will conduct the micrographic analyses using a combination of SEM, XRD, microprobe, and/or cathode luminescence (CL), as necessary. Approximately 15 fractured-core surfaces (already selected by LANL) will be prepared. For example, fracture surface mounts for SEM and thin sections across the fracture surface for microprobe or CL analysis will be prepared. Additionally, XRD analysis will be performed as needed on selected carbonate, clay, oxyhydroxide, or zeolite phases that cannot be adequately characterized using SEM or microprobe.

6.1.5.3 Data Analysis Activities

Data analysis activities related to the isotope/geochemistry mass-balance studies include the compilation and review of Yucca Flat geochemistry data and subsequent data interpretation including

geochemical modeling. These activities will further define and explain the geochemical evolution of groundwaters within the Yucca Flat groundwater flow system.

6.1.5.3.1 *Compilation and Review of Yucca Flat Geochemistry Data*

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

Groundwater geochemistry data will be extracted from the GEOCHEM2000 database. The data sets will include geochemistry data from well and spring locations within Yucca Flat and the surrounding area. The data will be evaluated to determine if there are any missing historical data, and if there are any data gaps within the GEOCHEM2000 database that can be filled. If so, the GEOCHEM2000 database will subsequently be updated to include the new data. The existing and incorporated data will then be used to support the geochemical modeling of the Yucca Flat flow system and to assist in the planning of data-gathering activities for the CAI. Once the compilation and review of existing data are complete, the regional groundwater flow model will be reviewed, and the hydrogeologic modelers will be consulted to assist in the selection of groundwater sampling locations to obtain new data to address identified data gaps. IT Corporation will be the lead organization for this activity.

6.1.5.3.2 *Data Interpretation*

Data obtained from the field and laboratory activities discussed in [Section 6.1.6.2](#) and the data compilation activities will be used to identify and verify groundwater flow paths, estimate groundwater ages, and evaluate groundwater flow velocities.

Identification of Groundwater Flow and Reaction Paths

Results from the groundwater sampling program combined with the existing geochemical data from GEOCHEM2000 will be interpreted to provide geochemical constraints on flow paths determined by hydrogeologic modeling. Data that will be used during this activity will include major-ion chemistry, stable isotope results, and selected radioisotope data. Geochemical models that simulate reaction

paths, such as NETPATH (Plummer et al., 1994) or PHREEQC (Parkhurst, 1995), may be used in the interpretation.

Flow path and groundwater age modeling can be performed using the computer program NETPATH (Plummer et al., 1994). NETPATH is an interactive FORTRAN program used to interpret net geochemical mass-balance reactions between initial and final waters along a hydrologic flow path. It can also be used to compute the mixing proportions of two to five initial waters and the net geochemical reactions that can account for the observed composition of a final water. The modeling will allow for the interpretation of geochemical reactions, mixing proportions, evaporation and/or dilution of waters, and mineral mass transfer in the chemical and isotopic evolution of groundwater.

Calculation of Groundwater Ages and Evaluation of Flow Velocities

Data permitting, calculated groundwater flow velocities based on geochemical tracers will be compared to velocities calculated from hydraulic measurements and from groundwater flow modeling. Based on the results, consistent interpretations of hydrogeological and geochemical data will be made.

Dissolved isotopic species such as ^3He , CFC, and dissolved inorganic and organic ^{14}C will be used to estimate groundwater ages and flow velocities. The ^3He and CFC data can be used where groundwater travel times are less than approximately 40 years, and ^{14}C data can be used to estimate travel times for situations where groundwater is older. Dating groundwater with ^{14}C requires knowledge of groundwater flow paths and geochemical reactions along the flow path, because dissolved carbon is typically involved in reactions in the groundwater environment. Important chemical reactions that could affect ^{14}C transport are dissolution and precipitation of carbonate minerals along fracture surfaces and isotopic exchange with carbonates or soil gas reservoirs. Groundwater ^{14}C ages will be corrected to account for these reactions using data obtained during this investigation (e.g., $\delta^{13}\text{C}$ data from groundwater and calcite and ^{14}C data for calcite).

6.1.6 Reanalysis of Existing Tracer Test Data

Transport of radionuclides in the LCA out of the Yucca Flat Basin is likely the most important pathway for radionuclide migration. While more than a hundred boreholes in the Yucca Flat area

tagged the LCA, few penetrate the LCA to a substantial depth, and only a few tests have been conducted to determine either hydraulic or transport parameters for the LCA.

Three two-well recirculating tracer tests have previously been conducted in the Bonanza King dolomite, which is one member of the group of formations included in the LCA HSU. These tests were conducted at the Amargosa Tracer Calibration Site in the Amargosa Desert in southern Nevada, approximately 24 kilometers southwest of Mercury, Nevada. This site was initially developed to study the velocity of groundwater movement through carbonate rocks underlying the Nevada Test Site and the Amargosa Desert (Johnston, 1968), and further tests were run to determine the effective porosity and apparent longitudinal dispersivity in the carbonate aquifer (Leap and Belmonte, 1992). Under the proposed activity, data from these tracer tests will be reanalyzed using newer techniques to estimate transport parameters. Determination of transport parameter values for the LCA at this site would provide additional information on the range of potential parameter values for this HSU.

6.1.6.1 Objectives

The objective of this activity is to determine hydraulic and transport parameters (i.e., hydraulic conductivity, effective porosity, dispersivity, and matrix diffusion) for the LCA using the existing test data. Reanalysis of these tests, in light of the current understanding of tracer transport processes, HSU properties, and using current analysis methods, may provide information more comparable to recent tests for use in determining representative parameters for predictive modeling of radionuclide transport.

6.1.6.2 Data Compilation

Details of these tests are not well documented in the few publications that present information and analyses for the tests; nor is the original data on the hydraulic and tracer tests currently available for evaluation. This task would begin with a search for original information from the agencies that conducted the tests and subsequently an evaluation of the available data for suitability for reanalysis.

6.1.6.3 Data Interpretation

Reanalysis would employ methods appropriate to the extent and quality of the available data, and incorporate current knowledge of the characteristics of the LCA. The type of analysis and products

from reanalysis would be dependent upon the extent, completeness, type and quality of the data available.

6.1.7 Laboratory Transport Studies

Laboratory transport studies will help estimate parameters describing solute transport, as well as colloid and colloid-facilitated transport. The activity description provided here is based on two memoranda from LANL (Reimus, 1999a and b).

Solute Transport

Measurement and assessment of radionuclide transport properties, specifically matrix diffusion parameters for ^3H , ^{14}C , and technetium (^{99}Tc) and retardation of ^{14}C , will be conducted using core from various hydrogeologic units beneath Yucca Flat (primarily in the vicinity of and at similar depth as nuclear test cavities below the water table). The core will include representative samples from both the volcanic tuffs in which the nuclear tests were conducted and the LCA, where groundwater velocities are expected to be much greater than in the volcanics. This information will feed into transport modeling efforts at all scales up to the full CAU-scale model. It will also help refine groundwater age estimates derived from ^{14}C analyses. The intent of these studies is to provide source-term, process- and CAU-scale modelers with matrix diffusion coefficients and fracture transport parameters of key mobile radionuclides (^3H , ^{14}C , and ^{99}Tc), as a function of rock properties (e.g., matrix permeability, matrix porosity, matrix petrography, fracture-coating minerals, and features such as filled fractures). These studies will also help identify and quantify ^{14}C transport mechanisms to assist in flow and transport model calibrations.

Colloid and Colloid-Facilitated Transport

Colloid transport experiments will be conducted in the same fractures used for solute transport experiments. These experiments will involve eluting actinides or other sorbing radionuclides with high associated risk through the fractures either simultaneously with colloids or as species that are already sorbed onto the colloids. The transport of both the colloids and the radionuclides will be measured relative to a conservative tracer such as tritiated water at different flow rates, with different colloids, and possibly with different relative concentrations of the radionuclides and colloids. This matrix of experiments will help identify transport processes and provide estimates of parameters

describing those processes, which can be incorporated into process- and CAU-scale models. The choice of radionuclides and colloids used in the experiments will depend on preliminary risk assessment calculations and on field data.

6.1.7.1 Objectives

The specific objectives of these studies are as follows:

- Obtain laboratory estimates of radionuclide transport parameters (e.g., matrix diffusion, dispersion, and sorption), and the uncertainty associated with these parameters. This information will be used in the CAU-scale fate and transport model.
- Gain experimental insights into colloid transport processes, and obtain estimates of parameters describing those processes. Information will be used to improve the CAU-scale model.

6.1.7.2 Laboratory Data Collection

Activities associated with laboratory data collection include core selection, diffusion cell experiments, fractured-core column experiments, and colloid transport experiments.

6.1.7.2.1 Core Selection

The studies will be conducted by LANL using core from existing boreholes in Yucca Flat. Existing core will be collected from the USGS Core Library and Data Center in Mercury, Nevada. The selection of core for the study will be based on the perceived importance of the various HSUs in conducting radionuclides to the accessible environment and the proximity of boreholes to predicted transport pathways or areas of concern. In particular, core of the VCU will be selected from boreholes based on (1) their proximity to a cluster of nuclear detonations conducted below the water table in Yucca Flat and (2) the availability of information on fractures and mineralogy in the holes from recent reports (Prothro et al., 1999). Core from the LCA will also be selected, depending upon availability. Additional considerations in the selection of core will include the physical condition of the core and the presence of features significant to transport such as fractures and mineral alteration products. At least initially, core selection will emphasize obtaining naturally fractured core from below the water table with varying degrees of mineral alteration products on fracture surfaces.

6.1.7.2.2 Diffusion Cell Experiments

Diffusion cell experiments will be conducted to measure radionuclide diffusion coefficients in rocks with and without fracture coatings (or filled fractures) to determine (1) the amount of matrix diffusion expected in various rock types and (2) the influence of fracture coatings on diffusive mass transport. The hypothesis that coatings may provide a barrier to matrix diffusion will be tested. Radionuclides used in the diffusion cell experiments will include ^3H , ^{14}C , and ^{99}Tc . Associated with each diffusion cell experiment, matrix porosities will be measured to determine the dependence of diffusion coefficients on porosity. Also, saturated permeabilities will be measured to determine the diffusivity dependence on this property and to estimate the relative importance of diffusive and advective transport. The goal will be to build a defensible database of radionuclide matrix diffusion parameters as a function of rock type and fracture characteristics for UGTA modeling efforts. The rocks used in the diffusion cell and fractured column experiments will be analyzed petrographically at LANL. Additionally, subsamples of fracture surfaces will be analyzed by ITLV using SEM, Energy Dispersive X-ray Spectrometry, CL, and high-resolution transmission advection microscopy (HRTEM).

6.1.7.2.3 Fractured-Core Column Experiments

In parallel with the diffusion cell experiments, transport experiments will be performed to evaluate matrix diffusion and dispersion processes in fractured cores.

The transport experiments will be conducted under saturated, flowing conditions in the fractured cores. Cores with axial fractures will be enclosed and saturated in a leak-free system, and a suite of tracers will be simultaneously injected into one end of the fracture while the effluent from the other end is monitored for the appearance of tracers. The experiments will involve the same rock types and same tracers (i.e., ^3H , ^{14}C , and ^{99}Tc) as the diffusion cell experiments. Additional radionuclides or tracers may also be used. The breakthrough curves of conservative tracers with different diffusion coefficients, and possibly some reactive tracers, will be compared to quantify the amount of matrix diffusion, dispersion, and possibly sorption occurring in the fractures. The expectation is that tracers having larger diffusion coefficients will have breakthrough curves with lower peak concentrations and longer tails than tracers with smaller diffusion coefficients. These differences will be quantified

to determine the amount of diffusional mass transfer between the flowing water in the fractures and the essentially stagnant water in the surrounding rock matrix.

If a radionuclide appears to be sorbing in the fractures, batch sorption experiments will also be conducted to quantify the degree of sorption to the core material. These tests will allow a more quantitative and defensible interpretation of the fracture tests. Depending upon the availability of appropriate core, column experiments will be conducted using cores from the same lithologic unit with both mineral-coated natural fractures and uncoated, probably artificially induced fractures. The comparison of solute transport results in coated and uncoated fractures will yield additional information about the influence of fracture coatings on matrix diffusion and sorption in the case of reactive tracers.

6.1.7.2.4 *Colloid Transport Experiments*

Studies on the transport of colloids through fractured core will also be performed. This work is an extension of the matrix diffusion studies discussed above. The primary focus of the work will be to evaluate the potential for colloids to facilitate the transport of strongly-sorbing radionuclides such as actinides.

The colloids selected for study will include pure minerals and naturally occurring colloids consisting of inorganic phases identified from field characterization efforts. Radionuclides will either be coeluted with the colloids through the fractures that were used in solute transport studies, or they will be presorbed onto the colloids before being eluted through the fractures. In either case, the breakthroughs of the radionuclides and colloids through the fractures will be measured relative to a conservative tracer such as tritiated water.

Experiments may also be conducted using both inorganic colloids and polystyrene microspheres, with the goal of comparing the transport behavior of these two types of colloids. Studies may also be conducted to determine the attachment and detachment kinetics of colloids to/from stationary surfaces. Detachment processes, in particular, can be very important in determining the risks associated with colloid-facilitated radionuclide transport.

6.1.7.3 Data Interpretation

Data from the diffusion cell and fractured column experiments will be interpreted using either semi-analytical or numerical models that describe the transport processes occurring in the experiments. Key parameters in the models will be estimated from the data by adjusting the parameter values to achieve a best fit to the data sets. In the case of the fractured column experiments, responses for different tracers will be fitted simultaneously to obtain highly constrained estimates of the transport parameters. Inability to fit a data set may indicate that the assumed model is inadequate to capture the transport behavior.

The breakthrough curves generated during the colloid transport experiments will be used to understand the transport processes at work and to estimate values for the transport parameters describing these processes. The transport behaviors resulting from both types of colloids will be compared to allow defensible inferences to be made about the transport behavior of inorganic colloids based on the behavior of the microspheres in field tracer tests.

6.1.8 Rainier Mesa Colloid Transport Studies

Horizontal tunnels bored into Rainier Mesa were used to conduct more than 60 underground nuclear weapons effects tests for the Defense Nuclear Agency from 1957 to 1992. All these tunnel tests were conducted above the water table. Tuffs and lavas in the tunnel complexes were variably fractured by inelastic failure adjacent to these explosions. The resulting fracture system allows groundwater recharge from the surface of Rainier Mesa to infiltrate and interact with residual radionuclides from the tests. The tunnels now provide unprecedented access to an evolved hydrologic source term of radionuclides transported by groundwater through volcanic tuffs under variably saturated flow conditions. Of note, water presently discharging from E-Tunnel is known to contain concentrations of tritium, fission products, and alpha-emitting radionuclides above background. Data from Rainier Mesa tuffs should be applicable to tuff units in Yucca Flat since the tuffs at Rainier Mesa and older tuffs deposited in deeper portions of Yucca Flat are stratigraphically similar. Results may also be extrapolated to younger tuffs that overlie the older tuffs at Yucca Flat.

Earlier work by the UGTA field program on Pahute Mesa demonstrated that low concentrations of plutonium and other relatively insoluble fission product radionuclides can be transported through

fractured volcanic rocks on Pahute Mesa in association with colloids (Kersting et al., 1998). The colloids include clays, zeolites, and quartzo-feldspathic minerals which apparently serve as sorption sites for actinides and fission products released from the explosion cavity. The water samples used in this work were collected from pumped wells drilled to the depth of the nuclear tests conducted on Pahute Mesa. Questions have been raised about the effect of the pumping to artificially mobilize colloids and the plutonium sorbed to these particulates. This study will investigate colloid-facilitated radionuclide transport under natural flow conditions, avoiding the mechanical stresses and high velocities associated with high-volume pumping. The water samples will be collected from natural discharges from fractures in the tunnel ceiling and walls to provide a realistic measure of the ambient colloidal load, sizing, and mineralogy.

