Nevada
Environmental
Restoration
Project

DOE/NV--977

National Nuclear Security Administration

Corrective Action Decision Document/ Corrective Action Plan for Corrective Action Unit 443: Central Nevada Test Area-Subsurface Central Nevada Test Area, Nevada

Controlled Copy No.: ___
Revision No.: 0

November 2004

Environmental Restoration
Division

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

Available for public sale, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Phone: 800.553.6847
Fax: 703.605.6900
Email: *orders@ntis.gov*
Online ordering: *http://www.ntis.gov/ordering.htm*

Available electronically at *http://www.osti.gov/bridge*

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Phone: 865.576.8401
Fax: 865.576.5728
Email: *reports@adonis.osti.gov*

DOE/NV--977

CORRECTIVE ACTION DECISION DOCUMENT/ CORRECTIVE ACTION PLAN FOR CORRECTIVE ACTION UNIT 443: CENTRAL NEVADA TEST AREA-SUBSURFACE, CENTRAL NEVADA TEST AREA, NEVADA

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

Controlled Copy No.: ___

Revision No.: 0

November 2004

CORRECTIVE ACTION DECISION DOCUMENT/ CORRECTIVE ACTION PLAN FOR CORRECTIVE ACTION UNIT 443: CENTRAL NEVADA TEST AREA-SUBSURFACE, CENTRAL NEVADA TEST AREA, NEVADA

Approved by: Signature Approved Date: 10/28/04

Peter A. Sanders, Acting Project Manager
Offsites Project

Approved by: Signature Approved Date: 10/28/04

Robert M. Bangerter, Acting Division Director
Environmental Restoration Division

Table of Contents

Table of Contents *(Continued)*

Table of Contents (Continued)

List of Figures

List of Figures (Continued)

List of Figures *(Continued)*

List of Figures (Continued)

Number ***Title*** ***Page***

List of Figures *(Continued)*

List of Tables

List of Acronyms and Abbreviations

AEC	U.S. Atomic Energy Commission
ANN	Artificial Neural Networks
ARARs	Applicable or relevant and appropriate requirement(s)
BLM	U.S. Department of the Interior, Bureau of Land Management
Bq	Becquerel
Bq/L	Becquerel per liter
CADD	Corrective Action Decision Document
CADD/CAP	Corrective Action Decision Document/Corrective Action Plan
CAI	Corrective Action Investigation
CAIP	Corrective Action Investigation Plan
CAP	Corrective Action Plan
CAS	Corrective Action Site
CAU	Corrective Action Unit
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
CFR	*Code of Federal Regulations*
CNTA	Central Nevada Test Area
COC	Contaminant of concern
COPC	Contaminant of potential concern
CP	Control plane
CPU	Central processing unit
DDA	Data Decision Analysis
DOE	U.S. Department of Energy
DOE/NV	U.S. Department of Energy, Nevada Operations Office
DQO	Data Quality Objective
DRI	Desert Research Institute

List of Acronyms and Abbreviations *(Continued)*

EC	Electrical conductivity
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
FFACO	*Federal Facility Agreement and Consent Order*
FMP	Fluid Management Plan
ft	Foot
F&T	Flow and transport
ft/d	Feet/day
GA	Genetic Algorithms
GLUE	Generalized likelihood uncertainty estimator
h_m	Measured head
h_s	Simulated head
HWAAs	Hazardous waste accumulation areas
IDW	Investigation-derived waste
K	Hydraulic conductivity
km	Kilometer
LLW	Low-level radioactive waste
L/d	Liters per day
LTHMP	Long-Term Hydrologic Monitoring Program
m	Meter
m/d	Meters per day
m^2/g	Square meters per gram
m^3/d	Cubic meters per day
MCL	Maximum contaminant level
mg/kg	Milligrams per kilogram
µg/L	Micrograms per liter
MOA	Memorandum of Agreement

List of Acronyms and Abbreviations *(Continued)*

mrem/yr	Millirem per year
mSv/yr	Millisievert per year
NAC	*Nevada Administrative Code*
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NDEP	Nevada Division of Environmental Protection
NEPA	*National Environmental Policy Act*
NMC	Number of Monte Carlo realizations
NNSA/NV	U.S. Department of Energy, National Nuclear Security Administration/Nevada Operations Office
NNSA/NSO	National Nuclear Security Administration/Nevada Site Office
NTS	Nevada Test Site
NTSWAC	Nevada Test Site Waste Acceptance Criteria
PCB	Polychlorinated biphenyls
pCi/L	Picocuries per liter
pdf	Probability distribution function
PPE	Personal protective equipment
PVC	Polyvinyl chloride
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
RCRA	*Resource Conservation and Recovery Act*
RMS	Root mean square
RMSE	Root mean square error
RV	Reference value
RWPT	Random walk particle tracking
SAAs	Satellite accumulation areas
SDWA	*Safe Drinking Water Act*
SIS	Sequential indicator simulation

List of Acronyms and Abbreviations *(Continued)*

SGS	Sequential Gaussian simulation
TPH	Total petroleum hydrocarbons
UGTA	Underground Test Area
USFS	U.S. Forest Services
USGS	U.S. Geological Survey
2-D	Two-dimensional
3-D	Three-dimensional

Radionuclides

^{26}Al	Aluminum-26
^{241}Am	Americium-241
^{243}Am	Americium-243
^{14}C	Carbon-14
^{41}Ca	Calcium-41
^{113m}Cd	Cadmium-113m
^{36}Cl	Chlorine-36
^{244}Cm	Curium-244
^{60}Co	Cobalt-60
^{135}Cs	Cesium-135
^{137}Cs	Cesium-137
^{150}Eu	Europium-150
^{152}Eu	Europium-152
^{154}Eu	Europium-154
^{3}H	Hydrogen-3
^{166m}Ho	Holmium-166m
^{129}I	Iodine-129
^{85}Kr	Krypton-85
^{93m}Nb	Niobium-93m
^{94}Nb	Niobium-94
^{59}Ni	Nickel-59
^{237}Np	Neptunium-237
^{107}Pd	Palladium-107
^{238}Pu	Plutonium-238
^{239}Pu	Plutonium-239
^{240}Pu	Plutonium-240

Radionuclides *(Continued)*

^{241}Pu	Plutonium-241
^{242}Pu	Plutonium-242
^{85}Rb	Rubidium-85
^{151}Sm	Samarium-151
^{121m}Sn	Tin-121m
^{126}Sn	Tin-126
^{90}Sr	Strontium-90
^{99}Tc	Technetium-99
^{3}H	Tritium
^{232}U	Uranium-232
^{233}U	Uranium-233
^{234}U	Uranium-234
^{235}U	Uranium-235
^{236}U	Uranium-236
^{238}U	Uranium-238
^{90}Y	Yttrium-90
^{90}Zr	Zirconium-90
^{93}Zr	Zirconium-93

This page intentionally left blank

Executive Summary

This Corrective Action Decision Document/Corrective Action Plan (CADD/CAP) has been prepared for the subsurface at the Central Nevada Test Area (CNTA) Corrective Action Unit (CAU) 443, CNTA - Subsurface, Nevada, in accordance with the *Federal Facility Agreement and Consent Order* (FFACO) (1996). CAU 443 is located in Hot Creek Valley in Nye County, Nevada, north of U.S. Highway 6, about 48 kilometers north of Warm Springs, Nevada.

The CADD/CAP combines the decision document (CADD) with the corrective action plan (CAP) and provides or references the specific information necessary to recommend corrective actions for the UC-1 Cavity (Corrective Action Site 58-57-001) at CAU 443, as provided in the FFACO.

The purpose of the CADD portion of the document (Section 1.0 to Section 4.0) is to identify and provide a rationale for the selection of a recommended corrective action alternative for the subsurface at CNTA. To achieve this, the following tasks were required:

- Develop corrective action objectives
- Identify corrective action alternative screening criteria
- Develop corrective action alternatives
- Perform detailed and comparative evaluations of the corrective action alternatives in relation to the corrective action objectives and screening criteria
- Recommend a preferred corrective action alternative for the subsurface at CNTA

A Corrective Action Investigation (CAI) was performed in several stages from 1999 to 2003, as set forth in the *Corrective Action Investigation Plan for the Central Nevada Test Area Subsurface Sites (Corrective Action Unit No. 443)* (DOE/NV, 1999). Groundwater modeling was the primary activity of the CAI. Three phases of modeling were conducted for the Faultless underground nuclear test. The first involved the gathering and interpretation of geologic and hydrogeologic data into a three-dimensional numerical model of groundwater flow, and use of the output of the flow model for a transport model of radionuclide release and migration behavior (Pohlmann et al., 2000).

The second modeling phase (known as a Data Decision Analysis [DDA]) occurred after the Nevada Division of Environmental Protection reviewed the first model and was designed to respond to concerns regarding model uncertainty (Pohll and Mihevc, 2000). The third modeling phase updated the original flow and transport model to incorporate the uncertainty identified in the DDA, and focused the model domain on the region of interest to the transport predictions. This third phase culminated in the calculation of contaminant boundaries for the site (Pohll et al., 2003).

Based on the potential exposure pathways, two corrective action objectives have been identified for CAU 443:

- Prevent or mitigate exposure to groundwater contaminants of concern at concentrations exceeding regulatory maximum contaminant levels or risk-based levels.

- Reduce the risk to human health and the environment to the extent practicable.

Based on the review of existing data, the results of the modeling, future use, and current operations at CNTA, the following alternatives have been developed for consideration at CAU 443:

- Alternative 1 - No Further Action
- Alternative 2 - Proof-of-Concept and Monitoring with Institutional Controls
- Alternative 3 - Contaminant Control

The corrective action alternatives were evaluated based on the approach outlined in the *Focused Evaluation of Selected Remedial Alternatives for the Underground Test Area* (DOE/NV, 1998a). Each alternative was assessed against nine evaluation criteria. These criteria include overall protection of human health and the environment, compliance with appropriate requirements, long-term effectiveness, reduction of the toxicity, mobility, or volume of contamination, short-term effectiveness, implementability, cost, state acceptance, and community acceptance. Based on the results of this evaluation, the preferred alternative for CAU 443 is Alternative 2, Proof-of-Concept and Monitoring with Institutional Controls.

The preferred corrective action alternative was chosen for its technical implementability, focusing on performance, reliability, feasibility, safety, and cost. Alternative 2 was judged to meet all requirements for the technical components evaluated, and will control inadvertent exposure to contaminated groundwater at CAU 443. Implementation of the corrective action and post-closure activities are described in the CAP portion of this document (Section 5.0 to Section 7.0).

1.0 Introduction

This Corrective Action Decision Document/Corrective Action Plan (CADD/CAP) has been prepared for the subsurface at the Central Nevada Test Area (CNTA), Corrective Action Unit (CAU) 443, CNTA - Subsurface, in accordance with the *Federal Facility Agreement and Consent Order* (FFACO) that was agreed to by the State of Nevada, the U.S. Department of Energy (DOE), and the U.S. Department of Defense (FFACO, 1996). The CADD portion of the document (Section 1.0 to Section 4.0) provides or references the specific information necessary to recommend corrective actions for the UC-1 Cavity (Corrective Action Site [CAS] 58-57-001) at CAU 443. The CAP portion of the document (Section 5.0 to Section 7.0) describes implementation of the corrective action and post-closure activities.

CNTA is located in Hot Creek Valley in Nye County, Nevada, north of U.S. Highway 6, about 48 kilometers (km) north of Warm Springs, Nevada (Figure 1-1). CNTA was the site of Project Faultless, a nuclear device detonated in the subsurface by the U.S. Atomic Energy Commission (AEC) in January 1968. The purposes of this test were to gauge the seismic effects of a relatively large, high-yield detonation completed in Hot Creek Valley (outside the Nevada Test Site [NTS]) and to determine the suitability of the site for future large detonations. The yield of the Faultless underground nuclear test was between 200 kilotons and 1 megaton (DOE/NV, 2000c). Two additional tests were planned for CNTA, but neither was completed (AEC, 1974). The subsurface source of contamination is the Faultless test cavity, and includes radioactive fission products, uranium, plutonium, and tritium (NNSA/NSO, 2004).

CAU 443 contains two additional CASs (Emplacement Well UC-3 [CAS 58-30-01] and Emplacement Well UC-4 (CAS 58-30-02]) but neither are addressed by this document. The UC-3 emplacement hole is a cased borehole open to a depth of 4,862 ft and covered with a welded steel plate and a concrete cap. It was determined during a Data Quality Objective (DQO) process with the State regulator that the borehole requires no further evaluation. The UC-4 emplacement hole is open to 5,500 ft and has been filled with drilling mud and covered with a concrete cap. The seven-step DQO process was also applied to UC-4 and identified total petroleum hydrocarbons (TPH) as the only potential contaminant of concern. Subsequent analysis of flow near the well bore and transport of TPH from the drilling mud found no significant migration (Lyles et al., 1998). Long-term

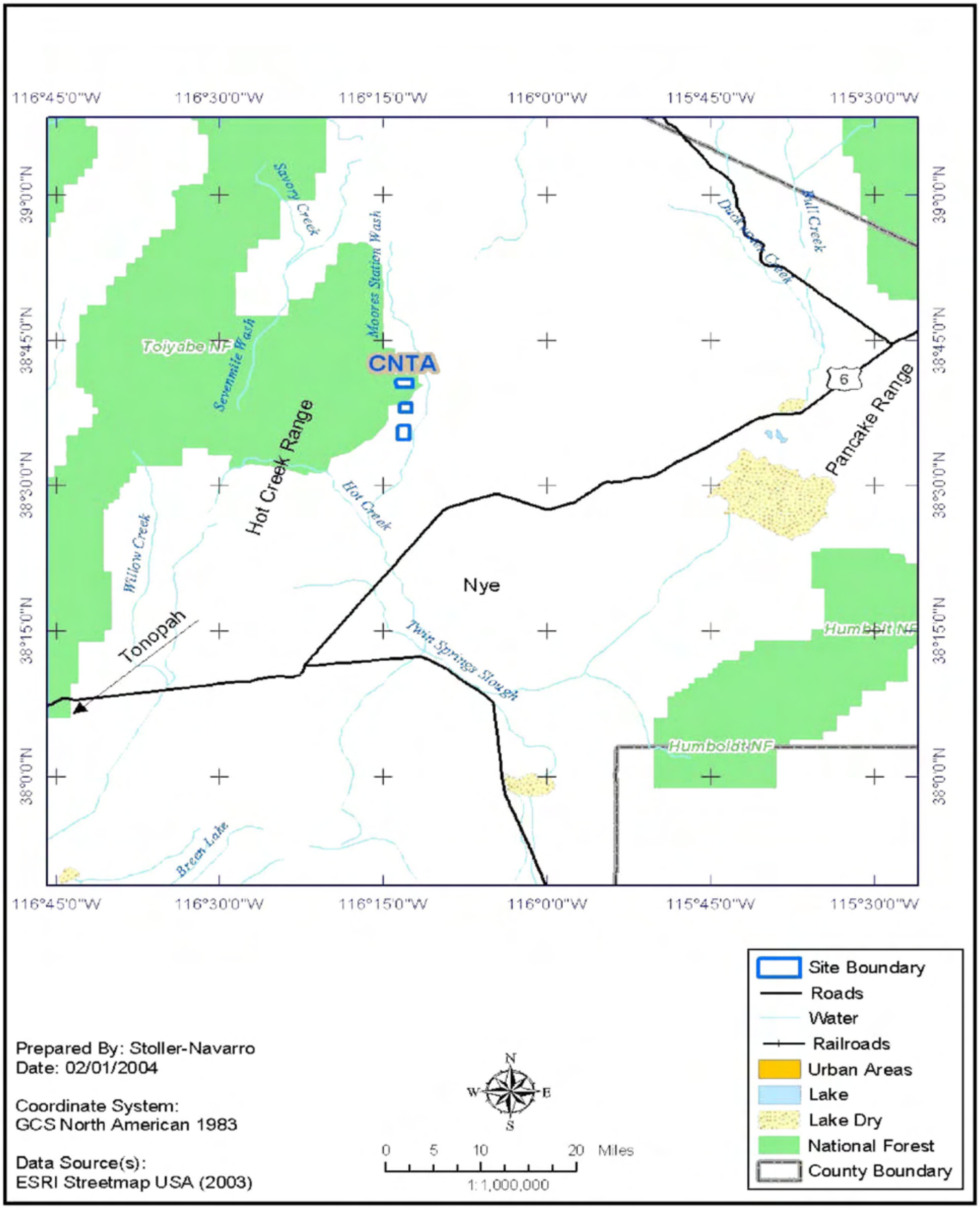


Figure 1-1
CNTA Location Map

stewardship of the site will include maintaining the integrity of the caps over these boreholes for physical safety. The emplacement holes and boreholes remaining at CNTA (UC-3 and UC-4) will be reviewed with the Division of Water Resources to assure proper abandonment.