6.1.8.1 Objectives

The objective of this activity is to investigate the geochemical and radiochemical controls on the movement of actinides introduced from underground weapons testing under ambient flow conditions such as found in the tunnel complexes. This study will provide information on transport of radionuclides under variably saturated conditions, and will help to define the range of colloid-facilitated transport that may be expected under various groundwater conditions. These studies will contribute to credible predictions of the hydrologic source term to be used for transport modeling to determine the CAU boundary.

6.1.8.2 Data Collection

Samples of water and rock will be collected from fractures in the E-, T-, and N-Tunnel complexes. The sampling locations will be as close as possible to nuclear weapons source terms while still complying with all radiological and mine safety requirements. In addition, water will be collected from ports in bulkheads and discharge elimination plugs erected for radiological containment. Samples will be analyzed for major elements, radiological constituents, and field parameters. Sequential filtering of large volume water samples will be used to measure the load and size of colloid constituents. Rock samples will be prepared for petrographic and scanning electron microanalysis to determine if the mineralogy of the fractured matrix is consistent with the colloid composition. Radiography will be used to map radionuclide sorption sites. This data will be

compared with like data sets from wells on Pahute Mesa to assess similarities and differences between the two systems.

6.1.8.3 Data Interpretation

Data on radionuclide transport in groundwater within the E-, T-, and N-Tunnel complexes on Rainier Mesa will contribute to a better understanding of the controls on the migration of actinides and refractory fission products under partially saturated and saturated conditions in fractured tuffs. The field data will be augmented by experimental measurements (e.g., sorption, speciation, and mineralogy) in the laboratory. Strengthening this study is the extensive characterization of the hydrology and geology of the Rainier Mesa tunnels done to support the nuclear testing program.

6.1.9 Analysis of Data for Phenomenological Models

As stated in [Section 3.0](#) of this document, phenomenology describes the effects of the nuclear explosion on the surrounding medium during and immediately following the explosion of an underground nuclear test. Phenomenological models that are representative of reality are essential to understanding the sources of groundwater contamination present at the underground nuclear test locations. Therefore, they are essential to the modeling of groundwater flow and contaminant transport away from underground nuclear tests.

Under this CAI activity, existing data from drill backs and minebacks, pretest, post-test, and calculational data will be analyzed to develop phenomenological models of the near-field environment of underground nuclear tests in Yucca Flat.

6.1.9.1 Objective

The purpose of this activity is to develop conceptual phenomenological models of the near-field environment applicable to the tests in Yucca Flat.

Specific objectives includes the following:

- Estimate dimensions of near-field physical components
- Identify the geologic features of the near-field environment
- Identify the hydrologic features of the near-field environment

- Estimate radionuclide concentrations and distributions within the near-field environment
- Define the composition and texture of the melt glass

The information contained in the phenomenological models will be used in the near-field model(s) to simulate the hydrologic source term(s).

6.1.9.2 Data Compilation

Existing pretest data, shock wave calculations, and post-test data from six to ten tests in the Yucca Flat area will be compiled. Data sources will include both published and unpublished data and analyses. A literature search for published information and a record search for unpublished data will be conducted, and the data will be cataloged and compiled. Much of these data may be classified and not releasable. However, unclassified features of the phenomenological models developed would be represented in the public release of the hydrologic source-term model.

6.1.9.3 Data Interpretation

Pretest data are collected before an underground nuclear test is conducted to acquire physical properties of the setting which are used to predict phenomenology of the planned test. It is well known that the explosions modify the underground environment near the nuclear tests. On a large scale, the modifications to the environment may include increases in fractures, temporary openings of planes of weakness, bulking due to collapse, and solidification of puddle glass. On smaller scales, modifications include heterogeneous glass formation, injection of molten glass near the cavity, and crushing of pore space and mineral grain surfaces.

The pretest data, shock wave calculations, and post-test data will be analyzed to evaluate the impact of the tests on the media in an attempt to better understand potential radionuclide transport mechanisms (prompt injection), pathways (slow collapse, chimneys, tensile fracturing distances), and radionuclide deposition (bedding planes, fractures, faults). One or more conceptual models of the physical effects and radionuclide distribution resulting from nuclear tests will be developed.

The data analysis will include the following:

- Estimating dimensions of the melt glass, cavity, chimney, and damaged zones

- Identifying the stratigraphy, mineral distribution and textures; bedding planes; faults (quantity, aperture, lining materials)
- Estimating properties relating to permeability (e.g., density, porosity)
- Estimating radionuclide concentrations and distributions
- Identifying melt glass composition and texture

These conceptual models will be incorporated into the near-field hydrologic source term modeling to provide a more realistic simulation of the release of radioactive material into the surrounding groundwater and subsequent near-field transport. The results of the analysis will be used to refine the model of radionuclide emplacement and the physical model of near-field rock properties relating to groundwater flow in the various lithologies in which nuclear testing was conducted. The resulting conceptual phenomenological models will be summarized in a technical report.

6.2 *Potential Additional Characterization Activities*

The potential for additional characterization activities is an integral part of the UGTA strategy as discussed in [Section 2.0](#).

If after completion of the CAU-scale model, DOE/NV and NDEP cannot agree upon the model or the contaminant boundary, then DOE/NV and NDEP will determine if the strategy, as defined in the FFACO, can still be achieved through the collection of additional data (FFACO, 1996). If both parties agree that the strategy can still be achieved, DOE/NV will collect additional data.

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

6.3 *Field Support Activities*

Field support includes those activities associated with waste management, health and safety, and sampling and analysis. These support activities, along with the current versions of the documents that

set forth the corresponding policies and practices to be followed, are discussed in the following subsections. The CAI activities will be conducted under the policies and practices that are in effect at that time. General descriptions of field support activities are provided to cover the CAI work that is described in previous sections of [Section 6.0](#) and potential future CAI work.

6.3.1 Waste Management

Waste management is one element of a comprehensive on-site compliance program to be implemented at Yucca Flat investigation sites. The development of this program is tailored to anticipated site conditions; however, it includes contingencies in the event field operating conditions change. Periodic field evaluations are conducted to ensure proper implementation of this program and on-site compliance. The program also includes waste minimization, discussed below, and fluid management, discussed in the sampling portion of this section. The details of the comprehensive compliance program may be found in the *Underground Test Area Subproject Waste Management Plan* (WMP) (DOE/NV, 1996e), the UGTA Fluid Management Plan (FMP) (DOE/NV, 1999c), and site-specific planning and field documents.

Waste management covers the segregation, tracking, characterization, and disposal of wastes generated during field activities. Yucca Flat CAI activities that are expected to generate waste may include: drill site construction, well drilling, well completion, well development, and sampling operations (herein termed well installation activities). Other investigation activities may include periodic groundwater sampling of newly installed wells and existing wells.

The largest volume of waste generated during drilling and sampling activities is effluent (fluids) and groundwater. The management of fluids and groundwater produced at the Yucca Flat wells is addressed in the UGTA FMP (DOE/NV, 1999c), discussed later in this section. Other wastes, such as sanitary and hydrocarbon waste, are generated as a result of the operation and maintenance of heavy equipment, as well as other support functions on the drill site.

6.3.1.1 Investigation-Derived Waste Management

Management of investigation-derived waste (IDW) is described in the UGTA WMP (DOE/NV, 1996e), which provides a general framework for waste management at Yucca Flat investigation sites. Details regarding the characterization, storage, treatment, and disposal of wastes

generated at Yucca Flat investigation sites is to be addressed in site-specific field instructions or similar working-level documents. All wastes generated as a result of the Yucca Flat investigation activities are to be managed and disposed of in compliance with applicable federal, state, and local laws and regulations.

Based on an evaluation of available data and technical input from scientists supporting the UGTA program, the wells that are currently proposed for completion are under far-field conditions. This indicates that the potential for generating radioactive waste is remote. As for any other well, in the event that the wells are found to be radionuclide-contaminated, they will be converted to near-field wells. The presence of tritium in excess of the fluid management criteria listed in the UGTA FMP (DOE/NV, 1999c) will require the well to be reclassified as a near-field well. The designation of near- and far-field is important since the waste management strategies for the near- and far-fields wells differ in one aspect. Near-field activities require establishment of a controlled area where radioactive contamination would be closely monitored and managed; far-field activities do not.

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

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

6.3.1.2 Waste Minimization

The generation of IDW is minimized through the implementation of the comprehensive compliance program. Waste minimization is achieved through the control of hazardous materials, materials substitution, and waste segregation. Hazardous materials are controlled, managed, and tracked in

accordance with Occupational Safety and Health Administration (OSHA) requirements and applicable procedures and protocols. Material substitution is implemented wherever possible to prevent or minimize the generation of a hazardous waste. Waste such as effluent and personal protection equipment (PPE) are segregated to the greatest extent possible to minimize the generation of hazardous, radioactive, and/or mixed waste.

6.3.2 Health and Safety

The health and safety of workers and the public and protection of the environment will have the highest priority during the Yucca Flat/Climax Mine CAI, in accordance with DOE Integrated Safety Management System. Worker protection will be achieved through compliance with DOE Orders, OSHA regulations, the primary Real Estate/Operations Permit (REOP) holder's Health and Safety Plan (HASP), and site-specific health and safety plans (SSHASPs). For example, should the ITLV hold a primary REOP on the site, then compliance with the ITLV HASP (IT, 2000) will be required. Requirements specified in these documents are subject to change, and the work performed for this CAI is to be conducted in accordance with the most current published versions of these documents.

When radiological constituents are present in groundwater at levels of occupational health concern or are anticipated due to the proximity of the well to an underground nuclear test, additional documents apply. Work controls are guided by the NTS Radiation Protection Program (RPP) (DOE, 1990), *NV/YMP Radiological Control (RadCon) Manual* (BN, 1996c), and 10 CFR 835, "Occupational Radiation Protection" (CFR, 1999b). The NTS RPP establishes the policy by which radiological doses are maintained within acceptable limits and radiation exposures are maintained as-low-as-reasonably-achievable (ALARA) below these limits. The *NV/YMP RadCon Manual* represents DOE-accepted guidelines and best practices for implementing NTS and Yucca Mountain Project radiation protection programs in accordance with 10 CFR 835 regulations (CFR, 1999b).

The HASP is the "governing" document under which all UGTA environmental restoration operations are conducted. The HASP prescribes the minimum procedures that will be followed while performing field operations and describes the roles and responsibilities of key project personnel. Its requirements are written to comply with DOE Orders and federal regulations such as 29 CFR 1910 (CFR, 1999c) and 29 CFR 1926 (CFR, 1999d).

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

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

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

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

The tritium concentration in groundwater produced at the surface is monitored hourly. If tritium is detected above the action level set in the SSHASP, operations are conducted in accordance with Radiological Work Permits. Precautions include wearing water-impervious clothing when handling

materials that have contacted the groundwater and the establishment of radiologically controlled areas to prevent the contamination of personnel. Engineering controls such as closed fluid transport systems and sampling enclosures may also be invoked to prevent worker contact with groundwater and keep potential exposure ALARA. Workplace radiological monitoring is specified in the Radiological Work Permit(s) and is used to control potentially-contaminated materials and to prevent these materials from leaving the established radiologically controlled area. Such precautions also control potential contamination from fission products.

6.3.3 Sampling and Analysis

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

6.3.3.1 Solid Sampling and Analysis

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

If contamination is suspected at a site, surface and subsurface soil samples may be collected prior to initiation of construction activities. At drilling pad sites, nonintrusive surface radiological surveys will be conducted with portable survey instruments. If warranted by the survey results, surface and shallow subsurface soil samples will be collected for field and laboratory chemical and radiochemical analysis.

Rock cutting samples are collected from the drilling fluid discharge line as the borehole is advanced. Core samples are collected using percussion sidewall, rotary sidewall, vertical rotary, or similar techniques. The sampling frequency and intervals for collection of rock cuttings and core samples are performed in accordance with task-specific plans and the appropriate procedures. Field screening for any potential contaminants is conducted at each sample interval. Field analysis of rock cuttings and

core samples is performed by on-site and off-site geologists to describe and identify the rocks penetrated during drilling operations. Laboratory testing to determine hydrologic, physical, and chemical properties may also be performed on selected cuttings and core samples.

The activities associated with the collection, processing, and description of cuttings and core are performed as directed in task-specific plans and in accordance with approved procedures such as AMEM-03-300 (DOE/NV, 1999a).

6.3.3.2 *Fluid Sampling and Analysis*

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

Fluids generated during all phases of the operation are managed in accordance with the requirements contained in the UGTA FMP (DOE/NV, 1999c), site-specific plans, field instructions, and as discussed in Sections 6.4.1 and 6.4.1.1. Fluids produced during drilling, well completion, and well development and testing are collected for both field and laboratory analysis. Fluids that do not meet the fluid management criteria for release to an unlined infiltration basin are contained in lined sumps.

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

Groundwater samples include characterization samples from newly installed wells and samples from wells used as water-supply wells for drilling and well construction. Groundwater characterization samples are collected from the newly installed wells at the completion of well development and periodically thereafter until the well is taken out of service or until monitoring is no longer required. Water-supply wells are sampled prior to their use. Sampling and analysis of the water-supply wells

ensure that the groundwater is free of target constituents. It also establishes background water chemistry and radiochemistry levels for constituents of concern and provide baseline data for wells not previously sampled.

Process fluid and groundwater samples are collected, processed, and transported in accordance with state and federal regulations, and applicable standard procedures. If on-site monitoring or other knowledge indicates the potential for environmental samples to meet the definition of hazardous material under U.S. Department of Transportation (DOT) regulations, internal contractor procedures for the transport of hazardous materials shall be followed. These contractor procedures mandate compliance with applicable DOT shipping regulations. Specific guidance for this type of sampling is provided in site-specific plans and instructions and in accordance with appropriate procedures. Process fluid samples collected for fluid management purposes are analyzed for selected metals, tritium, gross alpha, and gross beta parameters as specified in the UGTA FMP (DOE/NV, 1999c). All groundwater samples are then sent to an analytical laboratory to be analyzed for the parameters listed in Table 5-1 of the UGTA QAPP (DOE/NV, 2000). The analyses listed in this table include metals, major ions, general chemistry, age and migration parameters, radiological indicator parameters, nuclear fuel products, and other radionuclides.

6.3.3.3 *Quality Assurance*

All sampling and analysis tasks are conducted in accordance with the requirements of the UGTA QAPP (DOE/NV, 2000). [Section 7.0](#) of this CAIP provides a summary of the QA program.

6.3.3.4 *Field Quality Control*

Project participants ensure that field QC samples are collected and submitted to a selected analytical laboratory in a manner consistent with the UGTA QAPP (DOE/NV, 2000). The frequency, number, and type of QC samples collected during drilling activities are specified in site-specific plans, project plans, the UGTA QAPP (DOE/NV, 2000), and appropriate procedures. The types of QC samples may include field duplicates, equipment rinsate blanks, and, if necessary, rinsate source blanks. Collection and documentation of field QC samples are conducted in accordance with approved plans and procedures that meet the requirements of the UGTA QAPP (DOE/NV, 2000).

6.3.3.5 Waste Management

Waste in the form of PPE, sampling equipment, and drilling materials is generated as a result of this investigation. Specific requirements for characterization sampling of these wastes are contained in [Section 6.3](#) of this document and also in the UGTA WMP (DOE/NV, 1996e).

7.0 Quality Assurance

A comprehensive QA program has been developed for all activities performed under the UGTA Project, including those defined in this CAIP. That program is documented in the UGTA Quality Assurance Project Plan, Revision 3, dated August, 2000 (DOE/NV, 2000). This CAI requires all three different types of activities addressed in the QAPP: assessment of existing data, modeling, and collection of new data.

7.1 Assessment of Existing Data

Section 5.1 of the UGTA QAPP addresses evaluation of data, including existing data. During the data documentation evaluation for this CAI, flags will be assigned to indicate the level of knowledge about the data collection process and traceability in addition to the requirements in the QAPP. The five levels of Data Documentation Evaluation Flags are as follows:

- Level 1: Data are collected in accordance with DOE/NV ERP QAPPs, approved State of Nevada procedures, and/or participant-specific procedures. This ranking indicates that all supporting documentation for the data is on file and is available for review by data users.
- Level 2: Data are collected in accordance with approved plans and procedures as required for Level 1 with the exception that one or more documentation requirements may be deficient in some way. Examples of data documentation deficiencies may include lost or destroyed field-data collection forms or data acquired using interim or draft procedures.
- Level 3: Data are collected using accepted scientific methodology (e.g., ASTM, EPA methods, USGS procedures) and being accompanied by supporting and corroborative documentation such as testing apparatus diagrams, field or laboratory notes, and procedures.
- Level 4: Data are collected by a participating DOE/NV ERP organization or another organization not associated with the DOE/NV ERP prior to the issuance and implementation of project-approved standard policies, procedures, or practices governing data acquisition and qualification. The methods of data collection are documented and traceable; however, the validity and prudence of data use or compliance with referenced procedures is indeterminate. Supporting documentation may or may not exist.

Level 5: Data are obtained under unknown, undesirable, or uncertain conditions. When data documentation is unknown, any available supporting or helpful descriptions of the intended use and conditions of data capture should be described and listed in Part II of the Data Information Form.

Based on the traceability of the data, individual records will be further evaluated for suitability of use for the purposes of this CAI.

7.2 *Modeling*

The QA requirements for modeling are specified in Section 5.2 of the UGTA QAPP (DOE/NV, 2000) and generally consist of software/hardware configuration control, technical evaluation of new codes, code verification and validation activities, and software documentation. Output from modeling runs will be well documented and traceable to the code from which it was generated. Participating organizations' procedures will provide details for the specific methods used for performing these activities.

7.3 *Collection of New Data*

Extensive requirements for the collection of samples to obtain new data are provided in Section 5.3 of the UGTA QAPP (DOE/NV, 2000). Participating organizations' standard procedures must meet the requirements of the DOE/NV ERP procedures and will be used to perform sample collection, handling, documentation, and analysis.

Data from newly collected samples will be evaluated against the criteria established in the QAPP (DOE/NV, 2000) and this CAIP prior to use.

8.0 Duration and Records/Data Availability

The duration of the CAI and availability of associated data and records are provided in this section.

8.1 Duration/Data Availability

The duration of the work as described in this plan, up to and including the preparation of the Corrective Action Decision Document, is projected to be approximately 2.5 years following the initiation of the CAI. Quality-assured results of sampling will initially be available within 90-calendar days of the date on which they are collected for the purposes of this investigation.

8.2 Document/Records Availability

This CAIP and all unclassified primary supporting documents/documentation are available to the extent allowed by law (and as addressed in paragraph XIII.3 of the FFACO [1996]), in the DOE Public Reading Rooms located in Las Vegas and Carson City, Nevada, and from the DOE/NV UGTA Project Manager. The Nevada Division of Environmental Protection maintains the official Administrative Record for all activities conducted under the auspices of the *Federal Facility Agreement and Consent Order* (1996). For further information about where to obtain documents and other data relevant to this plan, contact Mr. Robert Bangerter, Project Manager, UGTA Project, at (702) 295-7340.

9.0 References

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Appendix A

Data Quality Objectives

A.1.0 Data Quality Objectives for Yucca Flat/Climax Mine: CAU 97¹

The Data Quality Objectives process is a systematic project planning tool developed by the EPA to help collect environmental data that are important to decision making. The EPA has published DQO guidance to assist users in implementing the process for various EPA programs (e.g., EPA, 1993 and 1994). Section 1.5, “Implementing Corrective Action Investigations and Corrective Actions,” of the Corrective Action Strategy (Appendix VI, FFACO [1996]), states that DQOs will be conducted. In addition, DOE and NDEP agreed to hold kickoff meetings at the start of the DQO process for each CAU (DOE/NV, 1996c).

In accordance with this agreement, a kickoff meeting for the Yucca Flat/Climax Mine DQO process was held on November 10, 1999. Participants included the DOE Project Manager, a NDEP representative, and contractor personnel. An attendance list for the meeting is provided in [Table A-1](#).

A.1.1 Data Quality Objectives Approach

The FFACO (1996) requires that the DQO process be used to plan the corrective actions, but does not specify the format that will be used to guide the process and report the results. The EPA has published various methods for implementing a systematic DQO planning approach. Among these

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1. The Yucca Flat and Climax Mine testing areas were originally defined as two separate CAUs in the FFACO: CAU 97 and CAU 100 (FFACO, 1996), but were later on combined into a single Corrective Action Unit (CAU 97). It was originally proposed to address each CAU individually because the geologic frameworks of the two areas are distinctly different. The Yucca Flat underground nuclear tests were conducted in alluvial, volcanic, and carbonate rocks; whereas, the Climax Mine tests were conducted in an igneous intrusion located in northern Yucca Flat. However, particle-tracking simulations performed during the regional evaluation (Section 5.5 of the regional model documentation package [IT, 1997a]) indicate that the local Climax Mine groundwater flow system merges into the much larger Yucca Flat groundwater flow system, during the 1,000-year time period of interest. These simulations indicate that groundwater flow paths passing through the underground nuclear tests of the Climax Mine CAU will enter northern Yucca Flat through the Lower Carbonate Aquifer. In addition, it is expected that smaller-scale contaminant transport modeling would also predict that contaminants from Climax Mine tests would enter the Yucca Flat groundwater flow system within the 1,000-year period of interest. Additional considerations for addressing the two CAUs jointly include reductions in administrative costs and classification issues. As the result of these considerations, the U.S. Department of Energy, Nevada Operations Office has determined that the best way to proceed is to investigate the two CAUs simultaneously and, therefore, requested the two CAUs be combined by adding the Climax Mine Corrective Action Sites to CAU 97. This request was accepted by the Nevada Division of Environmental Protection on March 21, 2000 (Liebendorfer, 2000).

Table A-1
DQO Kickoff Meeting Attendance List

Name	Organization
Bob Bangerter	U.S. Department of Energy, Nevada Operations Office
Bruce Hurley	U.S. Department of Energy, Nevada Field Office
Les Winfield	U.S. Department of Energy, Nevada Field Office
Clem Goewert	Nevada Department of Environmental Protection
Janet Wille	IT Corporation
Warda Drici	IT Corporation
Sig Drellack	Bechtel Nevada
Ken Rehfeldt	HSI Geotrans, Incorporated
Robert Sobocinski	IT Corporation
Tad Beard	Science Applications International Corporation
William Fryer	HSI Geotrans, Incorporated
Rick Waddell	HSI Geotrans, Incorporated
Barb Deshler	IT Corporation

methods is the three-step method (EPA, 1987a), which was later expanded to a seven-step method (EPA, 1993 and 1994).

Figure A-1 presents the DQO approach used for the Yucca Flat/Climax Mine CAU and its relationship to the two EPA methods (EPA, 1987a; 1993; and 1994). The approach used for the Yucca Flat/Climax Mine CAU (center column of Figure A-1) was a logical, orderly progression that resulted in a clear statement of the data needed for its Corrective Action Investigation. The approach consists of three major steps consistent with the three-step method (EPA, 1987a). Although the approach does not match the seven-step method (EPA, 1993), it offers many similarities.

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

The second step in the process is the definition of the information needed for the decision which includes the identification of the necessary data, the sensitive groundwater flow and transport

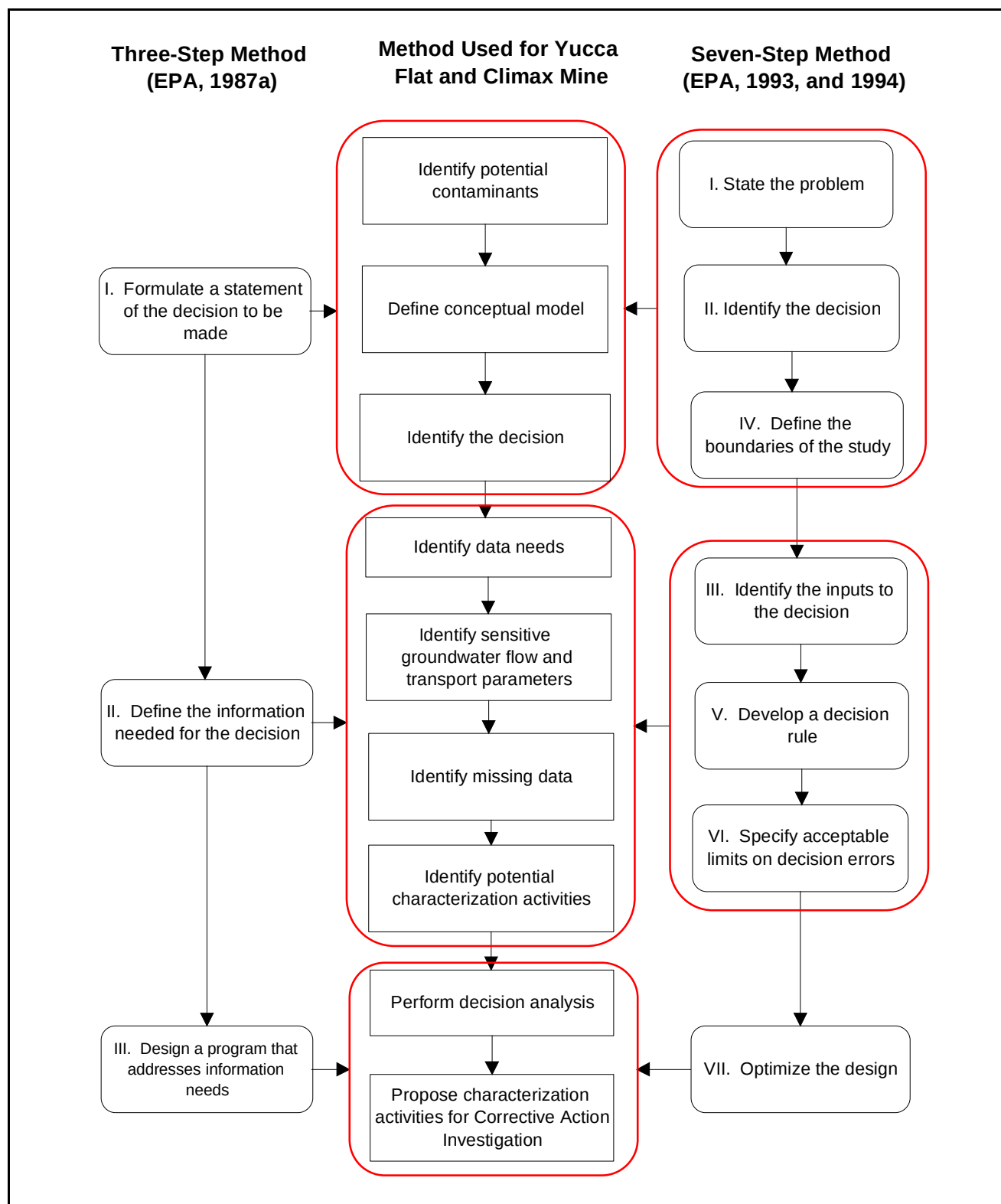


Figure A-1
Comparison of Data Quality Objectives Process Used
for Yucca Flat and Climax Mine with EPA Methods

parameters, and the additional data needed and associated characterization activities. This step corresponds to the third, fifth, and sixth steps of the seven-step process, to identify the inputs to the decision, develop a decision rule, and specify acceptable limits on decision errors.

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

The data quality objectives process feeds on several elements of the UGTA project, namely the FFACO (1996), the regional model of groundwater flow and contaminant transport (DOE/NV, 1997b), the VOIA (IT, 1999), and other factors unaccounted for in the VOIA. These relationships are illustrated in [Figure A-2](#). The statement of the decision, which corresponds to Step I of the DQO process, is derived from information obtained from the regional model, the FFACO, and the VOIA. The identification of the inputs to the decision, which corresponds to Step II of the DQO process, is entirely covered under the VOIA. The optimization of the design, which corresponds to Step III of the DQO process, is partly conducted under the VOIA. However, factors that are unaccounted for in the VOIA are also considered by the UGTA Project Manager to complete this last step of the DQO process.

The VOIA (IT, 1999) included the following steps:

- Compilation of existing data from the regional data documentation packages
- Identification of data needs and data gaps
- Identification of sensitive parameters
- Identification of quantity and quality of additional data needed and associated characterization options
- Costing of characterization options
- Quantification of effect of data characterization options on uncertainty reduction
- Comparison of characterization options through decision analysis

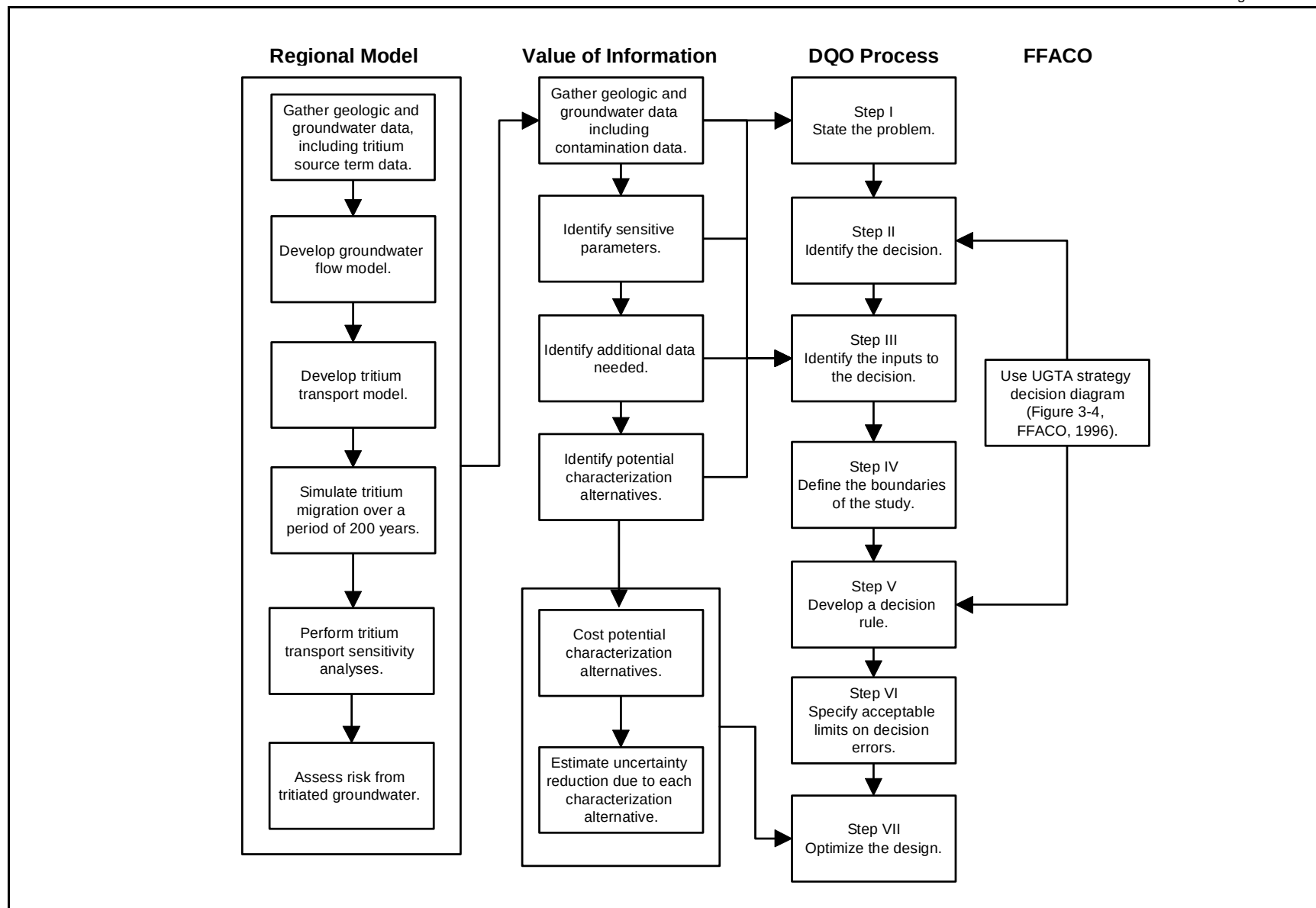


Figure A-2
Relationship of the Data Quality Objectives Process to Other UGTA Project Elements

A nonprobabilistic approach was used to identify the quantity and quality of the additional data needed for the Yucca Flat/Climax Mine CAI. This is not inconsistent with the EPA approach (EPA, 1987a; 1993; and 1994). As stated by EPA (1993), statistical procedures may not be applied to certain environmental problems. “Non-probabilistic or subjective (judgemental) sampling approaches can be useful and appropriate for satisfying certain field investigation objectives (EPA, 1993).” The approach used to design the characterization activities for the Yucca Flat/Climax Mine CAI was specifically directed at filling the data gaps relevant to contamination migration.