In 1997, the DOE Nevada Operations Office (DOE/NV) completed site characterization for the surface area at CNTA, and in 2001, completed surface closure on the site (DOE/NV, 2001).

1.1 Purpose

This CADD/CAP presents the results of the CAI conducted in accordance with the *Corrective Action Investigation Plan for the Central Nevada Test Area Subsurface Sites* (Corrective Action Unit No. 443) (DOE/NV, 1999) and develops, evaluates, and recommends a corrective action alternative for CAU 443. Further, it describes implementation of the corrective action and post-closure monitoring strategy, the proof-of-concept strategy, and the reporting procedures for implementing the selected corrective action. The evaluation of corrective action alternatives is based on process knowledge and the results of investigative activities conducted in accordance with the CAIP (DOE/NV, 1999).

1.2 Scope

The activities used to identify, evaluate, and recommend the proposed CAP alternative consisted of the following:

- Incorporate the results of the CAI and the groundwater modeling (Section 2.0)
- Develop a compliance boundary (Section 2.0)
- Develop corrective action objectives (Section 3.0)
- Identify corrective action alternative screening criteria (Section 3.0)
- Perform detailed and comparative evaluations of corrective action alternatives in relation to corrective action objectives and screening criteria (Section 3.0)
- Recommend and justify a preferred corrective action alternative for CAU 443 (Section 4.0)

Based on the results of the activities identified above, the preferred corrective action alternative for CAU 443 is Alternative 2, Proof-of-Concept and Monitoring with Institutional Controls. The proof-of-concept approach relies on the groundwater flow and transport model of the Faultless test at CNTA. Monitoring will be accomplished by placing monitoring well(s) downgradient from the nuclear test emplacement point. Periodic water sampling and testing will confirm that contamination is confined within the compliance boundary. Finally, institutional controls will be put in place to restrict subsurface use in the vicinity of CNTA.

Alternative 2 was judged to meet all requirements for the technical components evaluated, and will control inadvertent exposure to contaminated groundwater at CAU 443. Implementation of the corrective action and post-closure activities are described in the CAP portion of this document (Section 5.0 to Section 7.0).

1.3 CADD/CAP Contents

This CADD/CAP was developed in accordance with a standardized outline agreed to by the Nevada Division of Environmental Protection (NDEP) and DOE on August 26, 2003. The outline contains specific annotations prescribing the content of each section. Section 1.0 to Section 4.0 comprises the CADD portion of this document. The CAP portion is found in Section 5.0 to Section 7.0. Each is briefly summarized below:

Section 1.0 - Introduction: summarizes the purpose, scope, and contents of the CADD.

Section 2.0 - Corrective Action Investigation Summary: summarizes the investigation field activities, the results of the investigation, describes the contaminant and compliance boundaries, and the need for corrective action.

Section 3.0 - Evaluation of Alternatives: presents corrective action alternatives and documents the steps taken to determine a preferred corrective action alternative.

Section 4.0 - Recommended Alternative: presents the preferred corrective action alternative and the rationale for its selection based on the corrective action objectives and alternative screening criteria.

Section 5.0 - Implementation of the Corrective Action Plan: describes the proposed corrective action alternative and the key elements of its planned implementation

Section 6.0 - Schedule: presents the schedule for major activities and milestones for implementing the approved corrective action.

Section 7.0 - Post-Closure: discusses DOE's commitment to and plans for post-closure inspection, monitoring, and long-term stewardship based on the CAP.

Section 8.0 - References: provides a list of all referenced documents.

Appendix A: Proposed Engineering Specifications and Drawings

Appendix B: Validation Metrics and Application to the Faultless Model

All work was performed in accordance with the following documents:

- *Corrective Action Investigation Plan for the Central Nevada Test Area Subsurface Sites* (Corrective Action Unit 443) (DOE/NV, 1999)
- *Focused Evaluation of Selected Remedial Alternatives for the Underground Test Area* (DOE/NV, 1998a)
- *Underground Test Area Quality Assurance Project Plan, Nevada Test Site, Nevada*, Rev. 2, and Rev. 3, DOE/NV-341 (DOE/NV, 1998b, 2000b)
- *Federal Facility Agreement and Consent Order* (1996)

2.0 Corrective Action Investigation Summary

The corrective action investigation for CAU 443 focused on numerical modeling of groundwater flow and radionuclide transport. This focus is consistent with the strategy outlined in Appendix VI of the FFACO (1996). The CAIP was approved by the State of Nevada in 1999. The objectives of the CAIP are discussed below. To ensure all project objectives, health and safety requirements, and quality control procedures were adhered to, all investigation activities were performed in accordance with the following documents:

- *Corrective Action Investigation Plan for the Central Nevada Test Area Subsurface Sites* (Corrective Action Unit No. 443) (DOE/NV, 1999)
- *Underground Test Area Quality Assurance Project Plan, Nevada Test Site, Nevada*, Rev. 2, and Rev. 3, DOE/NV-341 (DOE/NV, 1998b, 2000b)
- *Federal Facility Agreement and Consent Order* (1996)

The following sections describe and summarize these activities, provide the investigation results, and identify the need for corrective action at CAU 443. The detailed investigation plan can be found in the CAIP (DOE/NV, 1999).

Specific objectives of the corrective action investigation were defined in the CAIP (DOE/NV, 1999) 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 UC-1 cavity and downgradient areas.
- Develop stochastic predictions of the contaminant boundary at an acceptable level of uncertainty.

These objectives were accomplished through CAI activities. Characteristics of the flow system, source of contamination, and transport processes were determined largely using existing data, as specified in the CAIP. In addition, new data were collected from wells in the area to provide current water levels, and laboratory experiments were conducted with material from archived cores to provide sorption information. A numerical model of groundwater flow and contaminant transport was developed based upon these data. This stochastic model analyzes a spectrum of equally possible configurations of the groundwater flow system, consistent with the uncertainties always present when representing subsurface conditions. This readily allows stochastic predictions of the contaminant boundary at any desired level of uncertainty.

In their review of the model, the NDEP expressed confidence in the technical approach and modeling techniques, but declined to accept the model until a quantitative analysis of overall model uncertainty, and the ability of new data to reduce that uncertainty, was performed (Liebendorfer, 2000). In response, DOE performed a Data Decision Analysis (DDA) using a two-dimensional (2-D) version of the CNTA model to quantify uncertainty and evaluate the effectiveness of possible data collection activities to address the uncertainties (Pohll and Mihevc, 2000). NDEP agreed with the conclusions of the DDA that although there is considerable uncertainty in the model input parameters, the uncertainty in the prediction of a contaminant boundary is low. The corrective action model was therefore approved by NDEP, pursuant to conditions that a validation plan be developed that addresses downgradient conditions and that trigger mechanisms be clearly identified that would cause revisiting the model (Liebendorfer, 2001).

Approval of the model led to the next step in the CAI strategy, the calculation of a contaminant boundary. The original three-dimensional (3-D) model was revised to incorporate the full uncertainty of the 2-D DDA model, and to focus on a smaller region closer to the test. A detailed approach to calculating the contaminant boundary was also developed. This approach considered options related to the modeling and statistical techniques employed and to regulatory and risk guidelines. Per a request from NDEP, preliminary boundary predictions for tritium at different time periods were provided to assist in preparing for the negotiation of the compliance boundary.

Each of the major elements of the investigation is briefly described below, with references to the detailed work.

2.1 Investigation Activities

The investigation consisted of three principal parts: data collection, the groundwater flow and contaminant transport model, and the DDA. Calculation of the contaminant boundary is presented in Section 2.2.

2.1.1 Data Collection

As specified in the CAIP, no field investigation was to be conducted during the CAI. During preparation of both the flow model and transport model, however, it seemed prudent to seek confirmatory data for two parameters (i.e., the water level data for wells in Hot Creek Valley and laboratory measurements of sorption behavior of valley formations). Activities were conducted using best scientific practice and the findings confirmed the existing data. Measuring water levels in wells in Hot Creek Valley supported the flow modeling. Laboratory measurement of sorption behavior of valley formations supported the transport model. Details on the determination of each of these parameters are discussed in the following sections.

2.1.1.1 Measurement of Regional Water Levels in Hot Creek Valley

The purpose of the field activity was to measure current water levels in wells in the general Faultless area. Previous hydraulic head measurements to determine valley-wide gradients were conducted in the mid-1960s. Because water levels depend on weather variations and groundwater withdrawals, they could have changed since that time.

Results of the water level measurements are reported in Appendix 1 of the modeling report (Pohlmann et al., 1999). Water levels were determined from available wells in Hot Creek Valley, the northern portion of Reveille Valley, and the southern portion of Big Sand Springs Valley between August 11 and 17, 1997. These well locations, along with the measured water levels, are shown in Figure 2-1. The hydraulic gradient is steep in the northern portion of Hot Creek Valley and becomes flatter south of the Faultless site, consistent with historic data. The field effort met the objective of providing current water level information for the modeling, and also confirmed the validity of the historic water-level data.

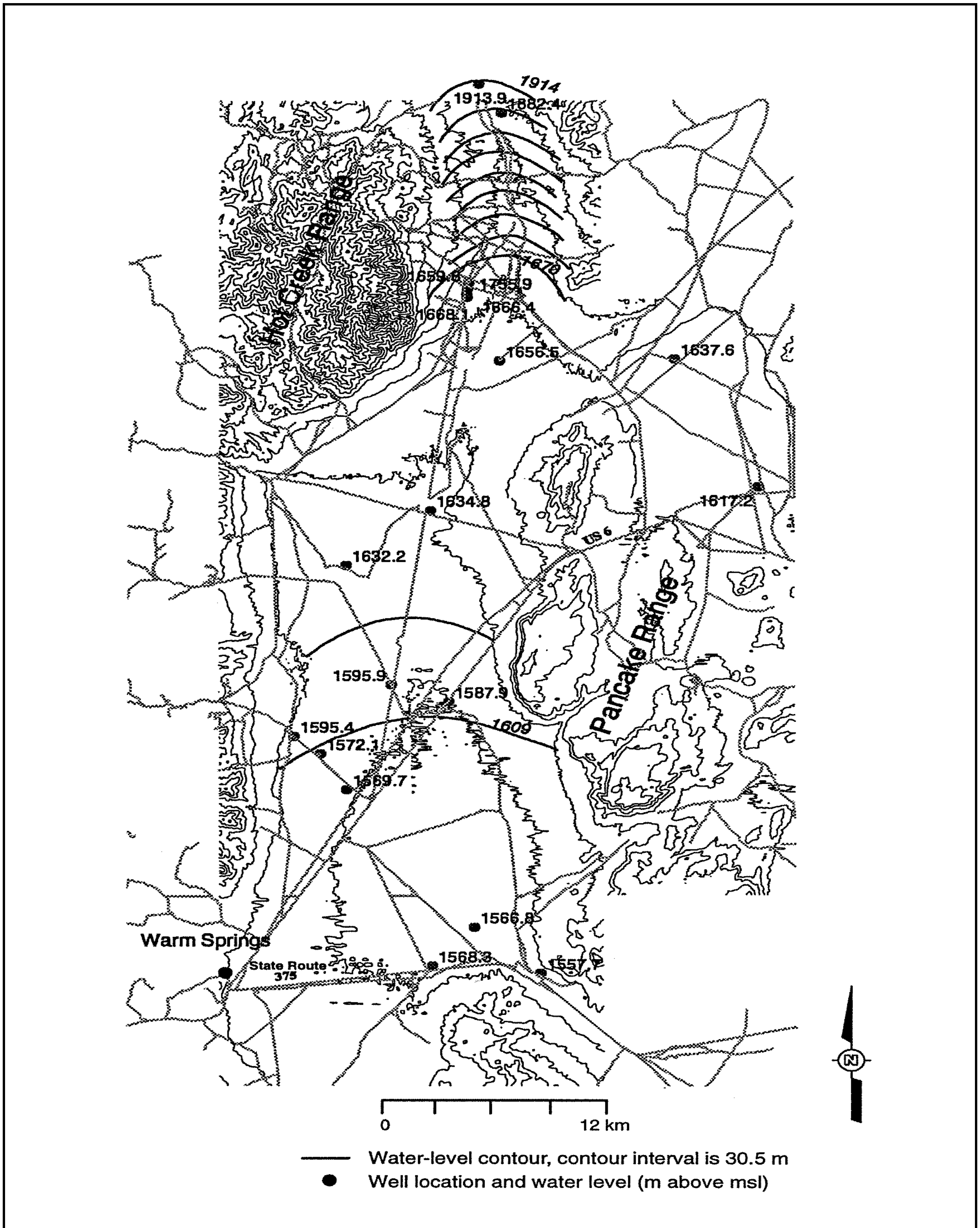


Figure 2-1
Well Locations and Water Level Measurements with Contoured Composite Groundwater Heads in Hot Creek Valley

2.1.1.2 Laboratory Study of Sorption

A laboratory study of anion and cation sorption on aquifer materials from CNTA was conducted to support the transport modeling. As with the water level study, historic data for distribution coefficients were available in the literature (Nork et al., 1971), but confirming the results was desirable given the very large sorption coefficients reported for cations and their significant impact on transport predictions. Details of the laboratory methods and results are contained in Appendix 5 of the modeling report (Pohlmann et al., 1999).

Experiments were conducted using core material collected during the drilling programs at CNTA and stored for the last several decades at the U.S. Geological Survey (USGS) Core Library in Mercury, Nevada. Five different horizons were sampled from three boreholes. Three aquifer materials were investigated: alluvium, tuffaceous sediment, and densely welded tuff. Most material was from borehole UC-1-I-1, as it was closest to the Faultless emplacement hole (UC-1). Alluvium was collected from UC-1-I-1 at depths of 546 to 551 meters (m), and at 611 m. Tuffaceous sediments from the same borehole were collected from 985 to 987 m and from 1,065 m. Spatial variability in the alluvium was investigated by a sample from 1,074 to 1,077 m in Uce-18. Welded tuff was not encountered in core from any nearby hole to UC-1, so the welded tuff interval at 296 m in HTH-3 was used. The experiments were conducted with simulated groundwater based on chemical analyses of groundwater from HTH-1. Batch equilibrium studies using different size fractions, batch rate-of-uptake studies using different size fractions, and column experiments were all conducted. Chemical surrogates were used to approximate the radionuclide source term. Strongly and moderately binding cations (lead, cesium, and strontium, respectively) and strongly and weakly binding anions (selenite and chromate, respectively) were evaluated for their affinity for the different aquifer materials.

Experiments with different size fraction particles do not show dramatic differences in sorption properties. This indicates that the specific surface areas of the size fractions do not vary significantly and are relatively high, suggesting a significant portion of the surface area is internal. The batch rate-of-uptake experiments show very fast uptake, suggesting fast sorption on easily accessible surface sites. Therefore, it is reasonable to assume these processes are fast compared to the slow groundwater velocity. The column experiments, although not providing quantitative estimates of retardation due to the absence of breakthrough, suggest a very large retardation factor for the cationic species, which is consistent with the values obtained from the batch equilibrium sorption experiments.

The laboratory study met its objective of providing retardation data to support the transport modeling, and confirmed the high sorption values reported in the historic literature.

2.1.2 Modeling

The CNTA CAIP (DOE/NV, 1999) establishes groundwater modeling as the primary activity of the CAI. The objective of the overall FFACO strategy for underground nuclear test sites is to define boundaries around each CAU to establish areas containing water that may be unsafe for domestic and municipal use. The CNTA CAIP states that this will be achieved by modeling groundwater flow and transport and by estimating the movement of contaminants using hydrogeologic data specific to CNTA.

The CAIP specifies that the model will be 3-D. It must also be capable of developing stochastic predictions to fulfill the contaminant boundary objective. The model approach discussed in the CAIP includes using sequential indicator simulation methods and geophysical logs to generate maps of hydrogeologic heterogeneity. According to the CAIP, contaminant migration will be simulated using the random walk particle-tracking (RWPT) method. Transport factors specific to underground nuclear test conditions are specified as being extrapolated from experience at the NTS. All of these approaches were incorporated in the modeling effort.