The regional model (DOE/NV, 1997b) was used in the VOIA (IT, 1999) to evaluate the impact that additional data collected under various potential characterization activities would have on the uncertainty associated with the location of the contaminant boundary. The simulations associated with this evaluation are very time-consuming. To shorten the computation time and simplify the process, the transport model (IT, 1996c) was used without running the groundwater flow model. Groundwater flux along a generic pathline was calculated from hydraulic heads (gradient) and hydraulic conductivities derived from the regional groundwater flow model (IT, 1997a). This groundwater flux term was used as an input to the regional contaminant transport model to simulate radionuclide transport along the generic pathline. Thus, the whole flow model was represented by the groundwater flux term in the transport model. A multiplier of the groundwater flux was used in the VOIA to represent the range of uncertainty in the groundwater flux term caused by the uncertainties associated with all parameters involved in the groundwater flow model (i.e., geology, recharge, hydraulic conductivity, flow path uncertainty). A slope multiplier was also used to account for the uncertainties associated with the length of the generic pathline from between the TCU and the LCA.

A.1.2 Data Quality Objectives Results

The DQO process used for the Yucca Flat/Climax Mine CAU is described in terms of the EPA three-step process ([Figure A-3](#)).

A.1.2.1 Formulation of a Statement of the Decision to be Made

The first step in the process is the *formulation of a statement of the decision to be made* which includes the identification of the potential contaminants, a description of the current conceptual model including the areas of uncertainty, and a statement of the decision at hand.

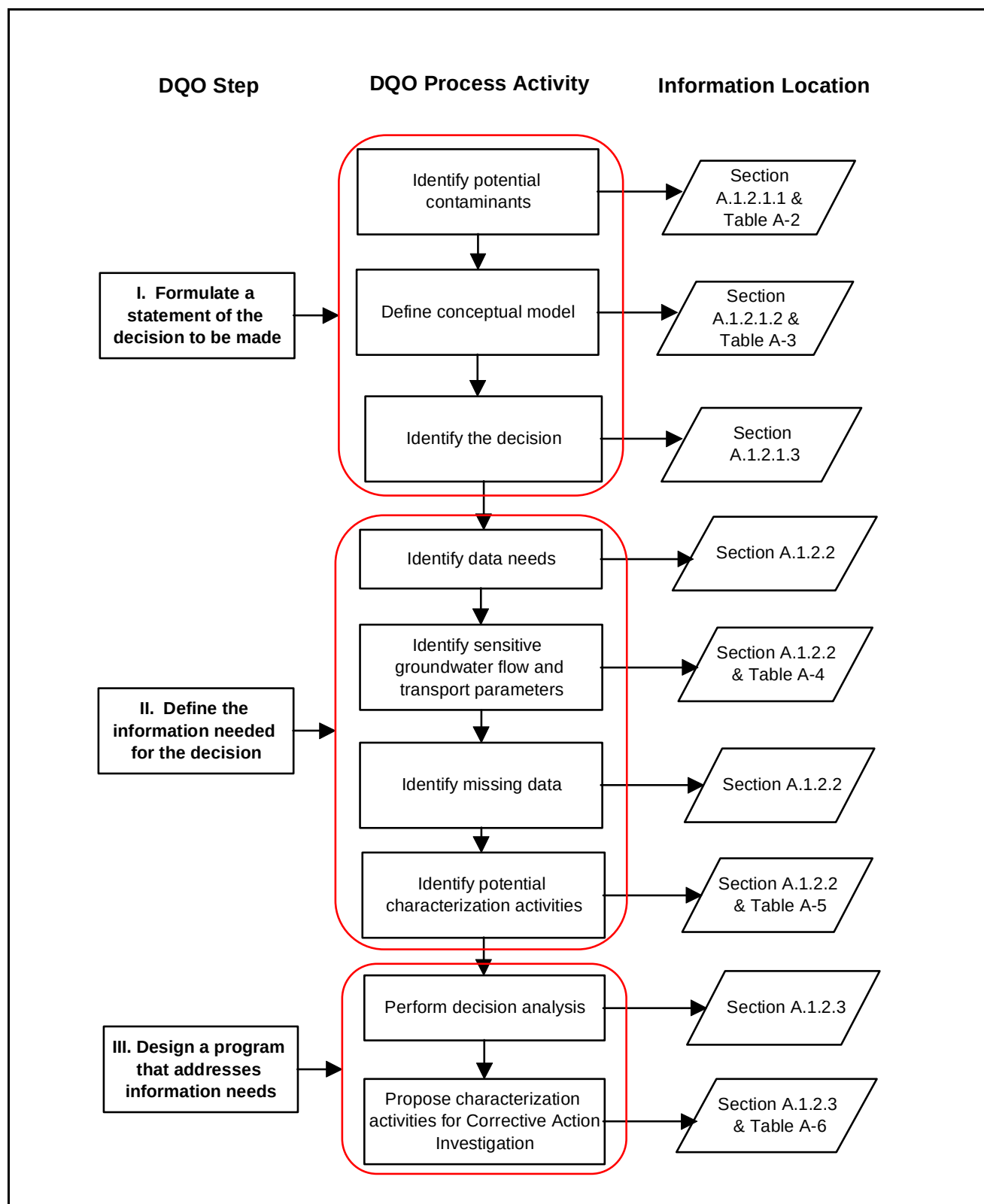


Figure A-3
Data Quality Objectives Process Used for Yucca Flat and Climax Mine

A.1.2.1.1 Potential Contaminants

Table A-2 lists the major potential contaminants which were selected based on empirical measurements, knowledge of the sources, and information about the risk posed by radioactive and hazardous contaminants. The table shows the range of values estimated by the UGTA TWG VOIA Subcommittee for each isotope included in the Yucca Flat/Climax Mine VOIA (IT, 1999). Concentration ranges for hazardous constituents were not estimated. Preliminary action levels are proposed for each potential contaminant. If these levels are exceeded, they will be used to trigger further action during the Corrective Action Investigation, either through measurements or modeling. The regulatory source of each PAL has been provided for information; however, the PALs are not intended as compliance levels at this time. Where available, *Safe Drinking Water Act* maximum contaminant levels are used (SDWA, 1996). Finally, the table lists analytical protocols for measuring the potential contaminants and specifies practical quantitation limits for each potential contaminant. This will enable comparisons to be made among the predicted range of concentration, PAL, and practical quantitation limit for each potential contaminant.

A.1.2.1.2 Conceptual Model

An overview of the current conceptual model of the Yucca Flat/Climax Mine CAU is presented in this section. A more detailed description will be presented in the CAIP.

Yucca Flat is an alluvial basin typical of the Basin and Range physiographic province and is located in the northeastern quadrant of the NTS. A total of 747 underground nuclear tests were conducted in Yucca Flat and Climax Mine. Of the 747 tests, 744 were conducted in Yucca Flat and three in Climax Mine. All Yucca Flat tests were conducted in vertical emplacement holes. Only one test was conducted in a shaft at Climax Mine; the other two tests were detonated in tunnels. Media contaminated by the underground nuclear tests of Yucca Flat and Climax Mine are subsurface soils within the unsaturated and saturated zones. Groundwater transport is the primary means of migration for the subsurface contamination away from the Yucca Flat and Climax Mine underground nuclear tests. Table A-3 presents a summary of the major elements of the conceptual model of the Yucca Flat/Climax Mine area, which are the groundwater flow system, contamination sources, current extent of contamination, future extent of contamination, current and future land use, potential receptors, and potential exposure routes. In addition, descriptions of the conceptual model of

Table A-2
Preliminary List of Major Potential Contaminants

Contaminant	Estimated Range of Dissolved Concentrations in the Test Cavity		Preliminary Action Level	Regulatory Source for PAL	Practical Quantitation Limit	Analytical Protocol
	Minimum	Maximum				
³ H (Tritium)	1E + 07	1E + 10	2E+04 pCi/L	40 CFR 141.16 (CFR, 1999b)	200 pCi/L	EPA-600/4-80-032 ^a Method 906
¹³⁷ Cs	1	1E + 03	5E+01 pCi/L	40 CFR 141.16 (CFR, 1999b)	20 pCi/L ^b	EPA-600/4-80-032 ^a Method 901.1
^{239/240} Pu	1E + 02	1E + 05	1.6E+00 pCi/L	10 CFR 20.1420 (CFR, 1999a)	1 pCi/L	NAS-NS-3050 ^c
¹⁴ C	1E + 02	1E + 05	2E+03 pCi/L	40 CFR 141.16 (CFR, 1999b)	10 pCi/L	EPA 520/5-84-006 ^d
⁹⁰ Sr	1E + D1	1E + 04	8E+00 pCi/L	40 CFR 141.16 (CFR, 1999b)	1 pCi/L	NAS-NS-3010 ^e
²³⁸ U	1E - 01	1E + 02	2.2E+01 pCi/L	DOE Order 5400.5 (DOE, 1990) 10 CFR 20.1420 (CFR, 1999a)	1 pCi/L	NAS-NS-3058 ^f
¹²⁹ I	1.48E - 02	1.48E + 01	5E-01 pCi/L	40 CFR 141.16 (CFR, 1999b)	10 pCi/L	EPA-600/4-80-032 ^a Method 906
²⁴¹ Am	1E + 01	1E + 04	1.5E+00 pCi/L	40 CFR 141.16 (CFR, 1999b)	1 pCi/L	HASL 300 (DOE, 1977)
²³⁷ Np	1	1E + 03	1.2E+00 pCi/L	40 CFR 141.16 (CFR, 1999b)	1.5 E-07 dpm/L	EPA 6020
Pb ^g (Lead)	NA	NA	1.5E+01 µg/L	40 CFR 141.80(c) (CFR, 1999c)	3 µg/L	SW-846 Method 6010 ^h

^a EPA, 1980

^b As required of analytical laboratories by DOE/NV (1996b)

^c Coleman, 1965

^d EPA, 1987b

^e Sunderman and Townley, 1960

^f Grindler, 1962; EPA, 1979

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

^h EPA, 1996

µg/L = Microgram(s) per liter

dpm/L = Disintegration per minute per liter

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Table A-3
Summary Conceptual Model of the Yucca Flat/Climax Mine CAU

Conceptual Model Element	Description	Source
Groundwater Flow System	The groundwater flow system of the Yucca Flat/Climax Mine CAU and downgradient areas includes all groundwater below the water table within a region stretching from the northern boundary of the Nevada Test Site, south and southwestward to Amargosa Valley. The region encompasses Climax Mine, Yucca Flat, Frenchman Flat and stretches down to the Amargosa Desert. Geologic units within this region include alluvium, bedded tuffs, welded tuffs, lava flows, fractured Paleozoic carbonates, and clastic confining units. Major aquifers include the LCA, the VA, and the AA. Several confining units also exist in the area.	Regional modeling results (DOE/NV, 1997b)
Contamination Sources	The hydrologic source terms of 747 underground nuclear detonations constitute the sources of groundwater contamination in Yucca Flat and Climax Mine. The major potential contaminants identified for the 1,000-year period of interest include tritium, cesium-137, plutonium-239/240, carbon-14, strontium-90, uranium-238, iodine-129, americium-241, neptunium-237, and lead.	Value of Information Analysis (IT, 1999)
Current Extent of Contamination	The contamination is currently located in the test cavities and their vicinity. The maximum horizontal distance from the location of an underground nuclear test is 300 to 500 m (984 to 1,640 ft) from the test locations. Vertically, the contamination is believed to extend into the LCA.	HRMP reports Regional modeling results (DOE/NV, 1997b)
Future Extent of Contamination	The potential contaminants are predicted to be moving south to southwest from Yucca Flat and Climax Mine toward the Amargosa Desert. Considering the 1,000-year time frame of interest, the lateral contamination was predicted to reach the southern end of the NTS. The direction of contaminant movement will vary spatially because of geologic variability and temporally due to changes in the amount and timing of recharge.	Regional modeling results (DOE/NV, 1997b) Value of Information Analysis (IT, 1999)
Current and Future Land Use	Yucca Flat is reserved as a nuclear test zone. The area located downgradient of Yucca Flat includes the southern portion of the NTS and a portion of the Amargosa Desert which is part of the public lands used for farming, mining, and recreation.	Environmental Impact Statement (DOE/NV, 1996a)
Potential Receptors	Off-site and on-site users of groundwater are potential receptors.	Environmental Impact Statement (DOE/NV, 1996a)
Potential Exposure Routes	Exposure routes include ingestion, dermal contact, irradiation, and inhalation. For the purpose of the CAI, the drinking water scenario is used in the definition of the contaminant boundary.	Regional evaluation (DOE/NV, 1997b)

groundwater flow and contaminant transport in Yucca Flat/Climax Mine area are provided in this section. The primary sources of information supporting the Yucca Flat/Climax Mine conceptual model were the regional modeling results (IT, 1996a through f; IT, 1997a and b; DOE/NV, 1997b) and the Yucca Flat/Climax Mine VOIA (IT, 1999).

Groundwater Flow System

This description of the groundwater flow system of Yucca Flat/Climax Mine area covers the geology and hydrogeology of the area.

The geology of the Yucca Flat/Climax Mine area comprises all rock units found in the region which consist of the following in chronogeological order: Precambrian and Paleozoic sedimentary rock units, Mesozoic granitic intrusives, Tertiary volcanic and sedimentary rocks, and Quaternary alluvial fill.

Precambrian and Paleozoic rocks are regionally extensive and occur under the basins as basement rocks. The uppermost 4,600 m (15,088 ft) of silicic clastics and carbonates are Cambrian through Pennsylvanian dolomite, interbedded limestone, and persistent shale and quartzite layers. The lowermost 3,000 m (9,840 ft) of the pre-Tertiary section consist of Late Precambrian to Middle Cambrian quartzites and siltstones. Outcrops of Precambrian and Paleozoic sedimentary rocks occur at the rim of the Yucca Flat basin.

Mesozoic intrusive rocks occur at the north-northeast edge of Yucca Flat. A granitic intrusive which intrudes Paleozoic and Precambrian rocks at the northern end of Yucca Flat forms the Climax Stock where the Climax Mine is located. The stock is exposed over an area of approximately 2.4 km (1.5 mi) north-south and 1.6 km (1 mi) east-west.

Outflow sheets of tuffs from the volcanic centers located west of the basin were emplaced on the irregular paleotopographic surface of the basin during the Tertiary Period. The youngest sediments of the valley are sand and gravel, derived from the volcanic and sedimentary rocks in the surrounding highlands. These sediments fill the Yucca Flat basin. The most prominent structures are related to basin-and-range extensional faulting that is generally younger than the volcanic rocks. Fault strikes are mostly north-south in Yucca Flat.

The hydrostratigraphy of the Yucca Flat/Climax Mine and immediate vicinity consists of several aquifers and confining units. The major aquifers are the Lower and Upper Carbonate Aquifers; the VA which consists of the Welded Tuff Aquifer, Vitric Tuff Aquifer, the TCU 2, and Topopah Spring Tuff Aquifer; and the AA. The main confining units are the Lower and UCCU; and the TCU 1. The hydraulic conductivity data available for the NTS region show that in general, the most transmissive aquifer is the LCA, followed by the AA and finally the VA (Table 6-2 of Volume IV of the regional evaluation model [IT, 1996b]). Based on site-specific data, the hydraulic conductivity of the LCA ranges between 0.005 and 228 m/d (0.02 and 748 ft/d), based on eight single-well tests. The hydraulic conductivity of the AA ranges between 0.06 and 2 m/d (0.2 and 7 ft/d), based on two single-well tests. No site-specific hydraulic conductivity data are available for the VA; however, data from the NTS region ranges indicates that the hydraulic conductivity of the VA varies between 0.0003 and 12 m/d (0.0009 and 40 ft/d).