There were three phases of modeling for the Faultless test. The first constituted assimilation of geologic and hydrogeologic data into a 3-D numerical model of flow and using the output of the flow model for a transport model of radionuclide release and migration behavior. This model included uncertainty in the spatial and hydraulic properties of the hydraulic conductivity field, and sensitivity analyses of other uncertain properties. The second model phase occurred after NDEP reviewed the first model, and was designed to respond to specific NDEP concerns that uncertainty be addressed in a more quantitative fashion. This second model, the DDA, was conducted on a 2-D slice through the original model. Following the DDA, the 3-D flow and transport model was updated to incorporate the uncertain parameters defined in the DDA, and to focus on the region of the flow domain of interest to the transport predictions.

All of these modeling phases are described below, following the sequence of steps defined for the ten-step modeling protocol prescribed in the dictionary section of Appendix VI of the FFACO (1996). The details of the original flow and transport model can be found in Pohlmann et al. (1999), and in the peer-reviewed scientific literature in Pohlmann et al. (2000). The DDA is presented by Pohll and Mihevc (2000). The updated 3-D model is described in Pohll et al. (2003).

2.1.2.1 Model Purpose

The purpose of the groundwater model was to characterize groundwater flow and transport of contaminants at CNTA through numerical modeling, using site-specific hydrologic data.

2.1.2.2 Conceptual Model

The two types of conceptual models (i.e., flow and transport) developed for CNTA are described in the following sections.

2.1.2.2.1 Conceptual Flow Model

The flow model represents a synthesis of available site data to provide a realistic description of groundwater flow for the transport calculations. The flow model is based on hydrogeologic conditions before the Faultless test, under the assumption that transport over the long term would be controlled by these factors rather than by the relatively short-term effects of the test. Furthermore, flow was considered to be at steady state owing to the large size of the Hot Creek Valley hydrologic system and the absence of excessive groundwater withdrawals. Local structural features such as faults were not explicitly included owing to the lack of information regarding their subsurface locations and hydraulic characteristics.

Hot Creek Valley contains hundreds of meters of alluvium derived from adjacent volcanic mountain ranges with minor carbonate contributions. Below the alluvium is a thick volcanic sequence comprised of tuffaceous sediments, nonwelded and welded tuffs, and rhyolite lavas. Three hydrogeologic categories are defined based on lithology, electrical resistivity, and hydraulic conductivity (K): Quaternary alluvium (geometric mean K of 2.4×10^{-3} meters per day [m/d]), Tertiary volcanics having low hydraulic conductivity (geometric mean K of 1.2×10^{-4} m/d), and Tertiary volcanics having high hydraulic conductivity (geometric mean K of 1.4×10^{-1} m/d).

Tuffaceous sediments and nonwelded tuffs generally fall in the category of low-*K* volcanic rocks and rhyolites and welded tuffs generally fall in the category of high-*K* volcanic rocks. Most of the volcanic section at the Faultless site is comprised of low-*K* tuffaceous sediments. The rhyolites and densely welded tuffs are highly fractured and faulted and, where present, are considered the primary pathways for groundwater flow and transport. Hydrogeologic investigation at the Faultless site identified no rhyolites and only a single 24-m thick interval of densely welded tuff south of the emplacement well.

Evidence elsewhere in the valley suggests the possibility of welded tuff at some depth below the emplacement horizon. The stochastic approach used in the modeling accounts for uncertainty in the lithology at depth, with some realizations including densely welded tuffs and some realizations that do not. Most of the volcanic section at the Faultless site consists of tuffaceous sediments and nonwelded tuffs that tend to be poorly sorted, well indurated, commonly zeolitized, and supported by a clay-cemented matrix. Although matrix porosity of these rocks may be relatively high, the clay and zeolite matrices reduce hydraulic conductivity to very low values.

Groundwater flow in Hot Creek Valley is a complicated system of overlapping and interacting components. To conduct flow modeling in such a setting, the ambient flow system was simplified to its principal horizontal and vertical components. Groundwater flow in the alluvium is directed toward the south, generally following the slope of the valley surface. Head relationships in the deeper volcanic system indicate flow toward the northeast and east toward regional discharge points in Railroad Valley. Strong, vertically downward hydraulic gradients are present in the area north of the Faultless site where elevations are higher and recharge from precipitation is likely to take place. To the south, strong vertical gradients from the volcanic section upward to the alluvium are present and may be related to regional discharge. An idealized cross section through a portion of Hot Creek Valley shows the conceptualization of the regional system (Figure 2-2).

Groundwater recharge that occurs in the higher elevations of the Hot Creek Range is included by implication with the strong vertically downward gradients in the portion of the model underlying the highest land elevations. Recharge was not applied areally to the top boundary of the model because recharge at the elevation of the Faultless site is minimal according to methods used to estimate regional recharge.

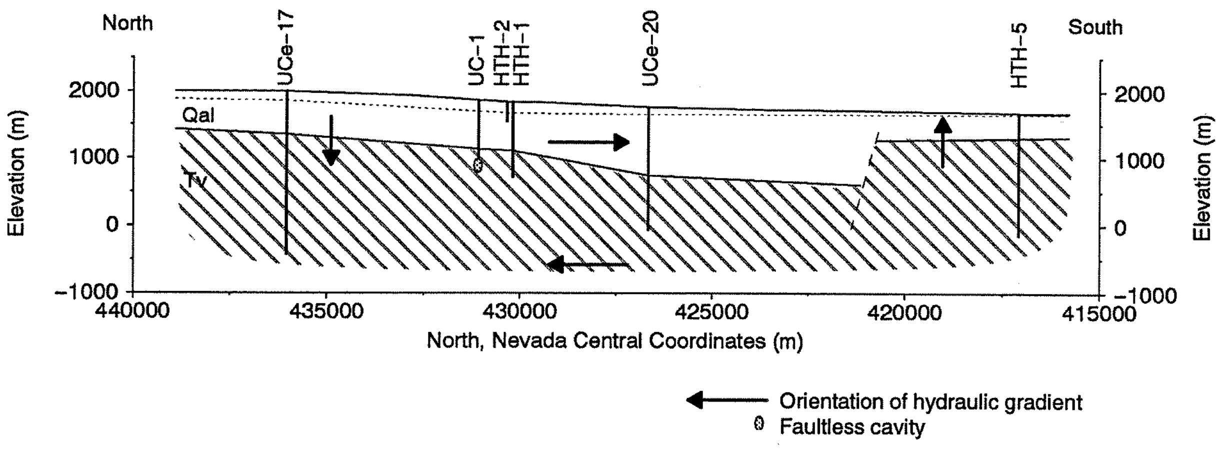


Figure 2-2
Diagrammatic Vertical Cross Section Showing Major Components of Conceptual Flow Model in Hot Creek Valley (Note: Dotted line represents the water table)

2.1.2.2.2 Conceptual Transport Model

The conceptual transport model describes the source of contaminants, how the contaminants are released, and the processes that control their migration through the groundwater system. The model is based on site-specific data, as well as information gained by decades of research into underground nuclear tests at the NTS.

Contaminants of potential concern (COPCs) are the radionuclides produced by the Faultless test and the daughters created by radioactive decay. The COPCs assumed to initially reside within the cavity and begin migration at the conclusion of the 30-year recovery to pre-test hydraulic head levels. Based on generic relationships related to depth of burial (Glasstone and Dolan, 1977), the cavity radius for Faultless is estimated as 100 m. The cavity is simulated in the model as a cube with edge lengths of 200 m. Radionuclides are apportioned between surface deposits on lithic clasts within the collapse cavity breccia and volume deposits in melt glass, based on their volatility and observations in post-detonation testing at other locations.

Surface-deposited radionuclides are released hydraulically after equilibration of the cavity with the surrounding flow system. No migration of radionuclides is assumed until the cavity has infilled with groundwater, following the dewatering caused by the thermal and compressional forces of the Faultless test. Early-time cavity conditions and near-field properties affected by the nuclear test were not considered in the analysis. Data within the collapse region around Faultless reveal a complex near-field environment characterized by faults, fractures, and elevated temperatures. The assumption was made in the modeling that these hydraulic and thermal changes are local and short-term, and that long-term transport (over the hundreds to a thousand years considered by the corrective action) can be approximated using the understanding of the pre-test hydrologic conditions.

Release from the melt glass is patterned after dissolution of volcanic glass and assuming a specific surface area of 0.05 square meters per gram (m^2/g). The radionuclides were grouped into six unique combinations of geochemical release fraction and retardation. The very long travel times simulated by the model render the release function an insensitive parameter, with the peaks of the breakthrough curves for the six solute classes passing the control plane in order of increasing retardation coefficient.

Once the radionuclides are released, they are subject to retardation processes that account for reactions with the aquifer matrix. Retardation factors were calculated from distribution coefficients derived from the equilibrium sorption experiments. These calculations were conducted using the three aquifer rock types, as described in the previous section. Distribution coefficients were scaled by a ratio between surface areas measured on the ground experimental material and surface areas measured using a particle size analysis. This resulted in a reduction in the distribution coefficient by up to two orders of magnitude. The retardation coefficients calculated using this scaled value still indicate significant decreases in contaminant velocities relative to groundwater velocity. The retardation coefficients vary from 1 (no retardation) to 8,000 for strongly sorbing cations. The retardation process of matrix diffusion was included for the scenario of transport by fracture flow through welded tuff units. Two different approaches to transport through the welded tuff were considered: migration through an equivalent porous medium (consistent with the porosity values measured on cores) and migration through fractures running through matrix blocks having porosity consistent with the core data.

Transport of radionuclides from the cavity to the control plane (CP) at the site land withdrawal boundary was calculated using particle-tracking methods on the same grid discretization and domain size as the groundwater flow model. Two fundamentally different conceptualizations of transport were evaluated: (1) treating all three hydrogeologic categories as a porous medium having a homogeneous porosity of 0.18 (consistent with core data from the site), and (2) treating the welded tuffs (Category 3) as a fractured unit having a homogeneous flow porosity of 0.005 accompanied by diffusion into a porous matrix. Both model formulations included the release function, retardation, radioactive decay, and ingrowth of daughter products. Prompt injection was considered in a sensitivity analysis. Unit mass values were used to avoid the security issues in the publicly released models. The results were scaled with the classified source mass values to obtain the contaminant boundary maps.

2.1.2.3 Computer Code Selection and Verification

The criteria used to select the flow code for the Faultless model are defined in the CAIP (DOE/NV, 1999) as follows:

- Fully three-dimensional properties
- Heterogeneous and anisotropic properties
- Flexible boundary conditions
- Steady-state or transient conditions
- Hydrologic sources and sinks

Additional computational considerations, also outlined in the CAIP, were the capability for multiple realizations, efficient data handling, pre- and post-processing of data, efficient numerical solvers, compatibility with existing hardware and software, and access to the source code. The groundwater flow code MODFLOW-88 (McDonald and Harbaugh, 1988) was used to solve for the hydraulic head field. Although several groundwater flow codes met the criteria, MODFLOW-88 was selected because it also provides the additional benefits of a long history of successful application to a wide variety of problems, widespread acceptance in the hydrogeologic community, and the ability to easily scale the code to the complexity of the modeling program through the code's modular design.

Three modules were used for the application of MODFLOW-88 to CNTA. The Basic module specifies the other modules that are to be used, the geometry of the model domain, the boundary conditions, and the time steps. The Block-Centered Flow module handles the grid discretization, aquifer type, and hydraulic parameters required to solve the finite difference equations. The Preconditioned Conjugate-Gradient module uses modified incomplete Cholesky preconditioning to efficiently solve the matrix of finite difference equations. The only modifications to the original code involved input and output: new routines were added to read the 3-D *K* maps and to save the maps of hydraulic head. The code also included an enhancement to calculate cell-to-cell Darcy fluxes using the following equation: $q(x) = -K(x)\nabla h(x)$. The modified code was verified by testing against the Darcy equation using a homogeneous *K* field.

Supporting the flow code, the SISIM and SGSIM codes (Deutsch and Journel, 1998) were used for the sequential indicator and sequential Gaussian simulations, respectively. The source codes were unmodified, although the original random number generator was replaced by a lagged Fibonnaci generator (Knuth, 1981; Marsaglia, 1985). This generator is initialized for each Monte Carlo realization by setting the seed to the Monte Carlo realization number and is more effective than previously used methods for producing streams of independent random deviates.

Criteria for the transport code are specified in the CAIP as follows:

- Advection, dispersion, adsorption, matrix diffusion
- Radioactive decay, daughter products
- Minimal numerical dispersion

The RWPT method was selected to solve the transport equation. Although other numerical approaches are available, (e.g., finite differences and finite elements), these can demand very fine grids and can introduce numerical dispersion. Moltyaner et al. (1993) have shown that the random walk method completely eliminates numerical dispersion as compared to finite differences and finite elements solutions. The RWPT code used for radionuclide transport underwent a rigorous comparative study with other transport codes, and was then verified through independent peer-reviewed publication (Hassan and Mohamed, 2003). Matrix diffusion was included in the 1999 transport model through a convolution of the non-decayed breakthrough curves with a retention function, following the approach developed by Cvetkovic and Dagan (1994) and Cvetkovic et al. (1999). With respect to matrix diffusion, that model included two conceptualizations of flow: porous media-based and fracture-based. The approach for handling matrix diffusion was enhanced in the focused model developed for the contaminant boundary determination by using the physically based method presented by Liu et al. (2000) that uses particle transfer probabilities to describe the diffusion of particles into the matrix and back into the fractures. This allowed the model to follow a dual-permeability conceptualization. This enhancement was verified by comparative study with other transport codes such as the analytical solution of fracture transport by Sudicky and Frind (1982) and the TOUGH2 numerical code (Pruess, 1991) as documented in Liu et al. (2000).

2.1.2.4 Model Design

The CNTA model was developed using stochastic methods that describe the natural subsurface heterogeneity in two phases. In the first phase, the geometry of the hydrogeologic categories was described using the sequential indicator simulation (SIS) algorithm. Drilling, aeromagnetic, and seismic data are used to define the boundary between the alluvium and volcanics. Geophysical log signatures, specifically electrical resistivity logs, are used to map the 3-D occurrence of the volcanic units. The SIS simulations were conditioned using lithologic and electrical resistivity logs from wells at the site. In the second phase, the distribution of hydraulic conductivity within each hydrogeologic category was described using the sequential Gaussian simulation (SGS) algorithm. The SGSs were conditioned using hydraulic conductivity data from the packer tests. The category geometry and hydraulic conductivity distribution for one realization is shown in Figure 2-3.

The scale of the 1999 model is intermediate between the scale of the near-test environment and the scale of regional groundwater flow. The domain extends from the UC-1 land withdrawal area south to include the UC-3 land withdrawal area, a distance of 8 km (Figure 2-4). It extends 6.5 km east to west. The thickness is 1,350 m, with its base at 290 m above sea level. The domain is discretized into a grid of 130 x 160 x 27 cubic cells of 50 m length. A vertical north-south slice through the 1999 model was used for the 2-D DDA model. The 1999 model was then reduced in size for the contaminant boundary calculations (Pohll et al., 2003) because the 1999 results demonstrated that areas east, west, and south of the Faultless land withdrawal area do not contribute to predictions of radionuclide migration. The 2003 model domain is 3.6 km long on each side (approximately twice the length of the land withdrawal area) and is centered over UC-1, and like the 1999 model is aligned in the north-south direction. The domain covers the same 1,350-m vertical section. Also consistent with the 1999 model, each cell in the uniform mesh is a cube with edge dimensions of 50 m.

The model simulates the complex hydraulic head relationships indicated by regional data (Figure 2-5). This includes southward flow through the alluvium, while flow in the deeper volcanic

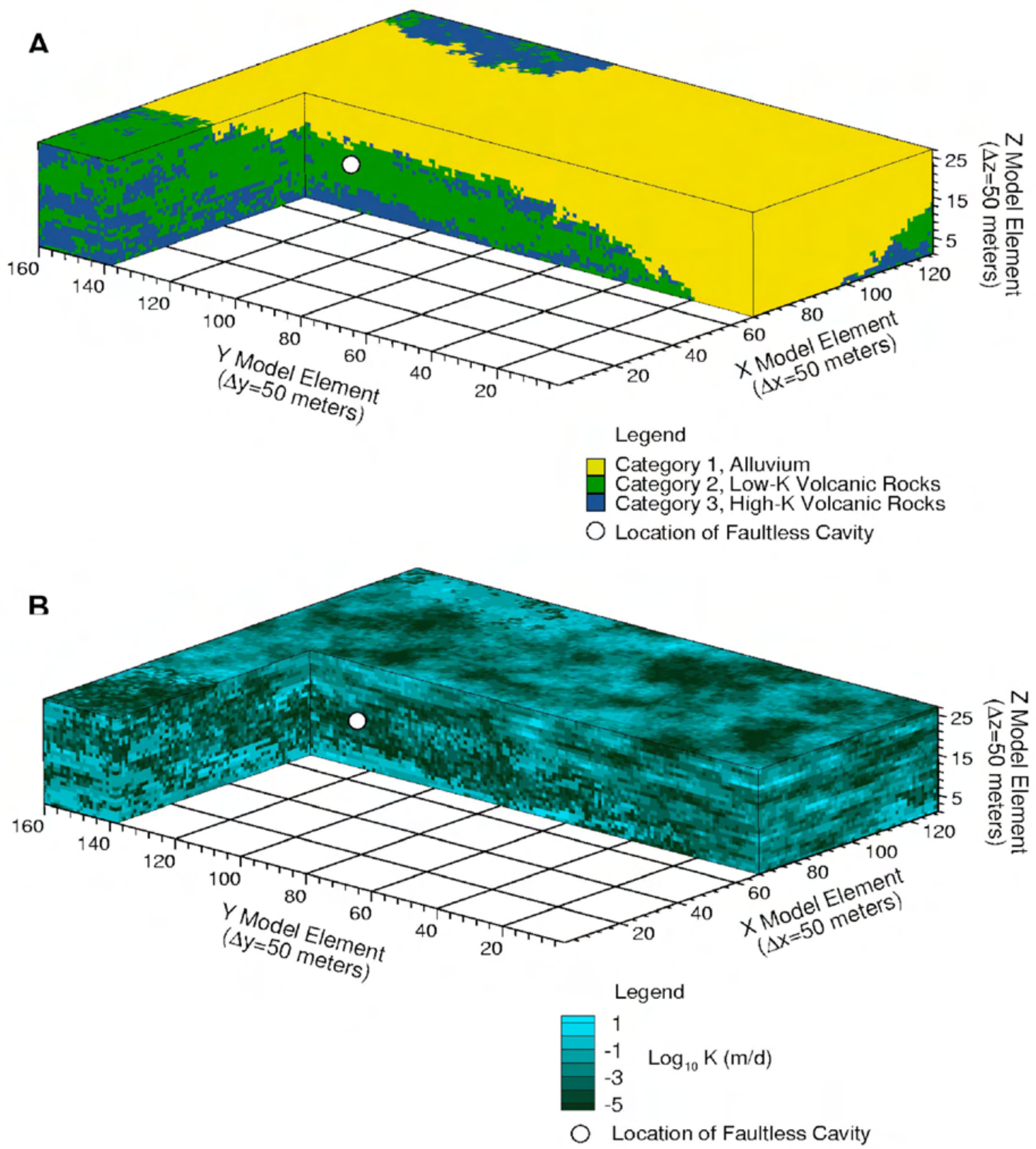


Figure 2-3
The Model Domain Showing a Single Realization of (A) the Three Hydrogeologic Categories, and (B) the Corresponding Distribution of Simulated Hydraulic Conductivity

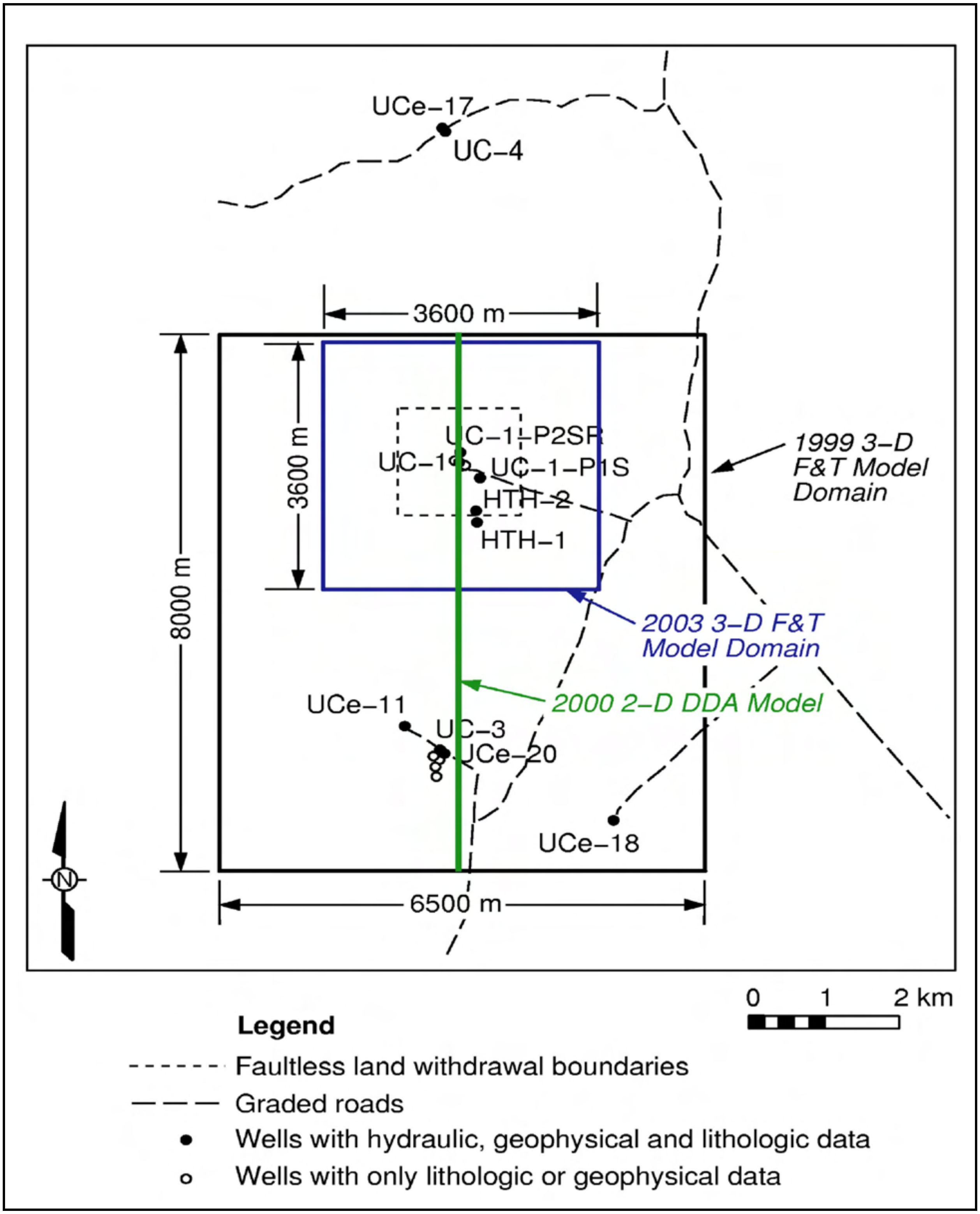


Figure 2-4
Map Showing the Three CNTA Model Domains Used During the CAI. The Contaminant Boundary is Calculated Using 2003 3-D Flow and Transport (F&T) Model Domain

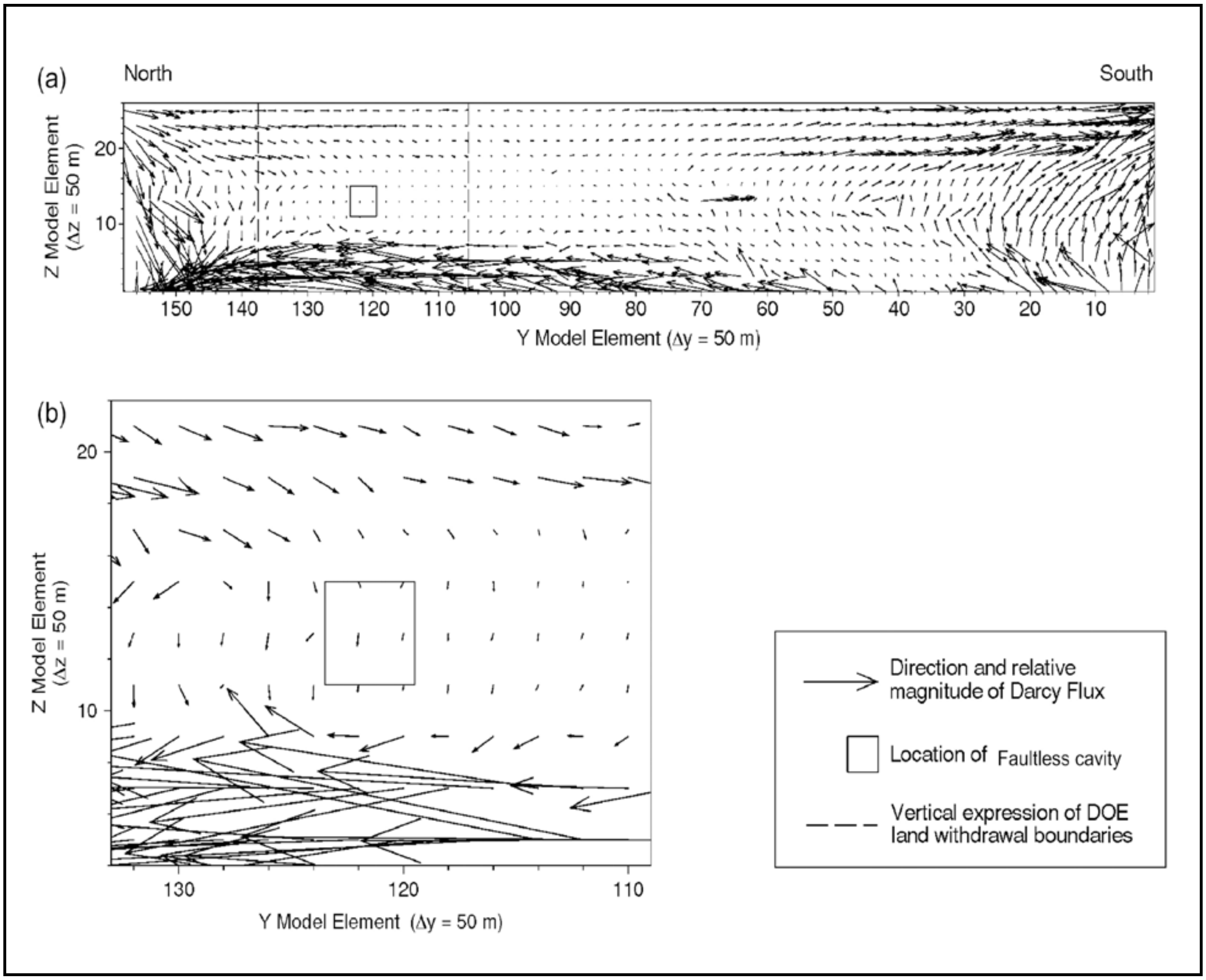


Figure 2-5
Directions and Magnitudes of Darcy Fluxes in a Vertical Cross Section Through the Faultless Cavity. The Flux Vectors Represent the Ensemble Mean of all Flow Realizations and are Shown for Every Other Cell. Part (b) Shows Detail of the Cavity Vicinity

section is directed northward to northeastward. Strong vertically downward hydraulic gradients are present in the north part of the domain, while strong vertical gradients upward from the volcanics to the alluvium are present to the south, consistent with discrete hydraulic head measurements. Groundwater recharge was not directly simulated in the model. Rather, the top of the model is a no-flow boundary, as are the east and west faces. The north, south and bottom faces are specified-head boundaries and are based on the head relationships observed in CNTA wells in Hot Creek Valley (Figure 2-6). In the 2003 model, the heads on the specified-head boundaries are treated

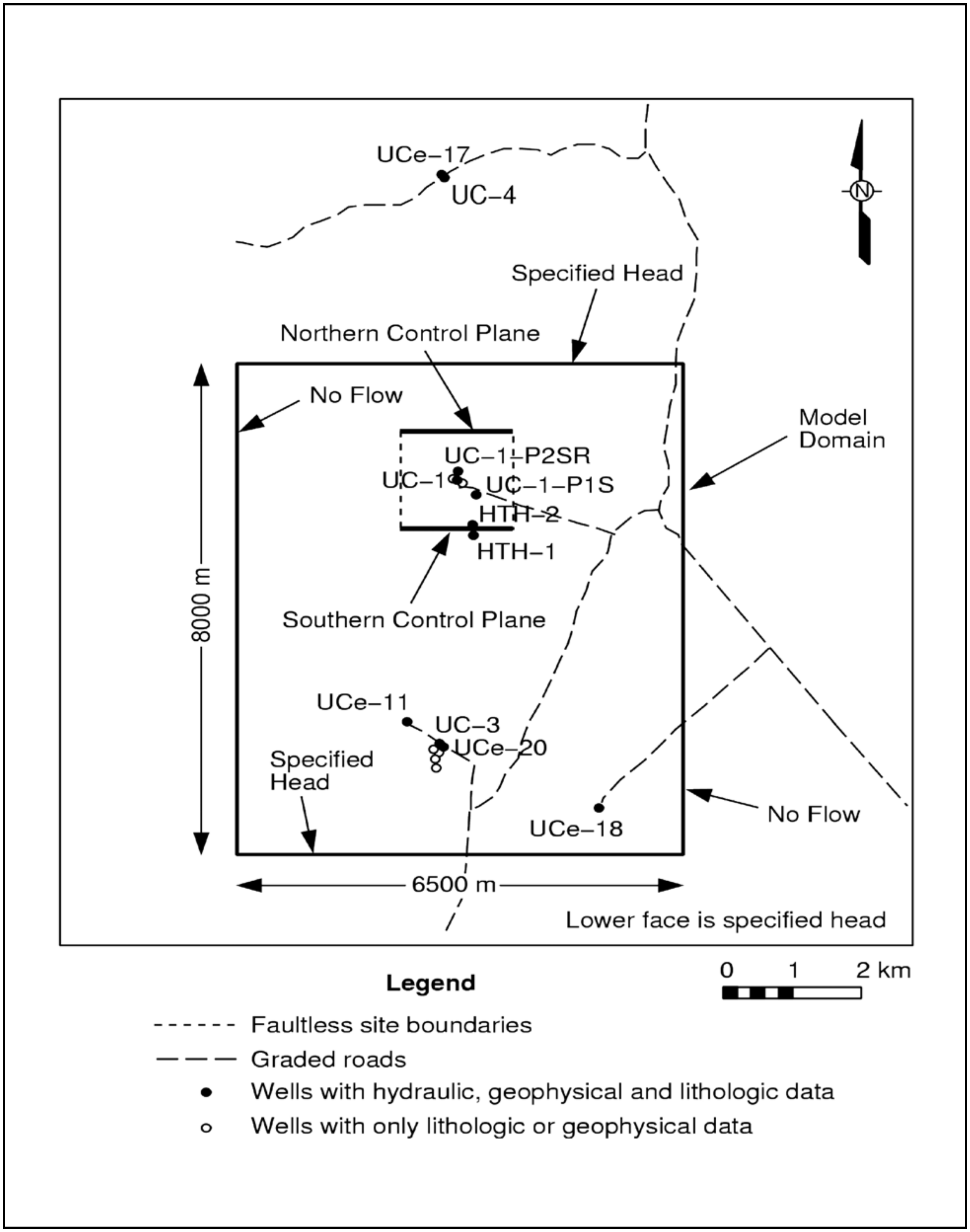


Figure 2-6
Boundary Conditions for the Original Faultless Site Flow Model

as uncertain and are varied using a method adapted from the DDA modeling (discussed below) so that each realization is based on a unique, but equally likely, distribution of boundary heads.

As was done for the 1999 model, boundary heads are estimated using head measurements made in the straddle-packed intervals of the CNTA exploratory wells UCe-20, UCe-18, and HTH-1. For the 2003 model, however, the specified heads include uncertainty through incorporation of the variation observed in the multiple straddle-packed intervals. Just as in the 1999 model, the process uses HTH-1 as the starting point, as it is located much closer to Faultless than the other wells. Estimates of head at the elevations of the top and base of the model at the location of HTH-1 were calculated in the 1999 model by vertical extrapolation of HTH-1 head values. The uncertainty in these values is quantified by the 95 percent confidence interval associated with the linear regression fit to the ten head measurements in HTH-1 (Pohll and Mihevc, 2000). Similarly, the horizontal gradients at the top and base of the model are determined using the uncertainty in the linear regression of head data from UCe-20, UCe-18, and HTH-1. For each Monte Carlo realization, heads at the top and bottom edge nodes of the northern and southern faces are extrapolated using these horizontal gradients and the heads estimated at the top and bottom at the location of HTH-1. The heads of the remaining nodes on the specified head boundaries are obtained by linear interpolation between the heads on the edges.