A number of wells provide water-level information in the areas of Yucca Flat and Climax Mine (Figure A-4). The available data suggest that groundwater elevations mimic the topography to some extent. Groundwater elevations are highest beneath Climax Mine and on the northern, eastern, and western edges of Yucca Flat and drop off gradually towards the axis of Yucca Flat and to the south (Figure A-4). Except for perched springs, no groundwater discharges from the regional flow system within the Yucca Flat/Climax Mine area and vicinity. According to the NTS regional model (DOE/NV, 1997b), groundwater flows south and southwest to eventually discharges at Franklin Lake Playa and Death Valley (Figure A-4).

Groundwater flow within the Yucca Flat/Climax Mine area is part of the NTS groundwater flow system, which is part of the Death Valley flow system. The Yucca Flat/Climax Mine groundwater flow system has no physical lateral hydrologic boundaries. Regional groundwater flow beneath the Yucca Flat/Climax Mine area occurs through fractures and solution cavities of the LCA. The general groundwater flow direction is to the south and southwest towards the Amargosa Desert (Figure A-4). The bulk of the groundwater flow from Yucca Flat/Climax Mine area to the Amargosa Desert occurs through a narrow band of the LCA which follows the axis of Yucca Flat along the Yucca Fault and extends south to northern Amargosa Desert. This band of LCA forms a preferential flow path because it is believed to have large transmissivities. The high-transmissivity zone ends in the Amargosa Desert where groundwater velocities decrease and flow splits into two directions, south

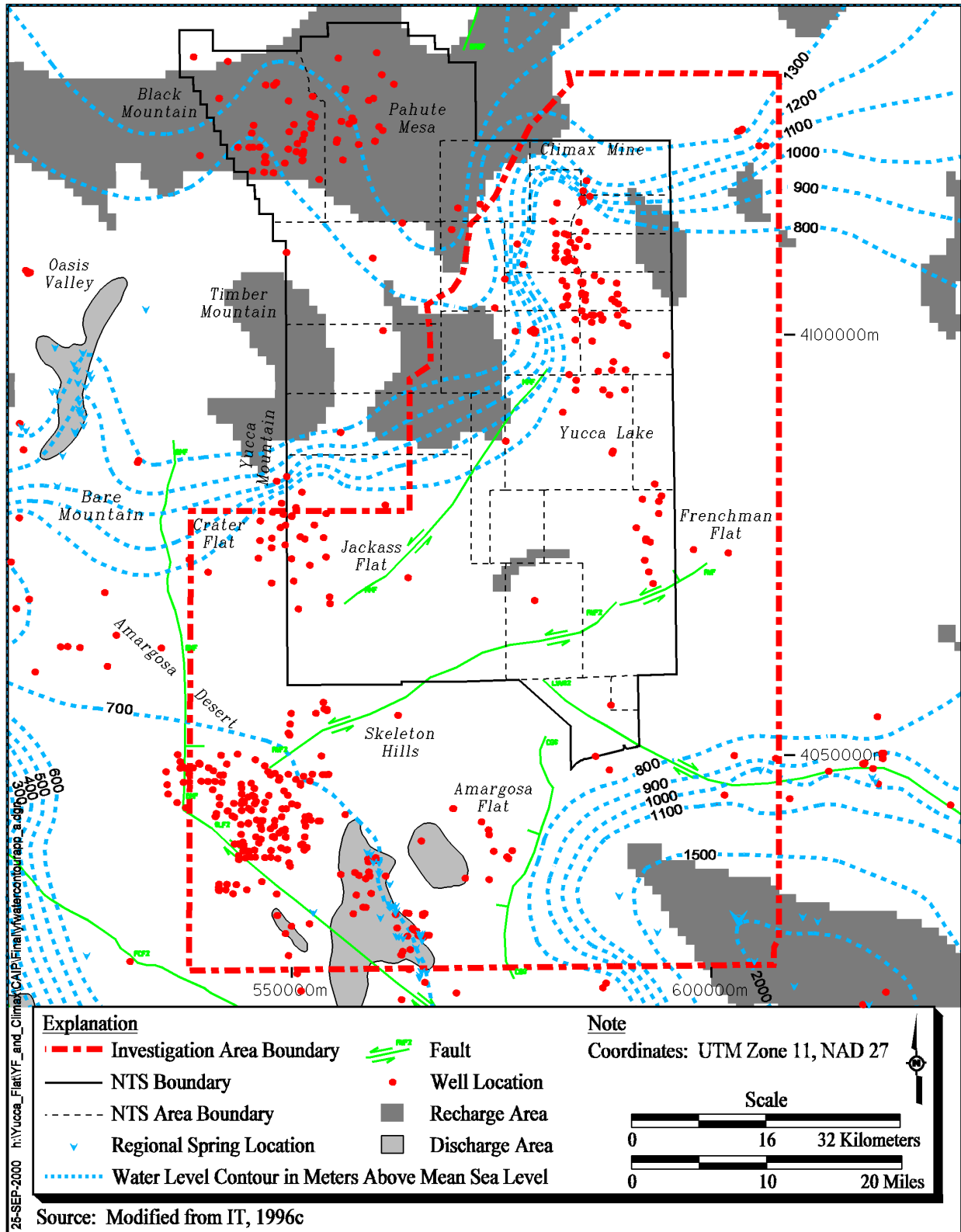


Figure A-4
Composite Predevelopment Water Level Contour Map
for the Yucca Flat/Climax Mine Investigation Area

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and southwest. Groundwater moving to the southwest towards the Death Valley discharge area slows down considerably when it moves into the AA of the Amargosa Desert. Groundwater moving to the south continues moving in the LCA until it discharges to the surface at Franklin Lake Playa (DOE/NV, 1997b). Observed trends of vertical hydraulic gradients are downward from the Cenozoic to the carbonate units.

Groundwater recharge occurs by underflow from areas located to the north, northwest and west of Yucca Flat, and from local precipitation. The flux into Yucca Flat from the north was calculated to be approximately 28,000 cubic meters per day (m^3/d) (DOE/NV, 1997b). This value is believed to be high; the actual flux value is likely to be lower. Groundwater flux from the west, the other major component of water entering Yucca Flat, is derived from an area west and northwest of Yucca Flat. Flow from the west was calculated to be about 1,750 m^3/d (DOE/NV, 1997b). Some groundwater recharge is believed to result from precipitation on the highlands of the Yucca Flat/Climax Mine area at Rainier Mesa and Shoshone Mountain. The main areas of areal recharge from precipitation are shown in [Figure A-5](#). No surface discharge from the regional flow system occurs within the Yucca Flat/Climax Mine area. A portion of the Yucca Flat/Climax Mine groundwater discharges at the Franklin Lake Playa. The remainder of the groundwater flows southwest through the Amargosa Desert and ultimately discharges at the Death Valley discharge area. In 1999, 306 million liters (81 million gallons) of groundwater were pumped from three water-supply wells located in Yucca Flat: Wells WW-4, WW-4A, WW-C-1 (USGS, 1999) ([Figure A-5](#)). This amounts to less than one third of the amount of subsurface inflow into Yucca Flat from the north and the west of about 11 million m^3 per year (as simulated by the regional model). Groundwater was also pumped from other water-supply wells located within the investigation area. These wells include: UE-16d WW to the west of Yucca Flat; UE-5c WW, WW-5B, and WW-5C in Frenchman Flat; Army 1 WW in Mercury Valley; and J-12 WW and J -13 WW in Jackass Flat.

Particle tracking simulations were performed during the regional evaluation (DOE/NV, 1997b). These simulations were used to identify the pathlines that imaginary particles would follow from given nuclear test locations through the groundwater flow model. Pathlines help define groundwater flow directions and potential migration pathways. The particle tracking results, Figure 7-26 in the regional evaluation report (DOE/NV, 1997b), show that pathlines originating at the Yucca Flat/Climax Mine test locations follow the general direction of flow, south and southwest, across the

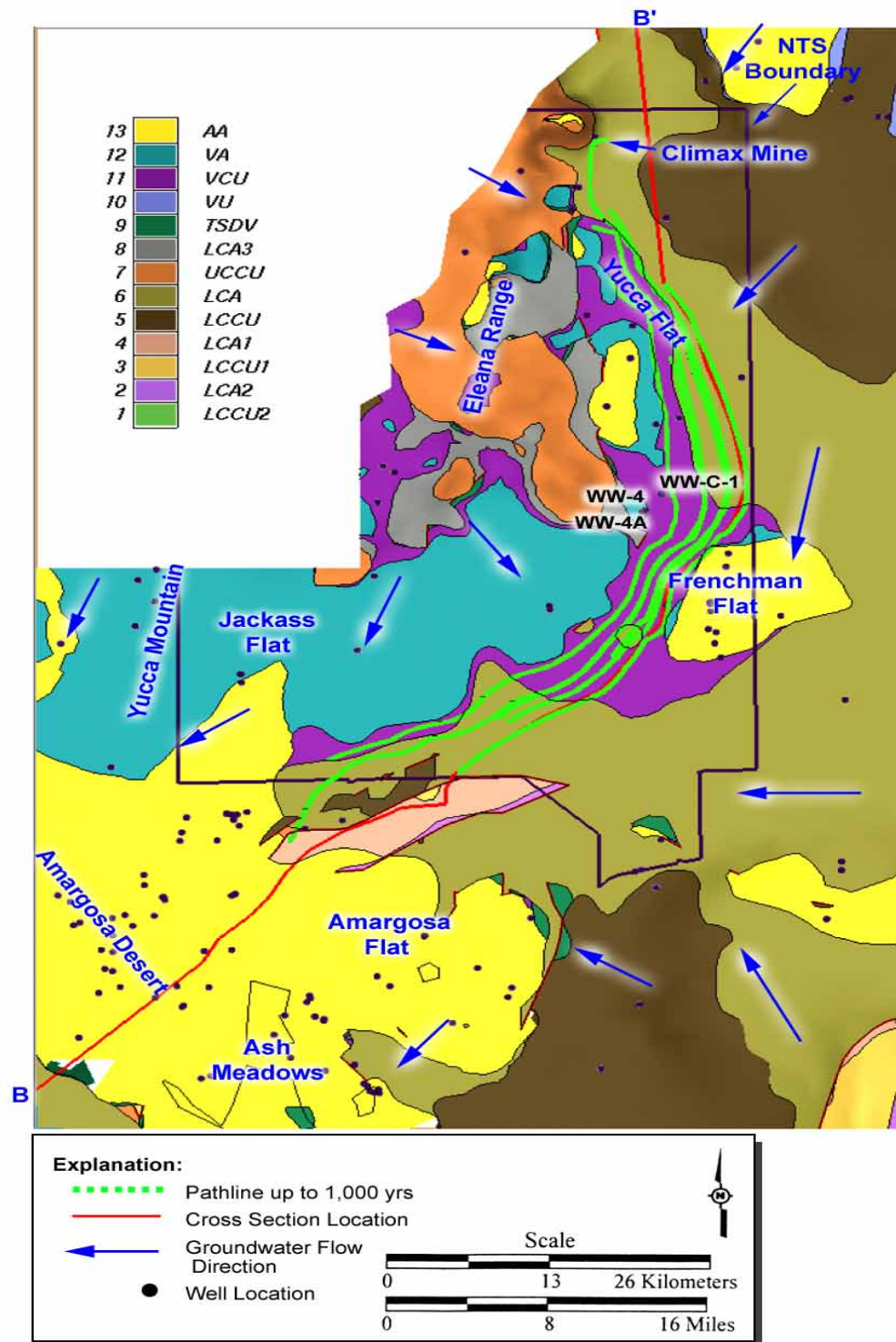


Figure A-5
Plan View of the Yucca Flat/Climax Mine Conceptual Model

Yucca Flat/Climax Mine area. The pathlines would indicate that groundwater ultimately discharges in the Franklin Lake Playa and Death Valley discharge areas, located to the south and southwest of the Yucca Flat/Climax Mine area.

Contaminant Transport

This overview of contaminant transport in the Yucca Flat/Climax Mine area includes summary descriptions of the sources of contamination, the release mechanisms to groundwater, migration routes, contaminant transport processes, and simulated extent of contamination.

Each of the underground nuclear tests resulted in a test cavity, rubble chimney and a disturbed area extending beyond the cavity by approximately one cavity radius. The saturated portion of the test cavity, rubble chimney, and disturbed area forms the volume of the contamination source created by a given underground nuclear test. Approximately 20 percent of the Yucca Flat and Climax Mine underground nuclear tests were detonated either below or within 100 m (328 ft) of the water table. Potential contaminants include radionuclides used and/or created during the nuclear test, and possibly other hazardous constituents used in the tests. As shown in [Table A-2](#), major radionuclides include: tritium, carbon-14, cesium-135/137, iodine-129, plutonium-239/240, strontium-90, americium-241, neptunium-237, and uranium-238 (IT, 1999).

During the nuclear tests, contaminants may have been promptly injected into the subsurface materials surrounding the nuclear device. However, it is believed that only a very limited amount of prompt injection occurs. Following the nuclear test, the cavity refills with groundwater and contaminant release into groundwater is initiated. No site-specific information on contaminant release processes exists. However, based on general information about underground nuclear tests, contaminant release processes into groundwater include leaching and ion exchange (Borg et al., 1976). Contaminants may leach from the melt glass, the rubble chimneys, or the fracture surfaces and pore spaces adjacent to the test cavities. Ion exchange processes may also release contaminants that are bound to minerals of the rubble after groundwater refills the rubble chimney.

The major contaminant migration processes of interest to the Yucca Flat/Climax Mine area include advection, dispersion, sorption, matrix diffusion, and radioactive decay. One underground nuclear test, BOURBON, was selected for tritium transport simulations during the regional evaluation (DOE/NV, 1997b). The results of these simulations for the BOURBON test are presented in

Figures 6-6 through 6-9 of the *Tritium Transport Model Documentation Package* (IT, 1996f). The simulated transport distance for the 20,000 pCi/L from the origin of the pathline was 20 km (12 mi) at the 50 percent confidence level, and at 35 km (22 mi) at the 95 percent confidence level. These locations of the extent of the 20,000 pCi/L are within the boundaries of the NTS.

A generic pathline was used to model transport from sources in Yucca Flat during the Yucca Flat/Climax Mine VOIA (IT, 1999). This pathline was constructed to represent flow from a source in the TCU to the LCA, and then downgradient in the LCA. Whereas most actual pathlines are expected to traverse the LCA and the AA of the Amargosa Desert before reaching the Death Valley discharge area, the generic pathline was assumed to stay within the LCA all the way to the discharge area.

The transport simulations were initially performed for all radionuclides of concern listed in [Table A-2](#). All but three of the radionuclides were eliminated because they were not found to contribute significantly to the predicted contaminant boundary within the 1,000-year time frame of interest. This was due to various factors such as low initial concentrations, low dose per concentration, short half-lives, and high distribution coefficients (resulting in substantial sorption) relative to other radionuclides of concern. The three radionuclides that were found to contribute to the prediction of the location of the contaminant boundary are tritium, carbon-14, and plutonium-239/240. The distance of the 4-mrem/yr dose at 50 percent confidence (using the prior distributions) within 1,000 years along the generic pathline is 58 km (36 mi) ([Figure A-6](#)) (Table F-2 on page F-4 of VOIA report [IT, 1999]). The distance calculated at the 95 percent confidence level is not representative of reality because it was assumed that the generic pathline would continue moving through the LCA all the way to Death Valley. In reality, pathlines originating from tests in Yucca Flat and Climax Mine enter and traverse the AA of the Amargosa Desert before reaching the Death Valley discharge area.

The results of the transport simulations performed during the VOIA (IT, 1999) were further extrapolated to selected underground nuclear tests to estimate the expected distance from the source of the 4-mrem/yr dose within a 1,000-year period. The corresponding distances are depicted in [Figure A-5](#), which also shows the locations of the water-supply wells. As shown in this figure, the water-supply wells are not expected to intersect contaminant migration pathways within the 1,000-year period. No contamination has been observed to date at these wells.