Using this process, uncertainty in hydraulic head measurements translates into a large degree of variability in the hydraulic boundary conditions of the flow model. Consistent with the conceptual model, groundwater flow is directed downward at the northern end of the domain, upward at the southern end, and to the north along the base.

The Faultless transport calculations employ the RWPT method and the 3-D Darcy flux fields using the same grid discretization and domain size as the groundwater flow model. The radionuclide source is assumed to be the entire Faultless cavity, which is simulated in the model as a cube having edge lengths of 200 m, and within which particles are uniformly distributed.

The classified radionuclide source for Faultless is presented by Goishi et al. (1995). It includes the total radionuclide inventory except for radionuclides either produced in such low quantities or decayed so rapidly that if the total amount produced during the test were dissolved into a volume of water equal to the volume of the cavity and allowed to decay for 100 years, that the resulting aqueous concentration would be less than one-tenth of the maximum permissible concentration

(Smith, et al., 1995). This effectively eliminates radionuclides with half-lives less than about ten years from the inventory. The 1999 model used a shorter list of 22 radionuclides determined to be of significance for remedial investigations at the NTS by the Source Term Committee of the Underground Test Area (UGTA) Technical Working Group (Smith, 1997). In addition, unclassified initial mass estimates for tritium (^{3}H), strontium-90 (^{90}Sr), and cesium-137 (^{137}Cs) were used to demonstrate the modeling results. The DDA also relied on these three nuclide estimates. The updated 2003 model, and the contaminant boundaries calculated with it, evaluated 32 radionuclides for the drinking water-based boundary, and 39 for the risk-based boundary.

The 1999 model treated all transport parameters deterministically (Table 2-1). The radionuclides chosen for inclusion in the model are grouped into six solute classes based on their ratio of hydraulic release to geochemical release, geochemical release coefficient, and retardation factor (Table 2-2). The transport of the radionuclides in each solute class is simulated as a group. Radioactive decay was not incorporated in the transport model, but was applied in post-processing for each individual nuclide. Each transport class is simulated with a unit source mass and then individual radionuclide responses are calculated in a classified environment where the true source mass is included in the analysis. The decay process, including in-growth, is included at this point for individual radionuclides.

One main purpose of the DDA was to include uncertainty in transport parameters, and this approach was carried through in the 2003 model. Random transport parameters in the 2003 model include the glass dissolution release rate, porosity, retardation, and matrix diffusion. Most of the parameters given in Table 2-1 remained the same, although the number of particles was increased to 40,000 for classes 4 and 6, simulation time was limited to 1,000 years (longer time frames were evaluated in the original model to confirm breakthrough behavior), and time steps varied from 2.5 to 1,526.8 days (the time step length for each realization is calculated within the RWPT code using the values of porosity for the three categories associated with that realization; step lengths are chosen so that the Courant numbers for the realization are less than one, to ensure that particles are not transported a distance equal to the dimension of one grid cell (50 m) in a single time step), porosity was variable, and the number of realizations was increased from 110 to 500.

Table 2-1
Values of Parameters Used in the Base-Case Simulations of Transport for the 1999 Model

Parameter	Value
Location of Source, Nevada Central Coordinates (m)	
Easting	191,675
Northing	431,075
Elevation (m above mean sea level [amsl])	885
Size of Source, edge length of cube (m)	200
Mass of Source, M_0	1.0
Infill Time	30 years
Number of Particles	20,000
Longitudinal Dispersivity, T_L (m)	0.05
Transverse Dispersivity, T_T (m)	0.005
Molecular Diffusion, D*	0
Effective Porosity	0.18
Number of Realizations	110

2.1.2.5 Model Calibration

The 1999 flow model was calibrated to ensure the model adequately simulates the observed behavior of the flow system. Two aspects of the CNTA model were adjusted during calibration: the vertical correlation length of *K* and the mean *K* of the alluvium. The vertical correlation length of *K* was adjusted during calibration as it was considered critical to the simulation of flow due to the presence of vertical gradients near the source. The *K* value of the alluvium was adjusted during calibration based on a value of *K* estimated from a pumping test at HTH-1 with observations in HTH-2. The *K* estimated from the pumping test is higher than the values of *K* estimated from packer testing in HTH-1 and in other wells completed in the alluvium (Dinwiddy and Schroder, 1971). The calibration targets were measured hydraulic heads in the uppermost packer interval of HTH-1, UCe-18, and UCe-20, and the head estimated for the top of the model domain at UC-1 based on the estimated horizontal gradient. The calibration was evaluated using the root mean square (RMS) residual between the measured head and simulated head at the four calibration targets. The model was

Table 2-2
Values of Parameters Specific to Individual Solute Classes

Parameter	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Total Time, t (years)	1.37×10^6	1.37×10^6	9.59×10^8	1.37×10^6	8.22×10^8	1.10×10^{10}
Time Step, Δt (years)	110	110	7.67×10^4	110	6.58×10^4	8.77×10^5
Release Ratio, Hydraulic Release / Geochemical Release	1.0/0	0.5/0.5	0.6/0.4	0.05/0.95	0.8/0.2	0.05/0.95
Retardation Factor	1	1	700	1	600	8,000
Geochemical Release Coefficient (1/d)	NA	1.17×10^{-6}	1.17×10^{-6}	1.17×10^{-6}	1.17×10^{-6}	1.17×10^{-6}
Radionuclides in 1999 model	^{3}H, ^{14}C, ^{85}Kr, ^{85}Rb	^{36}Cl, ^{129}I	^{90}Sr, ^{90}Y, ^{90}Zr	^{99}Tc	^{137}Cs	^{151}Sm, ^{152}Eu, ^{154}Eu, ^{234}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Am
Additional radionuclides included in 2003 model & Boundary Calculation	^{26}Al	^{41}Ca, ^{60}Co, ^{59}Ni	^{93}Zr, ^{93m}Nb, ^{94}Nb	^{107}Pd, ^{113m}Cd, ^{121m}Sn, ^{126}Sn	^{135}Cs	^{150}Eu, ^{166m}Ho, ^{232}U, ^{233}U, ^{235}U, ^{236}U, ^{238}Pu, ^{241}Pu, ^{242}Pu, ^{243}Am, ^{244}Cm

considered reasonably calibrated when the RMS residual for 250 realizations was less than 5 m (0.37 percent of the saturated thickness of the model). In addition to heads simulated at the top of the model, vertical gradients simulated at locations where well data were available were monitored to ensure that these gradients were consistent with the field data.

Calibration of the 2003 flow model was evaluated using the average of squared differences between the measured head (h_m) and the simulated head (h_s) at each of the ten straddle packer intervals in HTH-1. The root mean square error (RMSE) is calculated for each flow realization *m* using the expression

$$\mathrm{RMSE} = \left[1/n \sum_{i=1}^{n} \left(h_m - h_s \right)_i^2 \right]_m^{0.5} \tag{2-1}$$

where *n* is the number of calibration targets. The RMSE ranges from 0.76 to 8.3 m, with a mean value of 1.7 m, for the full set of 500 Monte Carlo realizations. As described above, the calibration of the 1999 model was accomplished through adjustment of the vertical correlation length of *K* and the mean of *K* in the alluvium (Category 1) using measured hydraulic heads in the uppermost packer intervals of HTH-1, UCe-18 and UCe-20 as the calibration targets. No adjustments to the construction and parameterization are made in the 2003 model with the exception of the uncertainty incorporated in the head boundary conditions, as described previously, and the value of the vertical correlation scale of *K*. During the calibration of the 1999 model, the vertical correlation scale of *K* was reduced from the value indicated by the spatial statistics. This reduction was not necessary to obtain acceptable RMSE values for the 2003 model, so the longer correlation length true to the data could be maintained.

Because the construction and parameterization of the 2003 model are both essentially the same as the corresponding volume of the 1999 model, the range of simulated heads, flow directions and fluxes are similar. Comparison of the mean head profiles simulated by both models at the location of HTH-1 shows that the new model provides an improved match to the observed head distribution near UC-1 (Figure 2-7). Calibration of the 1999 model was designed to match heads over a larger region and as a result, simulated heads at HTH-1 were not matched to the degree obtained in the current model. In addition, the closer proximity of the specified head boundaries in the 2003 model results in increased control over heads simulated in the model interior. However, incorporation of uncertainty in the head boundary conditions results in a greater range of simulation results in the 2003 model as compared to the 1999 model, as indicated by the wider range of the 95 percent confidence interval.

In a traditional stochastic numerical flow and transport model using Monte Carlo techniques, each of the realizations of flow receives equal weight in the transport analysis. This was the approach followed in the 1999 model. However, it is clear from the range of simulated results that some of the realizations fit the field data better than others. In an effort to honor site-specific field information throughout the 2003 modeling process, those realizations that are in good agreement with the field data are given a greater relative weight in the transport modeling than those that are in poor agreement.

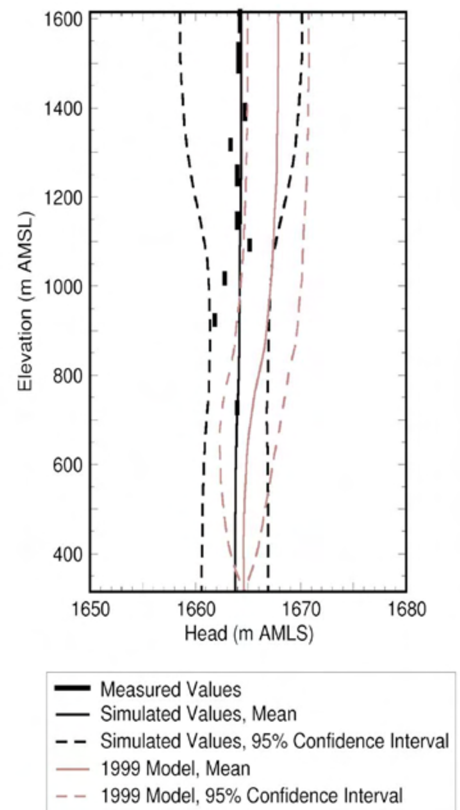


Figure 2-7
Profiles of Hydraulic Heads Simulated by the 1999 Model and the 2003 Model for Well HTH-1, as Compared to Measured Values

The weighting procedure used is the generalized likelihood uncertainty estimator (GLUE) (Beven and Binley, 1992) that extends Monte Carlo random sampling to incorporate the goodness-of-fit of each realization. The goodness-of-fit is quantified by the likelihood measure

$$L(\vec{Y} \mid \vec{\Theta}) = \left[\sum(\varepsilon)^2\right]^{-N} \quad (2\text{-}2)$$

where

$$\varepsilon = (h_s - h_m)_i \quad (2\text{-}3)$$

and $L\left(\vec{Y}\middle|\vec{\Theta}\right)$ is the likelihood of the vector of outputs, $\vec{Y}$ given $\vec{\Theta}$ is the simulated head at the point i, h_m is the observed head at that point, and N is a likelihood shape factor. The choice of N is subjective, although its value defines its relative function. As N approaches zero, the likelihood approaches unity and each simulation receives equal weight, as in the traditional Monte Carlo analysis. As N approaches infinity, the simulations with the lowest RMSE receive essentially all of the weight, which is analogous to an inverse solution. In this study, the value of N is assumed to be unity, which is a value typically used for this type of analysis (Beven and Binley, 1992; Freer and Beven, 1996; Morse et al., 2003).

Each of the 500 flow realizations from the 2003 model are weighted based on an application of the Bayes equation of the form:

$$P(\vec{\Theta} \mid \vec{Y}) = \frac{L(\vec{Y} \mid \vec{\Theta})P(\vec{\Theta})}{C} \tag{2-4}$$

where $P\left(\vec{\Theta}\right)$ is the prior probability of the input parameters produced by the Monte Carlo simulation, $L\left(\vec{Y}\middle|\vec{\Theta}\right)$ is the likelihood measure from Equation 2-2, C is a normalization constant, and $P\left(\vec{\Theta}\middle|\vec{Y}\right)$ is the posterior density. The posterior density is the probability of the input parameters occurring after taking into account the likelihood measure and is used to calculate the contaminant boundary as described in Section 2.2. Each of the 500 flow realizations receives a weight based on Equation 2-4, which is simply a normalization of the likelihood such that the sum of the weights for all realizations is unity. In this way, each transport realization is appropriately weighted according to the goodness-of-fit of its hydraulic head distribution to the available field measurements.

2.1.2.6 Sensitivity and Uncertainty Analysis: Data Decision Analysis

Sensitivity analyses performed with the 1999 model focused on parameters most likely to reduce the long travel times simulated by the model. The sensitivity cases studied included increasing the vertical correlation length of hydraulic conductivity, increasing the mean hydraulic conductivity of the alluvium, simulating prompt injection of tritium into the upper portions of the chimney, and increasing the local dispersion. None of these individual cases significantly altered the base-case transport results during the 1,000-year period of interest; however, combining the prompt injection scenario with the higher hydraulic conductivity in the alluvium created a scenario having tritium breakthrough at the southern land withdrawal boundary.

The characteristics of very low hydraulic conductivity and downward-directed gradients at the source control the transport behavior of radionuclides from the Faultless test. For sorbing radionuclides, strong sorption characteristics of the aquifer matrix are also important. The major uncertainties identified by the 1999 numerical model are the magnitude and direction of hydraulic gradients and the existence of densely welded tuffs below the nuclear test horizon, where no data exist.

The purpose of the DDA was to quantify the output uncertainty (prediction uncertainty) in the 1999 groundwater flow and transport model. Although the original model included uncertainty in the spatial distribution and hydraulic properties of various units, uncertainty in other model parameters was not included. Depending on the outcome of the first DDA objective, a secondary objective was to determine the most cost-beneficial characterization activities for reducing model uncertainty. Details of the CNTA DDA can be found in Pohll and Mihevc (2000). The DDA approach was first developed and applied to the Shoal underground nuclear test site (Pohll et al., 1999).

Using a sensitivity analysis performed with the original model, the DDA identified six parameters whose uncertainty is important to the model's ability to predict solute migration. These parameters are: (1) specified head boundary conditions, (2) spatial distribution of the welded tuff, (3) effective porosity, (4) sorption coefficients, (5) matrix diffusion coefficients, and (6) nuclear melt glass dissolution rates. Other parameters are also uncertain, but were found to not be as important to predictions of solute migration. Uncertainty in K was also included through the stochastic treatment of the spatially heterogeneous K field, as in the original model. The second uncertainty parameter listed above (spatial distribution of the welded tuff) was also addressed through this process. To accommodate the computational rigors of so many uncertain parameters and the large number of realizations needed for reliable statistics, the original 3-D model was converted to a 2-D cross section (Figure 2-8). This process was straightforward due to the boundary conditions in the 3-D model being constant along the x-direction.