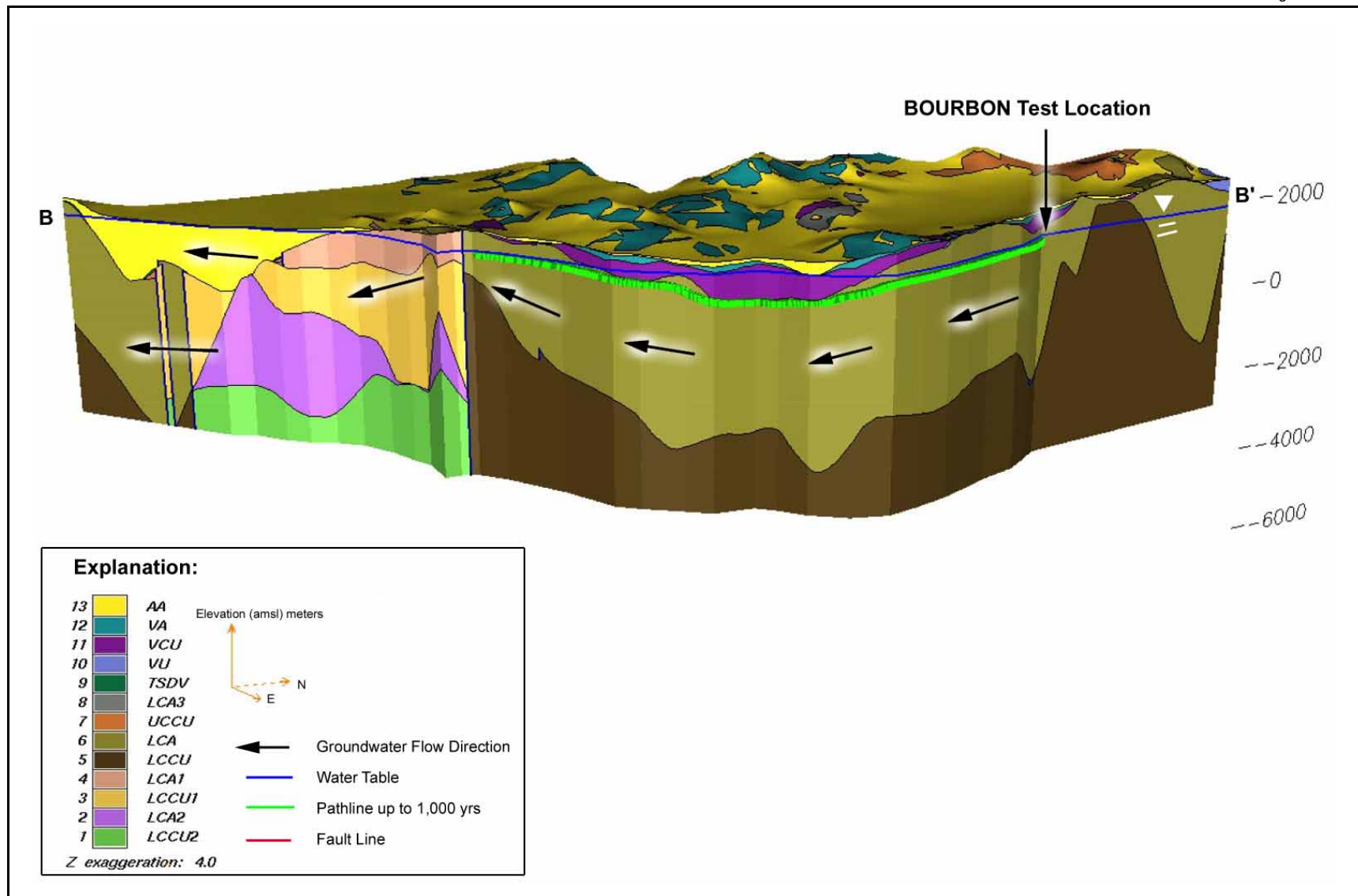


Figure A-6
Downgradient Distance of 4-mrem/yr Dose from Location of BOURBON Nuclear Test in Yucca Flat
at 50 percent Confidence Level and within 1,000 Years

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Uncertainties

The current conceptual model of the Yucca Flat/Climax Mine area has several areas of uncertainties which are as follows:

- A lack of subsurface geologic characterization for the entire Yucca Flat/Climax Mine area, and a lack of hydrologic characterization in specific areas
- Insufficient characterization of the hydrochemical framework of the Yucca Flat/Climax Mine region
- Limited knowledge of the contaminant transport processes and associated parameters
- Limited understanding of the contamination sources

A.1.2.1.3 Statement of the Decision

Based on the information on the potential contaminants and the current conceptual model described above, a statement of the decision was made as follows: *Can an acceptable groundwater flow and transport model be formulated for the Yucca Flat/Climax Mine area using the existing data?*

A.1.2.2 Definition of the Information Needed for the Decision

The second step in the process is the definition of the information needed for the decision which includes the identification of the necessary data, the sensitive groundwater flow and transport parameters, the additional data needed, and the associated characterization activities.

The information needed for the decision is necessary to develop a groundwater flow and contaminant transport model that represents reality at an acceptable level of uncertainty. This information consists of geologic data, groundwater data including contamination sources and concentrations in groundwater, and an understanding of the processes that cause contaminants to migrate in groundwater. As stated before, such information was gathered during the regional evaluation (DOE/NV, 1997b) and the Yucca Flat/Climax Mine VOIA (IT, 1999), and was used to define the current conceptual model described in the previous step. The areas of uncertainty that exist in this conceptual model correspond to data or information gaps identified during the regional evaluation (DOE/NV, 1997b). These include data gaps in uncharacterized portions of the area of interest and an insufficient understanding of the hydrochemical framework, contaminant transport processes at work

and the sources of contamination. Due to these uncertainties, it was determined that an acceptable groundwater flow and transport model could not be formulated for the Yucca Flat/Climax Mine area using the current conceptual model. Additional data were deemed necessary to address the areas of uncertainty.

The DQO approach used for the Yucca Flat/Climax Mine CAU to gather the missing information does not include the use of statistical procedures. A non-probabilistic approach was used instead. This is not inconsistent with the EPA approach (EPA, 1987a; 1993; and 1994). As stated by EPA (1993), statistical procedures may not be applied to certain environmental problems.

“Non-probabilistic or subjective (judgemental) sampling approaches can be useful and appropriate for satisfying certain field investigation objectives (EPA, 1993).” Such is the case for the Yucca Flat/Climax Mine CAU. The objective of the CAI is to predict the location of the contaminant boundary using a digital model. The prediction of a credible contaminant boundary must, therefore, rely on a digital model that is representative of reality, which in turn depends on how well-defined the conceptual model of the problem area is. The current conceptual model is believed to be sufficiently defined except in specific areas where relevant data gaps exist. Thus, the approach used to design the characterization activities was specifically directed at filling these data gaps.

To prioritize the additional data needed, sensitivity analyses were conducted on the regional model. The sensitivity analyses were performed to determine which groundwater flow and transport parameters have the most effect on the results of flow and transport modeling. In the Yucca Flat/Climax Mine VOIA, the results indicate that the most sensitive parameters are flux, effective porosity, matrix diffusion, hydrologic source term, and slope multiplier. In the one-dimensional transport model, flux is used to represent the results of the groundwater flow model and incorporates groundwater flow variables such as the definition of the HSUs (types, thickness, structure, and hydrologic properties) and recharge distribution. The slope multiplier was designed to account for uncertainties in the pathline before it reaches the LCA. [Table A-4](#) lists the five sensitive parameters along with their descriptions, and their importance in contaminant boundary predictions.

Based on the identified areas of uncertainties and the results of the sensitivity analyses, the following priority information needs were defined:

- TCU extent and mineralogy
- Structure of basin structures and structures within the basin

Table A-4
Sensitive Parameters in Transport Modeling

Parameter	Parameter Description	Importance
Diffusion (alpha) in the LCA	The diffusion mass transfer coefficient (alpha) controls, in part, the movement of radionuclides between the fractures and the rock matrix. It combines diffusion, matrix and fracture characteristics.	In saturated fractured rocks, most movement of groundwater and radionuclides occurs in the fractures. However, a fraction of the radionuclides will move into the rock's pore spaces, or diffuse in the rock matrix, and move back out into the fractures at a later time. This process reduces the concentration within the fractures and slows down the rate of radionuclide migration. Matrix diffusion is quantified by the diffusion parameter. The larger the diffusion parameter, the smaller the migration distance.
Hydrologic source term	As used here, this term refers to the concentration of radionuclides within the nuclear test cavity and chimney region that is available for groundwater transport.	Some of the radionuclides are contained deep within the glass that cooled from the melted rock following the detonation and are not readily available for transport. Others may be sorbed or held onto the surfaces of the glass or rock inside the cavity or chimney. The rate at which a radionuclide enters the groundwater, either by leaching out of the near surface of the glass or desorbing from the cavity materials, controls the concentration of that radionuclide in the groundwater. A rapid release rate produces a short-term but high concentration source term. A slow release rate produces a long-term contamination source at a smaller concentration.
Effective porosity in the LCA	Average large-scale effective porosity along the flow path.	In fractured rocks, not all fractures may be connected such that groundwater flow through the area actually moves through all or all parts of the fractures. Some fractures, parts of fractures, or networks of fractures may only be connected over the space of inches or feet, and the water contained within these "dead" networks is essentially stagnant. Effective porosity is a measure of the interconnected network of fractures along the flow path where groundwater predominantly flows and most contaminant migration occurs. The effective porosity is a major factor determining the speed with which groundwater moves in an aquifer. For a given flux, the smaller the effective porosity, the faster groundwater will move through an aquifer.
Slope multiplier across the TCU to the LCA	The actual distance that contaminants from any particular source would travel in the TCU before entering into the LCA.	The TCU is the confining unit that generally separates the sources from the LCA, in which transport is much faster. The longer the path length, the longer the time it would take contaminants to reach the LCA. Since the prediction of the maximum extent of the contaminant boundary is time limited due to decay of the contaminants, the longer time spent in the TCU reduces the predicted transport distance. Also, the regional flow model does not contain detail at the scale of the individual test that captures the true distance to the LCA for each individual source. Since the contaminant boundary may be determined by a presently undetermined subset of the sources rather than the average of all the sources, this uncertainty could be important.
Flux from the north	The rate of groundwater inflow into the Yucca Flat/Climax Mine area from the north, simulated in the regional flow model.	The amount of groundwater moving through an area is represented by the groundwater flux. Flux is currently the most important parameter in the prediction of potential contaminant migration rate. Uncertainty in the flux resulting from lack of knowledge about the geology, aquifer parameters, and recharge is accounted for in this parameter. This parameter is relatively hard to calibrate since it represents a small percentage of the flux in the regional model.

- Hydrogeologic data and groundwater chemistry data for the area located in the vicinity of Wells ER-6-1 and ER-6-2
- Verification of the origin and flow paths of groundwater and estimates of travel times from the Yucca Flat/Climax Mine area to the discharge areas
- Estimates of transport parameters, including effective porosity, dispersivity, matrix diffusion, adsorption and colloidal transport
- Definition of the near-field environment

During the VOIA (IT, 1999), an array of possible data-collection options was identified that could address the identified data deficiencies. The individual activities considered are provided in [Table A-5](#). The table lists the activities, describes each one, and also identifies the specific parameter(s) each activity is designed to address. Further information on the VOIA process is available in the VOIA (IT, 1999).

All data collected during these activities for purposes of improving the current conceptual model of the Yucca Flat/Climax Mine CAU must be collected using stringent QA procedures specified in a QA plan.

A.1.2.3 Design of a Program That Addresses Information Needs

The third and last step of the process is the *design of a program that addresses information needs*. During this step of the DQO process, further analyses conducted during the VOIA (IT, 1999) and the results of the regional evaluation (DOE/NV, 1997b) were used as tools to design a program that addresses the information needs.

During the VOIA (IT, 1999), the characterization options identified in the second step of the DQO process were evaluated and compared with respect to their cost and ability to reduce uncertainty in the model input parameters or the location of the contaminant boundary. The analysis compared the cost of executing the characterization options with their usefulness in reducing uncertainty and resulted in rankings of the options. The VOIA resulted in the determination of a short list of activities and groups that are optimal for the objectives of uncertainty reduction and cost minimization.

Table A-5
Potential Characterization Activities
(Page 1 of 3)

Activity	Activity Name	Activity Description
A1	Alternate Hydrogeologic Model	Develop an alternate hydrogeologic model for Yucca Flat which includes a structural interpretation of Northwest Yucca Flat and an extension of the Yucca Flat hydrostratigraphic model to area located north.
A2	New Wells North of Yucca Flat	Drill, install, and test three new holes to characterize the southern end of the Belted Range near the northern NTS border, north of Yucca Flat. Use wells to monitor water levels and groundwater chemistry.
A3a	New Wells on the Western Boundary of Yucca Flat	Drill, install, and test two new deep wells on the west margin of Yucca Flat to improve characterization of this area. Monitor the wells for water levels and groundwater chemistry on a regular basis.
A4	Isotope/Geochemistry Mass Balance Studies	Collect and analyze 20 water quality samples from springs and wells in Yucca Flat and vicinity (major ion chemistry, trace metals, and environmental isotopes), and use the data to characterize groundwater flux into the basin.
A5	Basin Recharge Studies	Conduct precipitation measurements in the uplands, flow monitoring in selected drainages, neutron probe investigations, and studies of inflow and infiltration in craters to improve the estimates of groundwater recharge.
A6	Groundwater Heads in the TCU and LCA	Monitor groundwater heads at six existing boreholes in the TCU and six existing boreholes in the LCA within Yucca Flat, to evaluate vertical gradient patterns.
A7	Potentiometric Trough in South-Central Yucca Flat	Drill two wells in south-central Yucca Flat penetrating the upper LCA, determine the geology, measure the vertical gradient, and collect groundwater samples from different depths to characterize the potentiometric trough.
A8	Geologic Structure of Major Faults	Drill three slanted boreholes through major faults with offset to the LCA and characterize the geology, vertical gradient, potentiometric head, and water quality of the HSUs present.
A9	Hydraulic Properties of Fault Zones	Drill two wells penetrating the upper LCA at the location chosen for the major fault studies. Determine the geology and vertical gradient. Conduct a suite of pumping tests to characterize the hydraulic conductivity within and across the fault zone.
A10	Geophysical Interpretation of the Paleozoic Framework	Incorporate the interpretation of the LCA surface and Paleozoic structure based on geophysical data into the Yucca Flat hydrostratigraphic model. Independently verify the inversion data set using data from existing seismic data.

Table A-5
Potential Characterization Activities
(Page 2 of 3)

Activity	Activity Name	Activity Description
A11	Variability of TCU Mineralogy	Evaluate existing mineralogic data, identify data gaps, acquire additional data from existing holes, and incorporate the information into a map illustrating the mineralogic variability of the TCU in Yucca Flat. Retardation capacity will then be assessed from the mineralogic properties of the TCU.
A12	Existing Phenomenologic Data On Test Effects	Analyze pretest data, shock wave calculations, and post-test data to evaluate the impact of the tests on the media. Include the information in the near-field geochemical and hydrologic source term models where appropriate.
A13	Mineback Data From Rainier Mesa Tunnel Tests	Investigate the effect of underground nuclear tests on the surrounding geologic media and post-test distribution of radionuclides. Synthesize the published and unpublished data into a conceptual model.
A14	Near-Field Sampling	Drill one borehole downgradient of a test cavity and rubble chimney, penetrating the subsurface two cavity radii above and below the working point. Collect water quality and solid samples from the borehole. Incorporate the data from this investigation into the hydrologic source term model.
A15	Test-Cavity Sampling	Drill into a test cavity to a depth of two cavity radii below the working point of the test. Multilevel well completion would be required to meet the sampling criteria. Collect water quality and solid samples from borehole. Incorporate the data from this investigation into the hydrologic source term model.
A16	Hydrologic Source Term Modeling	Conduct laboratory testing of radionuclide behavior using cavity samples and saturated debris, and geochemical and hydrologic modeling to determine the hydrologic source term for Yucca Flat and Climax Mine.
A17	Multi-Well Tracer Test in the LCA	Conduct a multi-tracer test in the LCA near BILBY using specifications similar to the BULLION Forced Gradient Experiment (FGE) [includes drilling one new well]. Analyze the results of the test using the numerical modeling methodology applied to the BULLION FGE.
A18	Analysis of Two Existing Tracer-Test Datasets	Analyze data collected during two multi-well tracer tests previously conducted in the LCA to obtain estimates of dispersivity and effective porosity values for the LCA.
A19	Laboratory Diffusion Studies	Conduct 12 laboratory diffusion tests on samples from the upper LCA to measure the diffusion rates of a variety of tracers. The measured values will be used to constrain diffusion rates derived from large-scale tracer tests.