The first step in the DDA was to determine prior distributions of the parameters. This was an assessment of the range of potential values and probability associated with each value. Ranges and uncertainty were estimated using site-specific data, augmented by literature values. Two solutes were

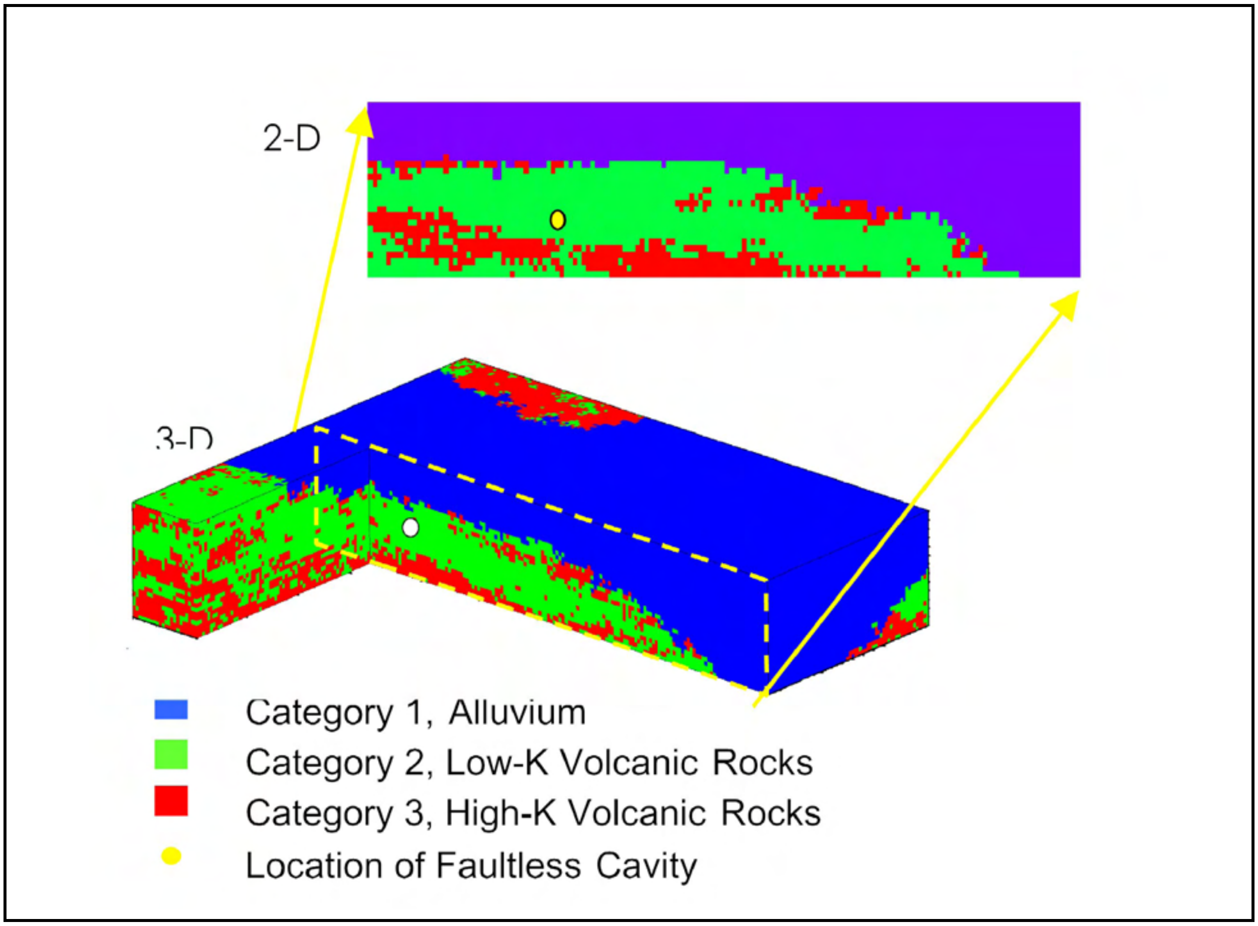


Figure 2-8
Model Conversion From 3-D to 2-D Domain. The Spatial Distribution of Lithologic Categories is one of the Many Equiprobable Realizations

used for the transport modeling to assess the transport features for a conservative (tritium) and reactive (^{90}Sr) solute. Transport was simulated over a period of 1,000 years as identified in the FFACO and the contaminant boundary was calculated as the metric of most interest. The maximum radius of the contaminant boundary was used to determine the uncertainty in the predictive capability of the model by comparing the size from one realization to another.

The DDA found that the 90 percent confidence interval for the maximum contaminant boundary radius ranged from 234 to 308 m for tritium, and from 234 to 302 m for ^{90}Sr (Figure 2-9 and Figure 2-10). The range between the upper and lower 90 percent confidence intervals (a measure of uncertainty) is 74 m for tritium and 68 m for ^{90}Sr. These results indicate that although there is a large amount of uncertainty in the input parameters, the uncertainty in the prediction of the contaminant boundary within the 1,000-year timeframe is relatively certain, with an error of less than 100 m. This results primarily from the low transport velocities. Uncertainty could potentially be reduced through additional characterization work, to values less than 74 m, but this would provide little value regarding management of the site.

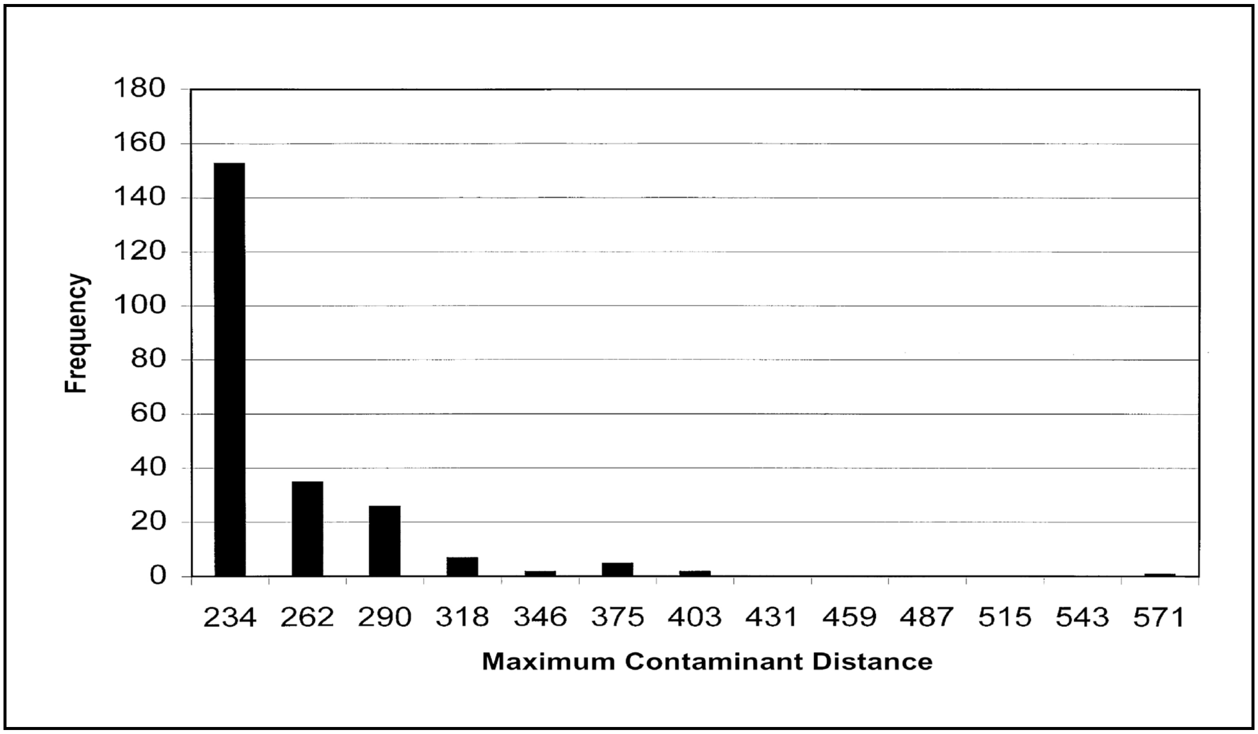


Figure 2-9
Histogram of Maximum Contaminant Distance for Tritium in the DDA Model

2.1.2.7 Model Verification

As described in their review of the DDA (Liebendorfer, 2001), NDEP considers the DDA as a partial verification of the flow and transport model. They also required a commitment for future model verification using an independent set of data. This will be accomplished through the model validation process as part of the corrective action for the site, as described in subsequent parts of this document.

2.1.2.8 Predictive Simulations

Predictive simulations of radionuclide transport from the Faultless test were conducted using all three of the models. During the 1999 modeling effort, the emphasis was on defining contaminant transport behavior by evaluating breakthrough curves at the northern land withdrawal boundary. As radionuclide mass was released from the cavity region, its movement was tracked through the model

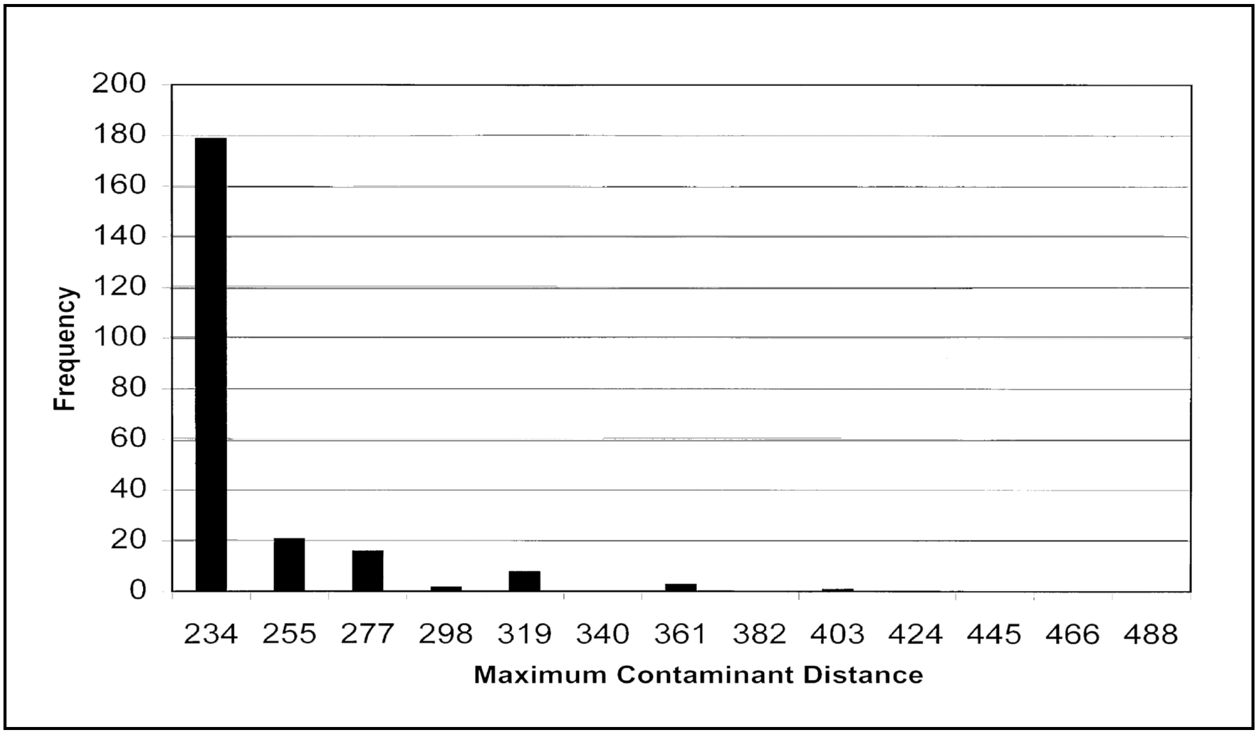


Figure 2-10
Histogram of Maximum Contaminant Distance for Strontium-90 in the DDA Model

domain. The peak passage at the CP was noted (after accounting for radioactive decay) and that time used to sum the particles and convert mass to concentration. Mass breakthrough curves and concentration breakthrough curves through time are calculated. As a quality check for the transport simulations, the simulations were allowed to run as long as necessary to obtain near-complete breakthrough for the undecayed case. This was in excess of a million years for the sorbing radionuclides.

The DDA used predictive simulations to evaluate the impact of parameter uncertainty on the model results. The contaminant boundaries for tritium and ^{90}Sr (calculated using an unclassified estimate for starting mass) were used as the metric. The 2003 model similarly calculated contaminant boundaries during the predictive simulation phase. The procedure for boundary calculation is presented in detail by Pohll et al. (2003) and in Section 2.2.

2.1.2.9 Presentation of Model Results

Per this step in the FFACO ten-step validation process, the results of the CAI modeling were presented in the original modeling report (Pohlmann et al., 1999), in the DDA report (Pohll and

Mihevc, 2000), and in the contaminant boundary report (Pohll et al., 2003). The findings of these reports were also provided to NDEP through presentation at technical meetings. The results are summarized here in Section 2.1.3.

2.1.2.10 Post-Audit

Appendix VI of the FFACO (1996) states: "The five year proof-of-concept is the model post-audit to establish, within a longer time frame, that the model is capable of producing meaningful results with an acceptable degree of uncertainty." The model validation and monitoring processes that will occur during this post-audit phase are described in detail in the CAP portion of this document. They involve obtaining new data from the Faultless site to compare with the model as required by the NDEP (Liebendorfer, 2001), as well as initiating monitoring of the groundwater system based on contaminant transport predictions.

2.1.2.11 Quality Assurance/Quality Control

The work carried out under the CAIP for CAU 443 was designed and implemented in accordance with the FFACO (1996) and the UGTA Quality Assurance Project Plan (QAPP) (DOE, 1998b, 2000b). As stated in the UGTA QAPP, three fundamental types of activities are necessary to accomplish project objectives. These are data assessment, flow and transport modeling, and data collection.

Data were evaluated against their intended use. This analysis consisted of screening, checking, verifying, and reviewing the data. Some of these data were decades old and their quality was assessed by review of the testing and analysis methods presented in published reports, and assessment of the data in the context of regional and general hydrogeologic knowledge.

Quality assurance of the numerical modeling work relied on several overlapping efforts. These are as follows:

- Project control procedures
- Personnel qualifications
- Technical control procedures
- Peer review

2.1.2.11.1 Code Evaluation

Code developed external to the Desert Research Institute (DRI) originates from commercial software firms and non-profit organizations (e.g., the MODFLOW-88 code from the USGS). External code is selected based on its technical capabilities to meet project needs and acceptance in the wider groundwater modeling community. Before selecting externally developed code for a particular modeling purpose, a rigorous review and comparison is conducted of the available pertinent codes. Internal modeling programs are developed when external programs are not available to meet project needs and/or when additional flexibility or new algorithms are required for the task at hand (e.g., the RWPT code used for radionuclide transport modeling).

2.1.2.11.2 Code Verification/Validation

Software verification and validation activities are intended to provide confidence that the software adequately and correctly performs all intended functions. Significant portions of the CNTA modeling were performed using externally developed software (e.g., SIS, SGS, MODFLOW-88). These software packages are subjected to rigorous test-case analyses, per the software's documentation, to ensure proper operation. Externally developed modeling programs are not, to the extent practicable, modified in any way. In some cases, modifications are not possible because the source code is proprietary and not available; however, even in the case of open-source software such as MODFLOW-88, internal modifications can prevent the application of the code to other modeling scenarios without further modifications and may increase uncertainty in the results. For these reasons, the modeling team prefers to develop input and output routines that provide the input data and accept the results in the default format of the codes. In addition, it is unlikely that internal changes would be required to, for example, improve performance or integrate additional functionality, as these factors would have been evaluated during code evaluation. Additional functionality is generally provided only by development and integration of auxiliary codes in the modeling system.

Individuals knowledgeable in the area of code development review all newly developed DRI computer codes. These reviews consider whether the assumptions are reasonable and valid, the correctness of the mathematical models, conformance of methods to accepted and published concepts, consistency of results with known data, reasonable and prudent use of data and analysis tools, and appropriateness for the intended purpose. Where appropriate, solutions are compared to analytically derived solutions to check the theory and application represented by the codes. In the case of the RWPT code used for radionuclide transport, additional quality assurance was provided through independent peer-reviewed publication of a rigorous comparative study with other transport codes (Hassan and Mohamed, 2003).

2.1.2.11.3 Documentation

Continual evaluation and record keeping are conducted during the modeling phases of the project to ensure that the work is internally consistent, well documented, and readily repeatable for the purposes of technical review and future model refinements. All developed and procured computer codes are uniquely identified and internally documented so that it is obvious to the user of the version they are implementing. Unique run identifiers are used to link model output with the corresponding model input; and the associated documentation identifies the specific input files, versions of the codes, and other related information so that the output for any run can be readily regenerated. This procedure is followed even during initial testing of model parameterization and boundary conditions, in order to track sensitivity to these fundamental aspects of the model. Computer software code documentation is maintained in project files.

2.1.2.11.4 Peer Review

Peer review is an assessment of the assumptions, calculations, extrapolations, alternate interpretations, methodology, acceptance criteria, and conclusions pertaining to interpretive work products generated through the use of computer software. Peer review is performed to ensure that interpretive work products are technically adequate, properly documented, and satisfy technical and quality requirements. Peer reviewers shall possess the appropriate subject matter/technical expertise and not have participated in preparing the original work.

The external review occurred at the conclusion of the draft model report and used the Modeling Subcommittee of the UGTA Technical Working Group. The review committee consisted of:

> Andrew F.B. Tompson (Chair), Lawrence Livermore National Laboratory
> David E. Prudic, U.S. Geological Survey
> Sirous Djafari, IT Corporation

Andrew Wolfsberg, Los Alamos National Laboratory
Vefa Yucel, Bechtel Nevada

The draft report was sent to the committee on November 16, 1998. Committee comments were incorporated into the model and model report before submission to NDEP. A comment response document was also prepared. The model report was delivered to NDEP for review on November 23, 1999. The regulatory review conducted by NDEP also serves as a peer review. Technical comments were received from NDEP in a letter dated March 17, 2000 (Liebendorfer, 2000). These comments were addressed through performance of the DDA.