Table A-5
Potential Characterization Activities
(Page 3 of 3)

Activity	Activity Name	Activity Description
A20	Single-Well Tracer Tests in the VA and the LCA	Conduct six single-well, multi-tracer tests, three in the VA and three in the LCA, to provide data on the variability of the diffusion parameter values for these units.
A21	Earth-Tide Analysis of the VA and the LCA	Develop the earth-tide analysis methodology and collect earth-tide data in Yucca Flat from eight wells in the VA and LCA. Install water-level monitoring equipment in each well and collect measurements for three months. Analyze the datasets to determine effective porosity values for the two HSUs.
A22	Seismic Surveys of the Yucca Flat Basin	Conduct two-dimensional seismic surveys along three, 10-km lines, oriented east-west across the western and southern areas of the Yucca Flat basin, and incorporate new information into the model.
A23	Analysis of Existing Seismic Data	Evaluate all existing seismic data, including aftershock mapping, for additional information on geologic structure in Yucca Flat. Analyze, interpret, and incorporate the seismic data into the Yucca Flat/Climax Mine CAU hydrostratigraphic model.
A24	High-Pressure Zone In Northern Yucca Flat	Evaluate the hydrogeological and radionuclide migration data available for the Tuff Pile area of Yucca Flat using FEHM.
A25	Elevated Groundwater Temperatures in Eastern Yucca Flat	Identify 10 boreholes in the CAU suitable for thermal profiling. Conduct a thermal profile during two different time periods. Evaluate the effect of the temperature distribution on the measured groundwater head distribution and the resulting effects on predicted flow paths.
A26	Potential for Karst in the LCA	Evaluate carbonate formations similar to the upper LCA that crop out along the basin margins and other areas at the NTS for karst development. Evaluate the paleohydrology associated with these formations to determine the likelihood of karst development in the LCA.
A27	Hydraulic Conductivity with Depth	Review the literature in addition to field logs for evidence of karst in the LCA. Evaluate core and borehole video logs for evidence of karstic features in the LCA.

Characterization activities were then selected for inclusion in the Yucca Flat/Climax Mine Corrective Action Investigation based on the results of the VOIA (IT, 1999) and other DOE concerns and responsibilities. All data collected during these activities for purpose of building the CAU model of the Yucca Flat/Climax Mine area will be in compliance with the QAPP (DOE/NV, 2000). The data collected may include “screening data” as defined by EPA (1993) to provide for the timely detection of contamination indicators (tritium for radionuclides and lead for metals), for health and safety, and fluid management purposes. The selected characterization activities are listed in [Table A-6](#).

Summary descriptions of these activities are as follows:

Table A-6
List of Activities Proposed for the Yucca Flat/Climax Mine CAI

Activity Number	Activity Description
1	Mineralogy Study of the TCU
2	Geophysical Interpretation of the Paleozoic Framework
3	Analysis of Existing Seismic Data
4	Hydrogeologic Investigation of Wells ER-6-1 and ER-6-2
5	Isotope/Geochemistry Mass Balance Studies
6	Analysis of Existing Tracer Test Data
7	Laboratory Studies of Transport Processes
8	Rainier Mesa Colloid Studies
9	Analysis of Data for Phenomenological Models

Characterization Activity 1: Mineralogy Study of the Volcanic Confining Unit

This is a joint activity between BN and LLNL. Its purpose is to define the extent and nature of the TCU. The definition of the extent and physical nature of the TCU will help in the construction of the CAU-scale HSU model. The definition of the mineralogic nature of the TCU will help assess its retardation capacity. This activity includes evaluation of existing mineralogic data, the identification of data gaps, the acquisition of additional data from existing holes, and the development of maps illustrating the findings. The results of this activity will be used to build the HSU model for the Yucca Flat/Climax Mine CAU, and to estimate the adsorption properties of the TCU to refine the CAU contaminant transport model.

Characterization Activity 2: Geophysical Interpretation of the Paleozoic Framework

This is a joint activity between BN and the USGS. Its purpose is to estimate with greater resolution the projected depth to the top of the Paleozoics and permit interpretation of juxtaposition of various HSUs at (major) faulted surfaces. The study includes the compilation and reevaluation of existing borehole information, surface gravity and aeromagnetic data, and seismic data within the Yucca Flat/Climax Mine area. The geologic information collected during this activity will be used to better understand the Paleozoic framework and the configuration of Mesozoic intrusive rocks, and to provide increased definition in the hydrostratigraphic model of the Yucca Flat/Climax Mine area.

Characterization Option 3: Analysis of Existing Seismic Data

A comprehensive reinterpretation of existing two-dimensional seismic data incorporating current structural understanding is proposed under this activity. Key features, such as fault locations and HSU pinchouts or juxtapositions, will be investigated on a basin-wide scale. The analysis is expected to allow for imaging to depths below those previously considered. In addition, the use of seismic data obtained from local arrays and from regional seismological stations during underground nuclear tests will be evaluated for its contribution to understanding of geologic structure in Yucca Flat. The activity includes gathering and interpreting existing seismic data. The results will be used to develop the CAU-scale HSU model.

Characterization Activity 4: Hydrogeologic Investigation of Wells ER-6-1 and ER-6-2

This activity includes the completion and testing of Wells ER-6-1 and ER-6-2 which were drilled in Yucca Flat in 1992 and 1993. The wells will be completed to provide information on the hydrogeology and groundwater chemistry of the area located in their vicinity. The objectives for completion of these wells are to provide for long-term water quality monitoring of the uppermost part of the LCA, and to provide for multi-level head monitoring. Water quality monitoring in the upper part of the LCA is intended to detect the presence of radionuclides transported in groundwater. Multi-level head monitoring will provide both HSU head information and vertical gradient information. This activity includes well completion and development, and sample collection and analysis. The information collected will contribute to the development of the CAU-scale groundwater flow and contaminant transport model.

Characterization Option 5: Isotopic and Geochemistry-Based Investigation

This investigation is a combined effort of the LLNL, DRI, USGS, and ITLV. Its objectives are to independently verify the flow paths, and to estimate the age and travel time of groundwater that flows from Yucca Flat/Climax Mine area to the discharge areas. The activity includes the collection and analysis of groundwater, drill-bit cuttings, and core samples with subsequent interpretation of the data. The results will be used to update the geochemical database as well as in geochemical modeling of reaction paths, and groundwater age and implications for groundwater flow paths will be assessed.

Characterization Activity 6: Analysis of Existing Tracer Test Data

The purpose of this activity is to investigate the transport of radionuclides in groundwater by reanalysis of existing tracer test data. The data were obtained during the Amargosa Desert tracer tests. The tracer test data will be reanalyzed to determine values of transport parameters such as effective porosity, dispersivity, and matrix diffusion for the LCA; and to evaluate the relative mobility of radionuclides. These values will be used in estimating the appropriate ranges to be used in the CAU-scale model contaminant transport model.

Characterization Activity 7: Laboratory Studies of Transport Processes

The purpose of this activity is to obtain laboratory estimates of radionuclide transport parameters such as matrix diffusion, dispersion, sorption, and estimates of parameters describing colloid transport processes. The laboratory studies will be conducted using cores from the Yucca Flat/Climax Mine area. Lithology, fracture characteristics, and fracture coatings of selected cores from existing boreholes will be characterized. Tests will also be conducted to determine matrix diffusion coefficient values for rock samples and the effects of the fracture cores on the diffusion rate. The laboratory investigation of colloid behavior will be conducted using sorbing tracers and microspheres. The results of these experiments will be used in the CAU-scale contaminant transport model.

Characterization Activity 8: Rainier Mesa Colloid Studies

The objective of this activity is to investigate the geochemical and radiochemical controls on the movement of actinides introduced from underground weapons testing under ambient flow conditions such as found in the tunnel complexes. This study will provide information on transport of radionuclides under variably-saturated conditions, and will help to define the range of colloid-facilitated transport that may be expected under various groundwater conditions. These studies will help in the development of better contaminant transport models.

Characterization Activity 9: Analysis of Data for Phenomenological Models

The purpose of this task is to improve the current conceptual phenomenological models. The activity includes the evaluation of the measured dynamics of nuclear tests and pretest calculations to better understand potential radionuclide transport mechanisms (prompt injection), pathways (slow collapse, chimneys, tensile fracturing distances), and radionuclide deposition (bedding planes, fractures, faults). This information will benefit near-field modeling for determining the hydrologic source term.

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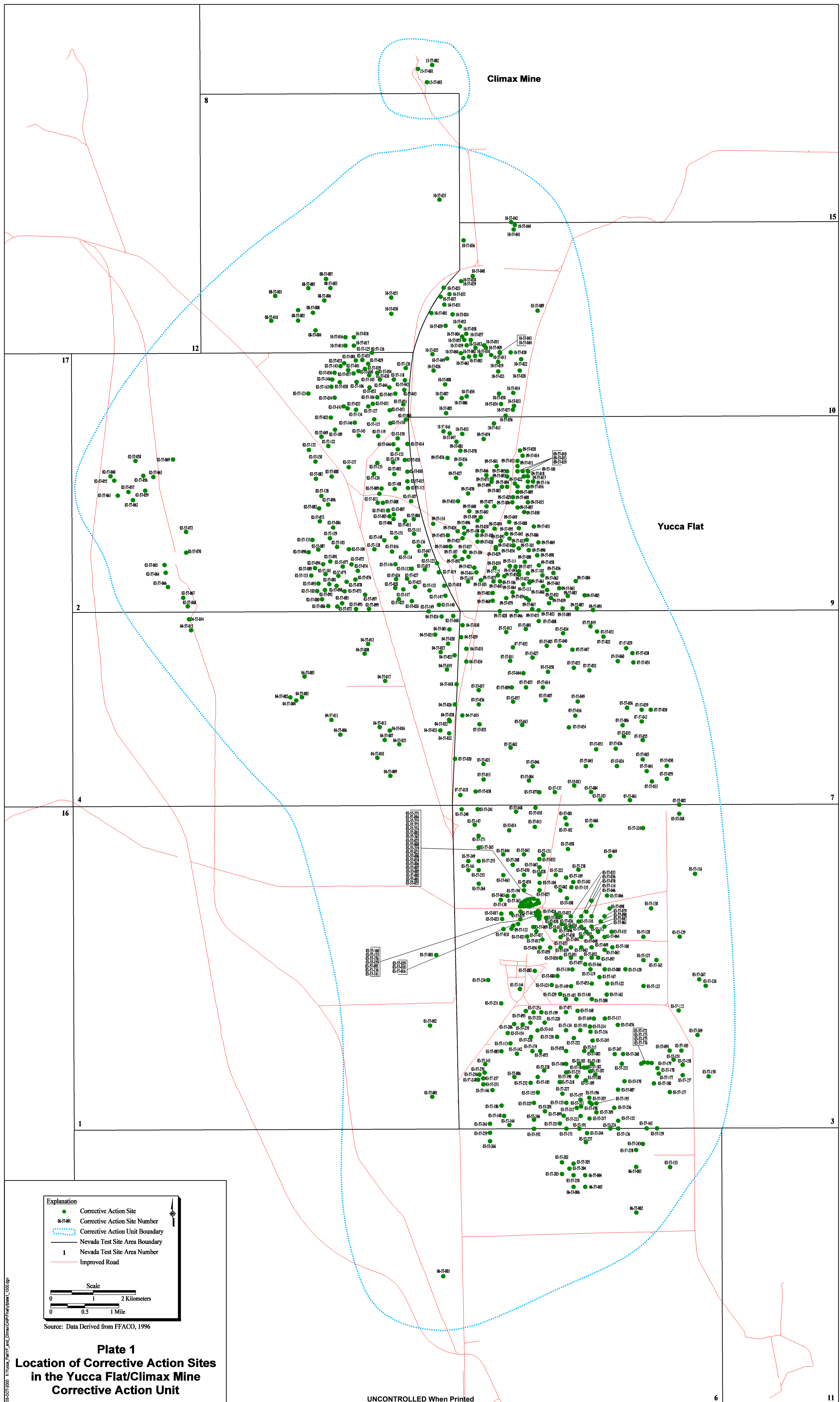
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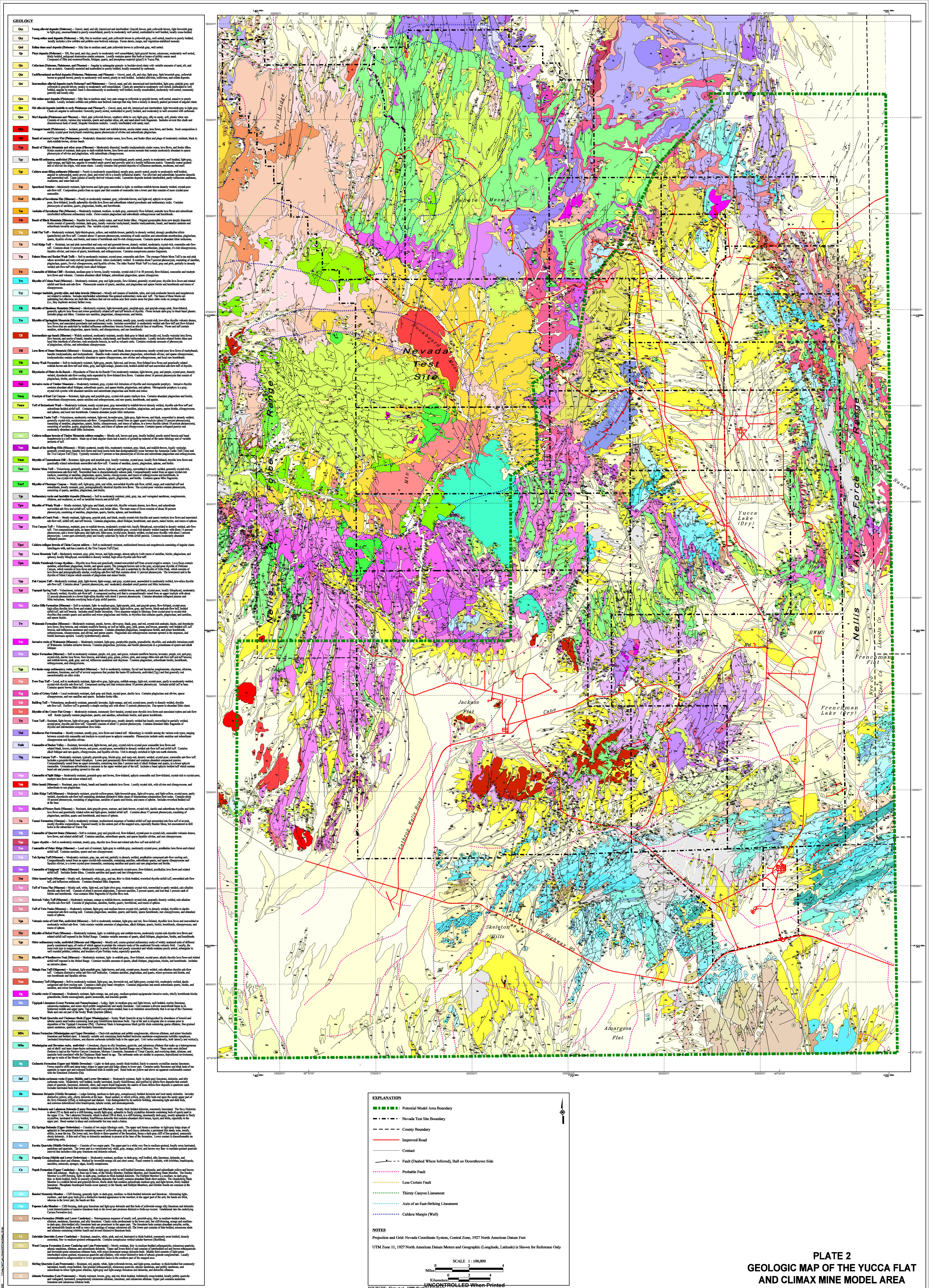
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Plates