Rigorous peer review also occurred through the process of publication in the open scientific literature. Pohlmann et al. (2000) presented the fundamental construction of the flow and transport model and Pohll et al. (2002) presented the DDA, both in peer-reviewed forums.

2.1.3 Modeling Results

The primary result of the Faultless modeling is the calculation of the contaminant boundary maps. These are presented in Section 2.2. The following describes the general hydrogeologic results of the 1999 flow model and the contaminant transport behavior. Many features resulting from the modeling were presented in figures in the preceding sections.

The immediate area of the Faultless test is characterized in the model as a zone of very low flow, directed downward and slightly to the north (Figure 2-5). Thus, flow that passes through the cavity region moves down through the low-*K* tuffaceous sediments before reaching hypothesized high-*K* pathways in the welded tuffs. Vertical flow rates in the source volume range from 3.2×10^{-9} to 5.8×10^{-6} m/d, so that the time of transport from the source to the welded tuffs is very long. This representation of low hydraulic conductivities and long groundwater residence times is consistent with the hydraulic properties of the chimney calculated based on water-level recovery rates, and with isotopic data from groundwater samples that indicate residence times on the order of many tens of thousands of years.

Very little breakthrough of contaminants is projected to occur at the UC-1 land withdrawal boundary during the 1,000-year period of interest. Using an unclassified estimate of initial tritium mass to scale the tritium breakthrough, the 1999 model gives an estimated peak mean concentration of almost

1 picocurie per liter (pCi/L), and a mean plus one standard deviation of 10 pCi/L, occurring at 153 years after the Faultless test. This transport is calculated with the fracture-flow conceptualization and is facilitated by densely welded tuffs stochastically simulated below the Faultless test based on sparse regional data; densely welded tuffs were not encountered at the UC-1 drillhole or instrument holes. Normalized mass fluxes of the remaining radionuclides in the source term are also very low. The peak mean breakthroughs of the radionuclides occur between 2,000 years for short-lived species with no retardation, up to millions of years for long-lived radionuclides with significant retardation, using the porous media conceptualization. As Table 2-2 indicates, there are six radionuclide classes differing in two aspects: the sorption characteristics and the hydraulic/geochemical release ratio. The latter has a minor effect on the rising limb of the breakthrough curve, and the retardation factor is responsible for the delayed arrival of mass for the classes with higher retardation.

The level of confidence in the model is obtained directly from the stochastic simulations. Monte Carlo methods describe the uncertainty in model predictions based upon an analysis of the uncertainty in model input parameters. Bayesian methods are used in combination with Monte Carlo techniques to weight each realization based on its ability to reproduce observed system behavior. Any confidence level can be presented for the model results, although the 95 percent level is used for the contaminant boundary.

Data limitations and the uncertainties they lead to in the model results are discussed in Section 2.1.2.6 (Sensitivity and Uncertainty Analysis). As presented there, the DDA (Pohll and Mihvec, 2000) evaluated the relationship between model uncertainty and parameter uncertainty and concluded that uncertainty reduction to values less than currently identified (74 m for tritium) would provide little value regarding management of the site. Unquantified uncertainties exist in the effect of the nearfield conditions that were not included in the modeling, which is based on regional, pre-Faultless characteristics.

The ability to calibrate the model to observed heads while simulating the complex regional flow patterns indicates that the numeric model supports the conceptual flow model. Similarly, the transport model results of very limited radionuclide migration support the conceptual model of transport through a strongly reactive substrate.

The final results of the modeling are the contaminant boundaries produced with the focused 2003 model, developed with the dual-permeability conceptualization. Those boundaries, as well as the methodology used to calculate them, are presented in Section 2.2.

2.2 Contaminant Boundary Determination

The purpose of the contaminant boundary calculation is to provide “the model-predicted perimeter which defines the extent of radionuclide-contaminated groundwater above background conditions exceeding the *Safe Drinking Water Act* (SDWA) standards” (FFACO, 1996). From the contaminant boundary predicted by the computer model, the compliance boundary is negotiated between NDEP and DOE (Section 2.3). Thus, the contaminant and compliance boundaries are the final product of the corrective action investigation.

The contaminant boundary for the Faultless test was calculated using the 2003 flow and transport model that incorporates aspects of both the original 3-D model and the 2-D model used for the DDA. The 2003 model includes the uncertainty in the 3-D spatial distribution of lithology and hydraulic conductivity from the 1999 model, as well as the uncertainty in the other flow and transport parameters from the 2000 DDA model. Additionally, the 2003 model focuses on a smaller region than was included in the earlier models; that is, the subsurface within the UC-1 land withdrawal area where the 1999 model predicted radionuclide transport will occur over the next 1,000 years (Figure 2-4). It is important to note that the groundwater flow and transport simulations provide predictions of radionuclide transport under ambient conditions.

The methodology used to calculate the contaminant boundary is summarized below. A detailed presentation of the approach is in Pohll et al. (2003).

2.2.1 Land Use and the Contaminant Boundary

No residences or other habitable structures exist on the CNTA. The CNTA has been withdrawn from all forms of public appropriation, including mining. Currently, there are no leases for oil and gas exploration on the CNTA. Other than groundwater monitoring wells, no water wells exist on the CNTA, and no water rights are filed with the Nevada Division of Water Resources, or the U.S. Department of the Interior, Bureau of Land Management (BLM). No water rights appear on the

Master Title Plat or in the Historical Index (DOE/NV, 2002). The site is managed by BLM under the BLM Resource Management Plan (BLM, 1997). The contaminant boundary for CNTA is based on these current conditions of no groundwater development, per agreement between NDEP and DOE.

2.2.2 Relationship Between Risk and Safe Drinking Water Act Requirements

Although the FFACO specifies the SDWA standards as the metric of concern for the boundary, it is possible to meet those standards while exceeding a lifetime excess cancer risk of 10^{-6}. The National Primary Drinking Water Regulations for radionuclides (EPA, 2000) identify 0.04 millisievert per year (mSv/yr) (4 millirem per year [mrem/yr]) as the total annual dose equivalent to an organ or the whole body that cannot be exceeded from internal exposure to beta particle and photon radioactivity. For beta/photon emitters the 4 mrem/yr equates approximately to a 50 pCi/L screening level. This annual dose equivalent, along with a 2 L/d consumption rate, is used as a basis for setting annual average activity-concentration limits for drinking water intake for beta particle and photon emitting radionuclides (EPA, 1976). This method is best described as the "critical-organ dose-limit approach" because it involves using an acceptable dose limit for a critical organ as a fundamental parameter for setting a concentration limit. In addition, the regulations require that the sum of the activity concentrations of alpha-emitting radionuclides must not exceed 15 pCi/L, and the sum of mass concentrations of uranium isotopes must not exceed 30 micrograms per liter (μg/L). The beta/photon maximum contaminant level (MCL) is 50 pCi/L and it is a screening level. MCLs are given in Table 2-3 below.

An alternative procedure uses radionuclide-specific lifetime radiogenic cancer risk coefficients (expressed as either a cancer mortality [fatal only] risk per unit activity or as a cancer morbidity [fatal and nonfatal combined] risk per unit activity [i.e., mortality risk/Becquerel [Bq] or morbidity risk/Bq]) for the U.S. population published by the EPA (1999), and derived using methods and models that take into account age and gender dependence of intake, metabolism, dosimetry, radiogenic risk, and competing causes of death in estimating the risks to health from internal or external exposure to radionuclides. Cancer risk coefficients have been tabulated for over 800 radionuclides individually (not categorically, as is done for MCLs, which also only address dose and not risk) and include values applicable to low-acute doses or low-dose rates from internal exposure through various media, including drinking water. Technically, these radionuclide-specific cancer risk

Table 2-3
Radionuclides Used for the Contaminant Boundaries and Related Parameters
(Pohll et al., 2003)
(Page 1 of 2)

Isotope	Isotope Symbol	Half life ($t_{1/2}$; yr)	Risk/pCi	Used in MCL Boundary	Used in Risk Boundary	MCL Standard	Emission Type
Tritium	H-3	1.23E+01	5.07E-14	x	x	20000 pCi/L	Beta
Carbon-14	C-14	5.73E+03	1.55E-12	x	x	2000 pCi/L	Beta
Aluminum-26	Al-26	7.30E+05	1.73E-11		x	n/a	Beta
Chlorine-36	Cl-36	3.01E+05	3.30E-12	x	x	700 pCi/L	Beta
Calcium-41	Ca-41	1.03E+05	3.53E-13		x	n/a	Beta
Nickel-59	Ni-59	7.60E+04	2.74E-13	x	x	300 pCi/L	Beta
Nickel-63	Ni-63	1.00E+02	6.70E-13	x	x	50 pCi/L	Beta
Strontium-90	Sr-90	2.91E+01	5.59E-11	x	x	8 pCi/L	Beta
Zirconium-93	Zr-93	1.50E+06	1.11E-12	x	x	2000 pCi/L	Beta
Niobium-94	Nb-94	2.00E+04	7.77E-12		x	n/a	Beta
Technetium-99	Tc-99	2.13E+05	2.75E-12	x	x	900 pCi/L	Beta
Paladium-107	Pd-107	6.50E+06	2.50E-13		x	n/a	Beta
Cadmium-113m	Cd-113m	1.41E+01	2.87E-11		x	n/a	Beta
Tin-121m	Sn-121m	5.50E+01	2.34E-12		x	n/a	Beta
Tin-126	Sn-126	1.00E+05	2.56E-11		x	n/a	Beta
Iodine-129	I-129	1.57E+07	1.48E-10	x	x	1 pCi/L	Beta
Cesium-135	Cs-135	2.30E+06	4.74E-12	x	x	900 pCi/L	Beta
Cesium-137	Cs-137	3.02E+01	3.04E-11	x	x	200 pCi/L	Beta
Samarium-151	Sm-151	9.00E+01	5.55E-13	x	x	1000 pCi/L	Beta
Europium-150	Eu-150	3.60E+01	4.33E-12		x	n/a	Beta
Europium-152	Eu-152	1.35E+01	6.07E-12	x	x	200 pCi/L	Beta
Europium-154	Eu-154	8.59E+00	1.03E-11	x	x	60 pCi/L	Beta
Holmium-166m	Hm-166m	1.20E+03	8.03E-12	x	x	90 pCi/L	Beta
Thorium-232	Th-232	1.40E+10	1.01E-10	x	x	15 pCi/L	Alpha
Uranium-232	U-232	7.00E+01	2.92E-10	x	x	30 µg/L	Uranium & Alpha
Uranium-233	U-233	1.59E+05	7.18E-11	x	x	30 µg/L	Uranium & Alpha
Uranium-234	U-234	2.46E+05	7.07E-11	x	x	30 µg/L	Uranium & Alpha
Uranium-235	U-235	7.04E+08	6.96E-11	x	x	30 µg/L	Uranium & Alpha
Uranium-236	U-236	2.34E+07	6.70E-11	x	x	30 µg/L	Uranium & Alpha

Table 2-3
Radionuclides Used for the Contaminant Boundaries and Related Parameters
(Pohll et al., 2003)
(Page 2 of 2)

Isotope	Isotope Symbol	Half life ($t_{1/2}$; yr)	Risk/pCi	Used in MCL Boundary	Used in Risk Boundary	MCL Standard	Emission Type
Uranium-238	U-238	4.47E+09	6.40E-11	x	x	30 μg/L	Uranium & Alpha
Neptunium-237	Np-237	2.14E+06	6.18E-11	x	x	15 pCi/L	Alpha
Plutonium-238	Pu-238	8.77E+01	1.31E-10	x	x	15 pCi/L	Alpha
Plutonium-239	Pu-239	2.41E+04	1.35E-10	x	x	15 pCi/L	Alpha
Plutonium-240	Pu-240	6.56E+03	1.35E-10	x	x	15 pCi/L	Alpha
Plutonium-241	Pu-241	1.44E+01	1.76E-12	x	x	300 pCi/L	Beta
Plutonium-242	Pu-242	3.75E+05	1.28E-10	x	x	15 pCi/L	Alpha
Americium-241	Am-241	4.33E+02	1.04E-10	x	x	15 pCi/L	Alpha
Curium-244	Cm-244	1.81E+01	8.36E-11	x	x	15 pCi/L	Alpha

coefficients can be applied to estimate the lifetime excess morbidity cancer risk due to chronic exposure over a lifetime to a constant environmental activity concentration by an average individual in a stationary population in the U.S. Consequently, summing the products of drinking water activity concentrations predicted for specific radionuclides (Becquerel per liter [Bq/L]), a corresponding radionuclide-specific cancer risk coefficient, and a conservative estimation of a lifetime exposure to drinking water will yield a total lifetime excess cancer risk for exposure to all of the radionuclides considered.

If the lifetime excess cancer-risk criterion is used at the EPA point of departure of 10^{-6}, the drinking water regulations will also be met, as they are based on risk values larger than 10^{-6}. Both boundaries (SDWA-based and risk-based) are presented by DOE to NDEP for consideration with the CADD. Title 40 *Code of Federal Regulations* (CFR) Part 300.430 states "For known or suspected carcinogens, acceptable exposure levels are generally concentration levels that represent an excess upper bound lifetime cancer risk to an individual of between 10^{-4} and 10^{-6} using information on the relationship between dose and response. The 10^{-6} risk level shall be used as the point of departure…".

2.2.3 Model Uncertainty and Boundary Calculation Process

If there were no uncertainty in the solute transport model, the risk-based or regulatory-based analysis would provide explicit definition of the boundary maps. In reality, the groundwater models contain a certain degree of uncertainty, which needs to be represented in an analysis of the boundary delineation. This was recognized in the FFACO and expressed as a requirement that the contaminant boundary be predicted at a 95 percent level of confidence. This requirement can actually be interpreted in two different, but complimentary, ways to map the 3-D extent where groundwater has been contaminated and the associated uncertainty. One approach is to identify the region in which we are 95 percent certain that contaminants exist and exceed the health risk or regulatory threshold. The boundary will then encircle the region that meets this criterion. The alternative approach is to identify the region where we are 95 percent certain that contaminants do not pose a health risk and therefore encompasses the region that fails to meet the boundary criterion. In other words, the water that does not pose a health risk is external to the region enclosed by the boundary. The description of the boundary in Appendix VI of the FFACO is ambiguous as to which of these two perspectives should be used for the contaminant boundary. The approach presented here follows the second alternative, identifying the region where it is 95 percent certain that contaminants do not pose a health risk.

Uncertainty in the groundwater flow and transport model is handled directly within a Monte Carlo type approach. Monte Carlo methods describe the uncertainty in model predictions based upon an analysis of the uncertainty in model input parameters. Bayesian methods are used in combination with Monte Carlo techniques to weight each Monte Carlo realization based on its ability to reproduce observed system behavior. The Bayesian methods (Section 2.1.3) allow one to “calibrate” the stochastic model within the framework of the uncertainty analysis.

The general approach to quantify the model uncertainty is described by the following steps:

1. Determine all model parameters that are considered uncertain. It is important to note that uncertainty is derived from parameter measurement errors, spatial heterogeneity, and errors in model conceptualization, each of which can be included in the uncertainty analysis.

2. Quantify the distributions of all uncertain parameters. This is typically done via a specification of a probability distribution function (pdf) for each parameter.

3. Perform numerical simulation of groundwater flow and transport with randomly sampled parameter distributions.

4. Calculate the likelihood function (e.g., weights) for each realization. The likelihood function is a measure of the "fit" between simulated and observed system behavior. For Faultless, hydraulic heads are used as the basis for calculating the likelihood measure.

5. Quantify the pdf for the simulated solute transport. In the context of calculating boundary maps, a pdf is created for each cell within the solute transport model that specifies the probability that radionuclide concentrations will exceed the MCL over a 1,000 year period. A risk-based boundary is calculated in addition to the regulatory boundary. The pdf for the risk-based approach describes the probability that the morbidity risk (i.e., fatal and nonfatal risks) is greater than 10^{-6}.