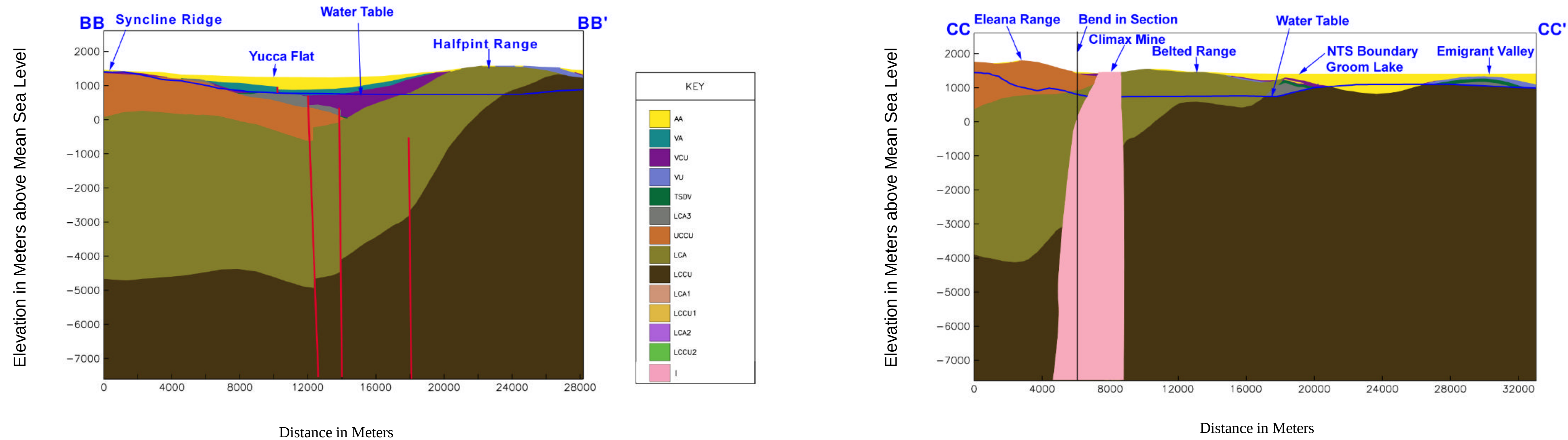
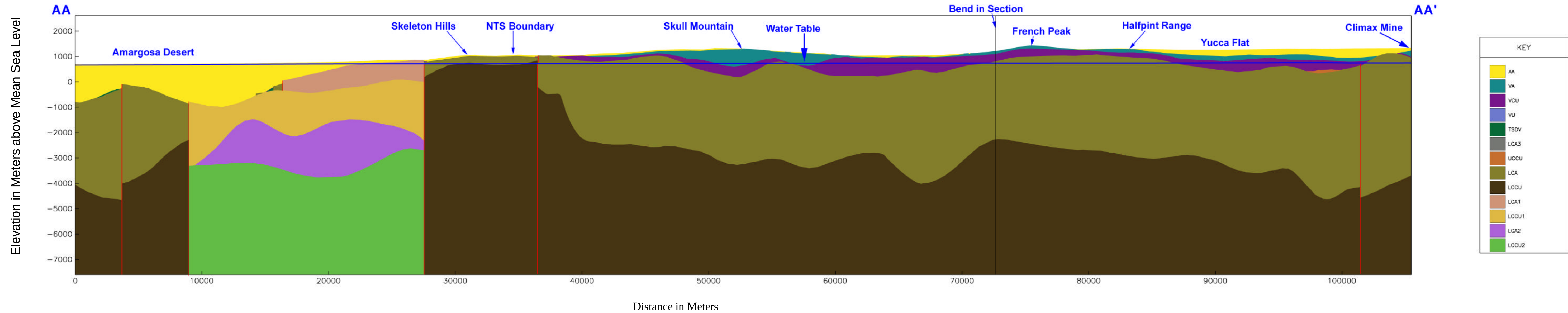
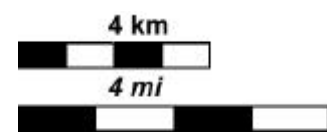


Plate 3

HYDROSTRATIGRAPHIC CROSS SECTIONS ACROSS THE YUCCA FLAT/CLIMAX MINE INVESTIGATION AREA

SCALE:



VERTICAL EXAGGERATION = 2X

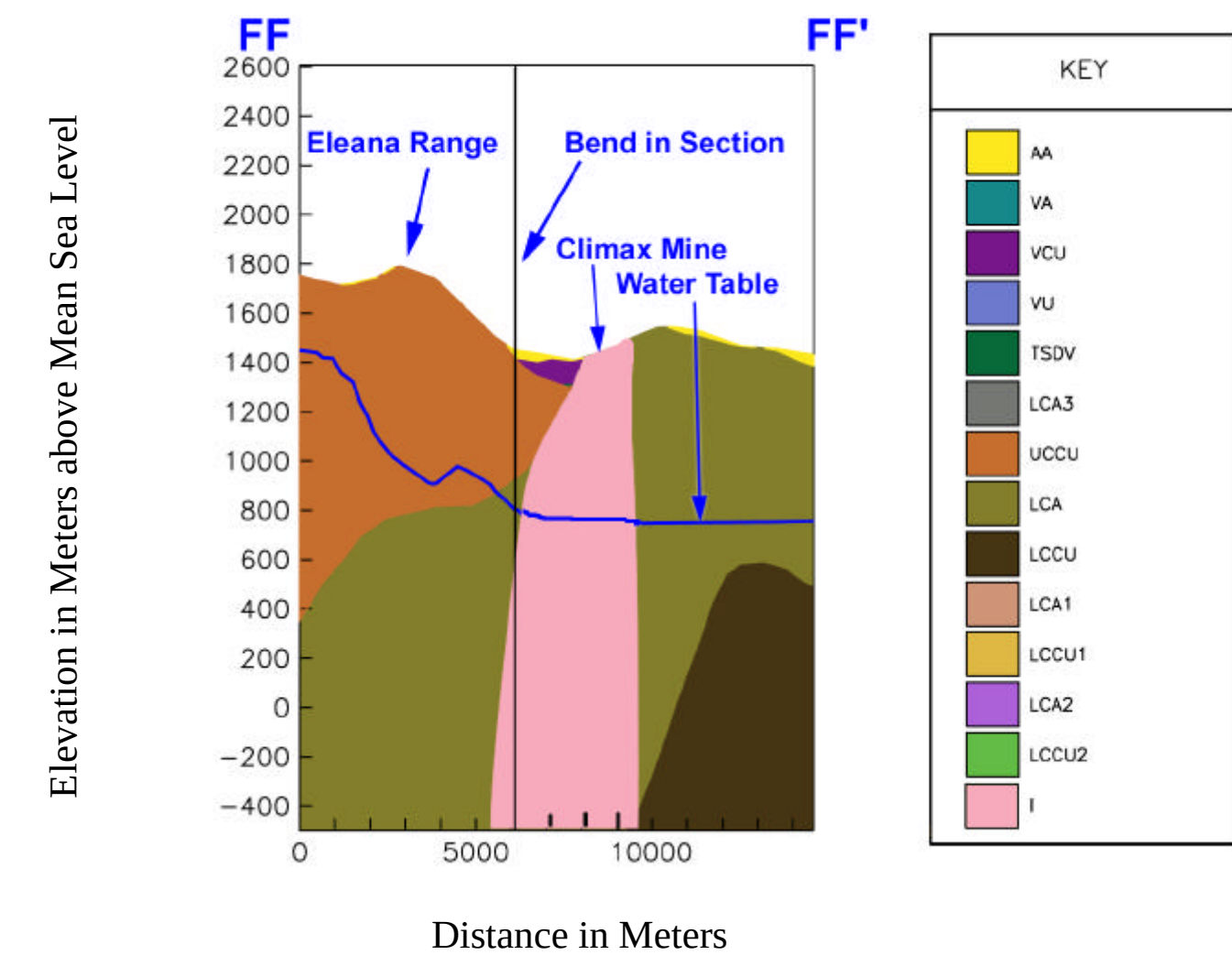
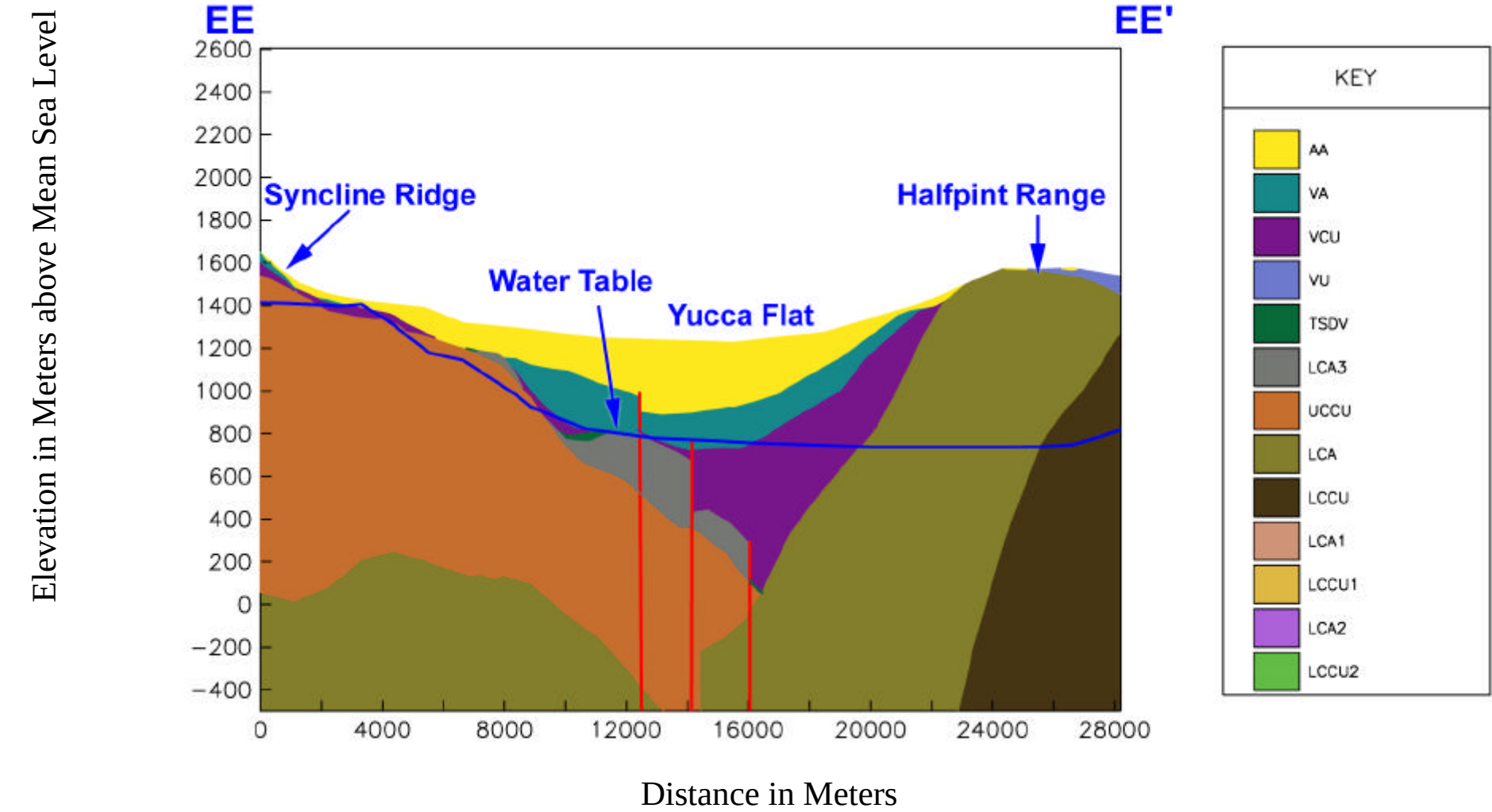
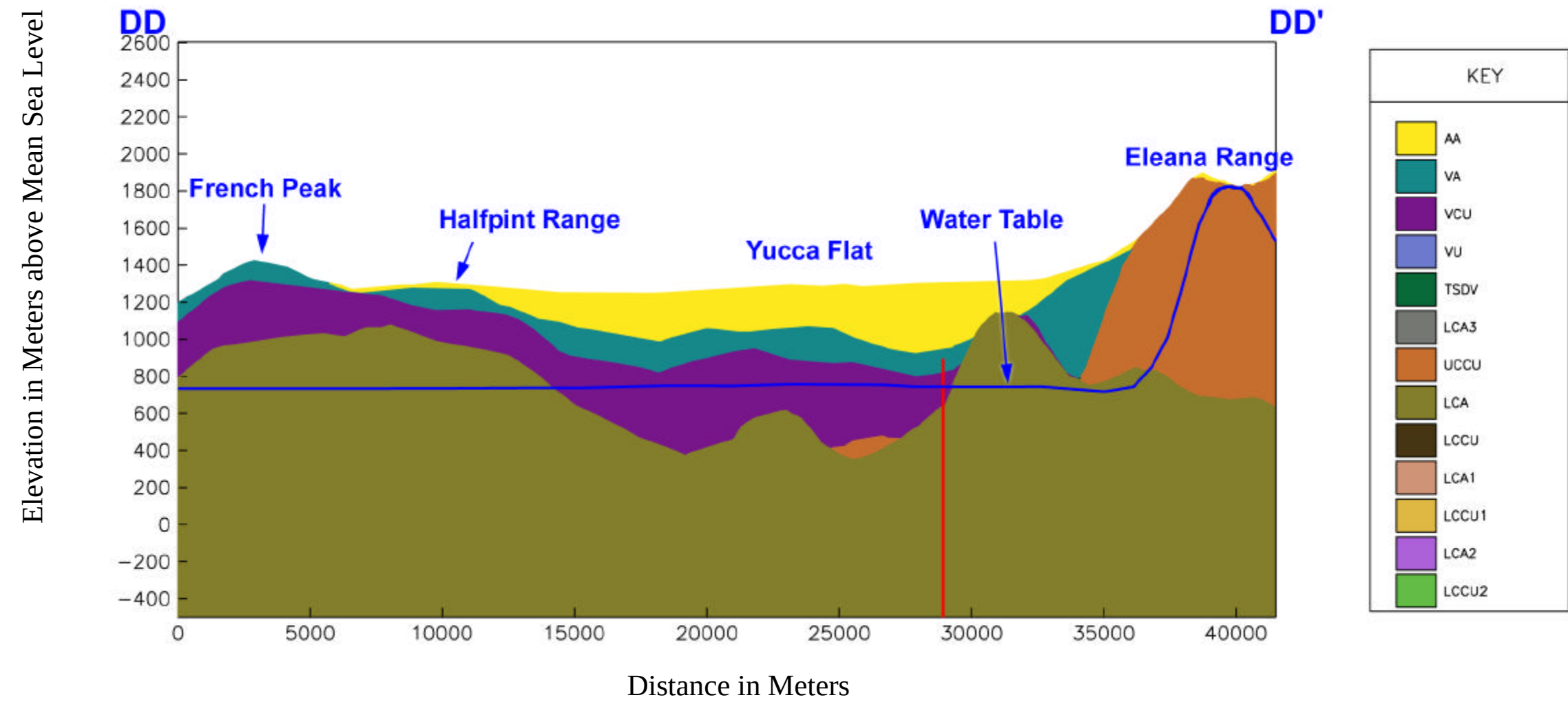
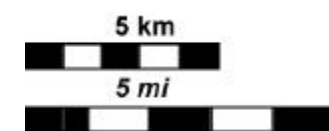


Plate 4

HYDROSTRATIGRAPHIC CROSS SECTIONS ACROSS THE YUCCA FLAT/CLIMAX MINE AREA

Scale:



VERTICAL EXAGGERATION = 7X

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