6. Determine the 95 percent confidence threshold for the contaminant boundary.

The quantification of the pdf for the risk-based analysis uses the results of the solute transport model and the source mass for individual radionuclides to determine if a fluid parcel exceeds a 10^{-6} risk threshold with the inclusion of model uncertainty. The risk-based approach yields a continuous pdf for each spatial position at 70-year intervals. Although the statistical analysis presented herein is for a risk-based boundary, the analysis is similar for a regulatory-based boundary.

A confidence interval defines a range of risk values for a given significance level (e.g., 95 percent), which describes the magnitude of the uncertainty inherent in the numerical model. A typical confidence region as defined by statisticians is given by:

$$\int_a^b f(x) = \gamma \tag{2-5}$$

where f(x) is the pdf, γ is the significance level and a and b are the lower and upper bounds of the confidence region (i.e., confidence levels). Figure 2-11 is a graphical representation of this type of definition. The dashed region represents an area equal to γ. This type of definition captures the central portion of the pdf, which is not appropriate for the definition of boundary maps, as the tails represent very high risk and very low risk values.

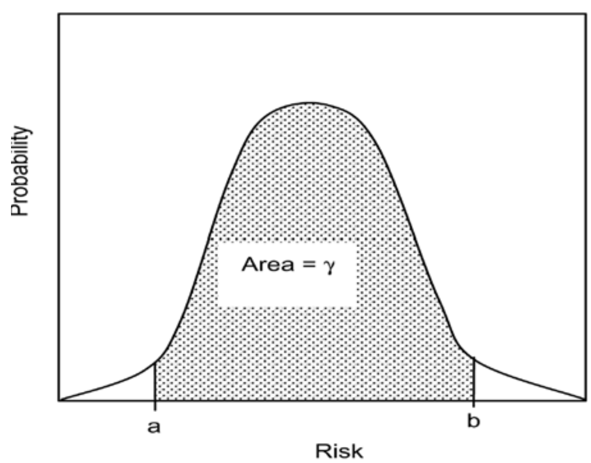


Figure 2-11
Probability Distribution Function
Showing How Typical
Confidence Levels are Determined

For the purposes of contaminant boundaries, the choice is made to focus on the region of “clean” water and as such, the lower end (i.e., uncontaminated region) of the pdf is used in the determination of the confidence threshold:

$$\int_{o}^{a_1} f(x) = \gamma \tag{2-6}$$

where a_1 is the threshold risk value that captures an area of size γ. Figure 2-12 shows a graphical representation of the proposed contaminant boundary confidence threshold. The contaminant definition captures all transport realizations with risk values greater than a_1 and determines the threshold risk value that captures our knowledge to a level equal to γ. If, for example, a γ was chosen at a 95 percent level, then the threshold value represents a risk value in which we are 95 percent confident that the risk value is less than or equal to a_1.

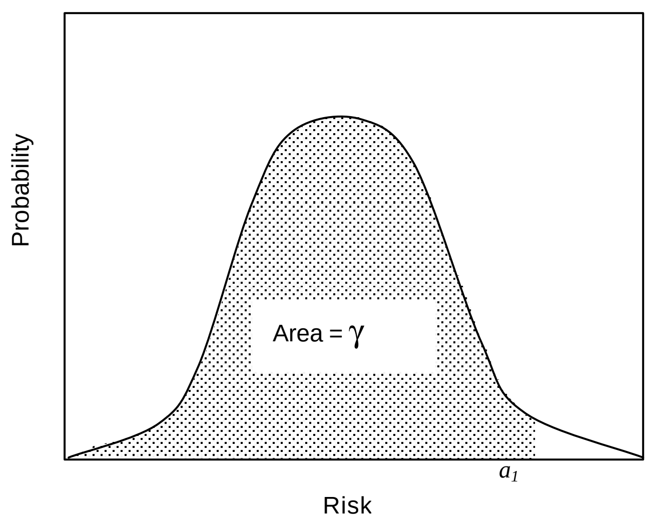


Figure 2-12
Probability Distribution Function Showing How the Risk Threshold is Calculated for the Contaminant Boundary

The boundary maps are created by determining the threshold risk value for individual locations at 70-year intervals. The weighted risk values (i.e., the probabilities incorporate the Bayesian likelihoods) are used to create a pdf of risk. The threshold risk value is determined as shown in

Figure 2-13. If the risk threshold is less than or equal to 10^{-6}, or the MCL of any category is not exceeded at the 95 percent level, then the location is considered to be external to the contaminant boundary. This process is repeated for all locations within the model domain. All cells that did not meet the above criterion define the contaminant boundary region. Therefore, the contaminant boundary is a 3-D surface that encloses all cells that have a risk threshold greater than 10^{-6} (or cells that violate the MCL). The boundary maps will be presented in three 2-D sections representing the x-y, x-z, and y-z Cartesian planes. The boundary sections are 2-D projections of the 3-D boundary surface. For example, the aerial view (x-y plane) represents the maximum extent of the 3-D boundary or volume as projected to the surface, as shown in Figure 2-14. A location is considered to be within the boundary if at any x-y location there is at least one vertical position that is found to be within the boundary. Similar projections are made for the x-z and y-z planes.

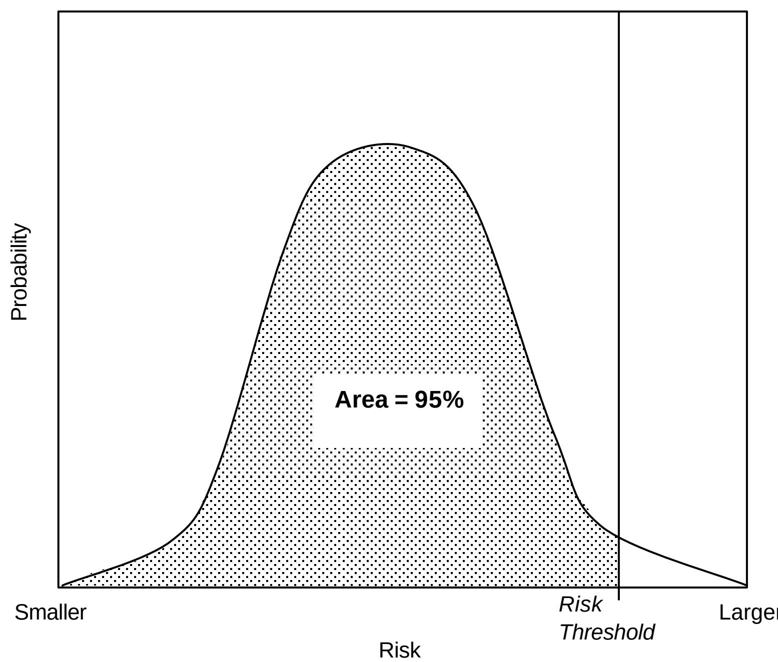


Figure 2-13
An Example of the Probability Distribution Function and How the Risk Threshold is Calculated for the Contaminant Boundary

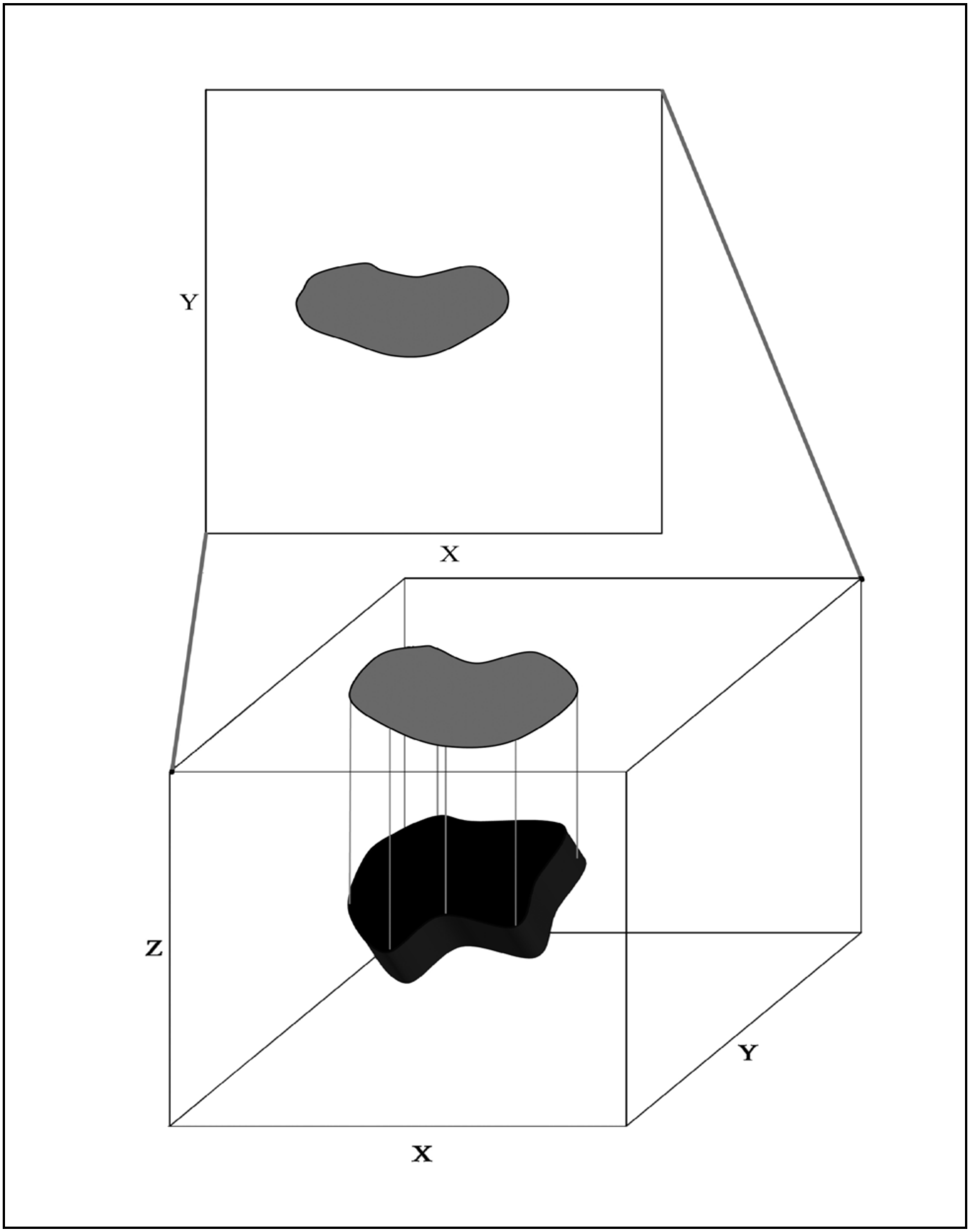


Figure 2-14
An example of a 3-D Contaminant Boundary and the Associated Mapping to an x-y Cross Section

2.2.4 Faultless Contaminant Boundary

Both a risk-based and regulatory-based approach are used to calculate a contaminant boundary for the Faultless test. The methodology used for the calculation focuses on identifying the region where there is a 95 percent certainty that water is “clean” based on either the risk or MCL standard. This region is external to (outside) the boundary. The region internal to this boundary is 5 percent certain to contain water exceeding the risk or MCL standard.

The source term used to scale the transport results from the model is the classified radionuclide source presented in Goishi et al. (1995). The types of radionuclides present in underground nuclear tests and their relative importance based on production, risk factor and MCLs can be discerned by examining the unclassified source term mass from the average of nuclear tests conducted in Areas 19 and 20 at the NTS (Smith, 2001). These radionuclides are assigned to the six transport classes considered for the Faultless model (Table 2-2). The source values used for the Faultless contaminant boundary are presented in Pohll (2002).

The contaminant boundary using the regulatory-based calculation at a significance level of 95 percent for the cumulative 1,000-year period after the detonation is presented in Figure 2-15. The contaminant boundary using the risk-based calculation at a significance level of 95 percent for the cumulative 1,000-year period after the detonation is presented in Figure 2-16. Although the regulatory- and risk-based calculations are based on slightly different risk thresholds, the boundary maps are identical. The similarities are due to the slow migration of radionuclides, which causes sharp contaminant fronts with large activity concentrations.

2.2.5 Boundary Through Time

There are two options available to present the temporal history of the contaminant boundary maps. One option is to produce maps that represent an instantaneous view of the boundaries for a given 70-year time interval and the other option is to present the cumulative boundary from time zero to a given time period. The latter option is used here, as it represents the maximum extent of the boundary at any given time within 1,000 years and is consistent with Appendix VI of the FFACO (1996).

No significant changes occur to the size of the cumulative boundary during the 1,000-year period. This can be seen by examining the boundary at 100 years. The contaminant boundary using the regulatory-based calculation at a significance level of 95 percent for the cumulative 100-year period

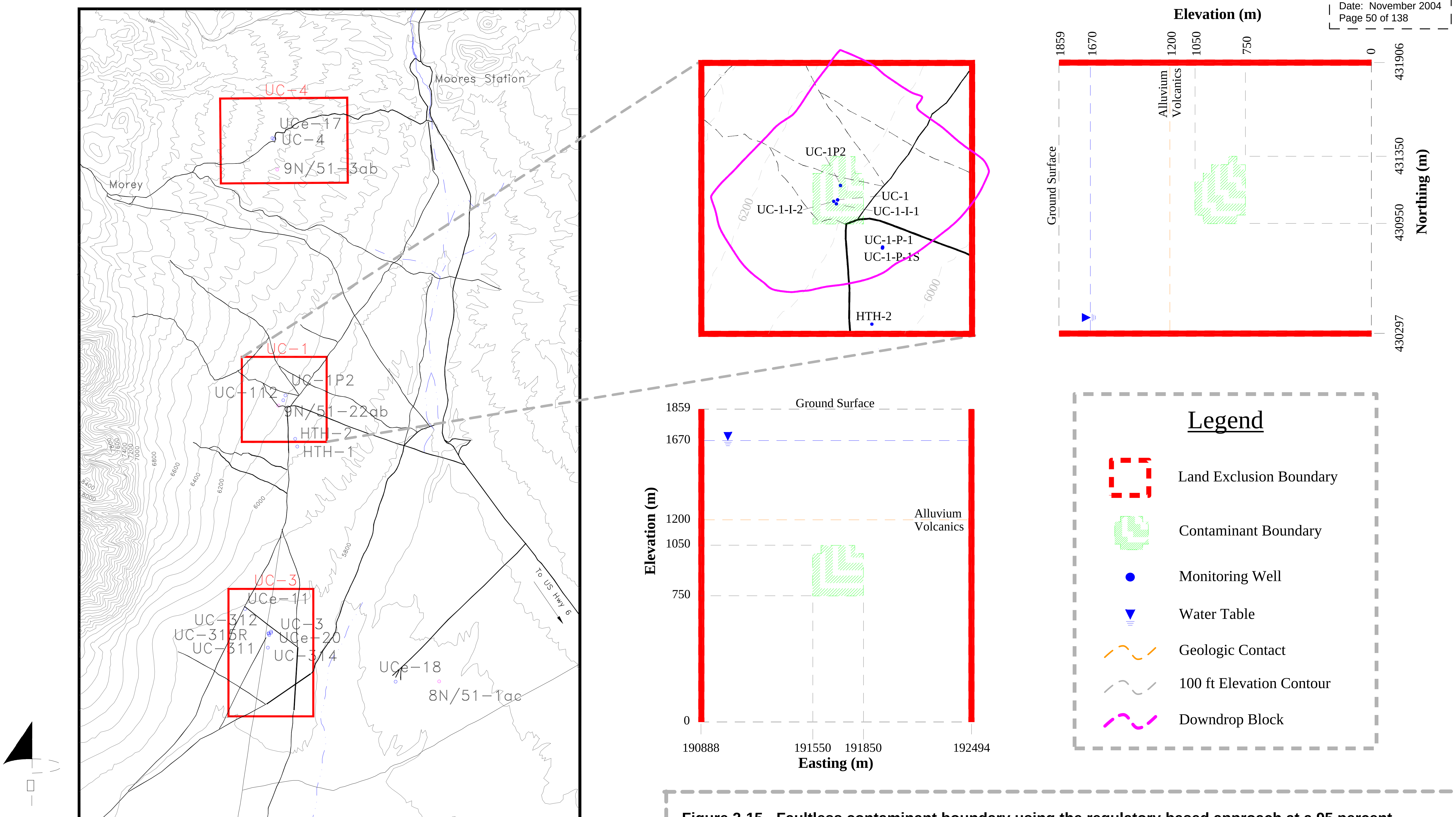


Figure 2-15 - Faultless contaminant boundary using the regulatory-based approach at a 95 percent significance level at 1,000 years after detonation. Modified from Pohll et al. (2003).

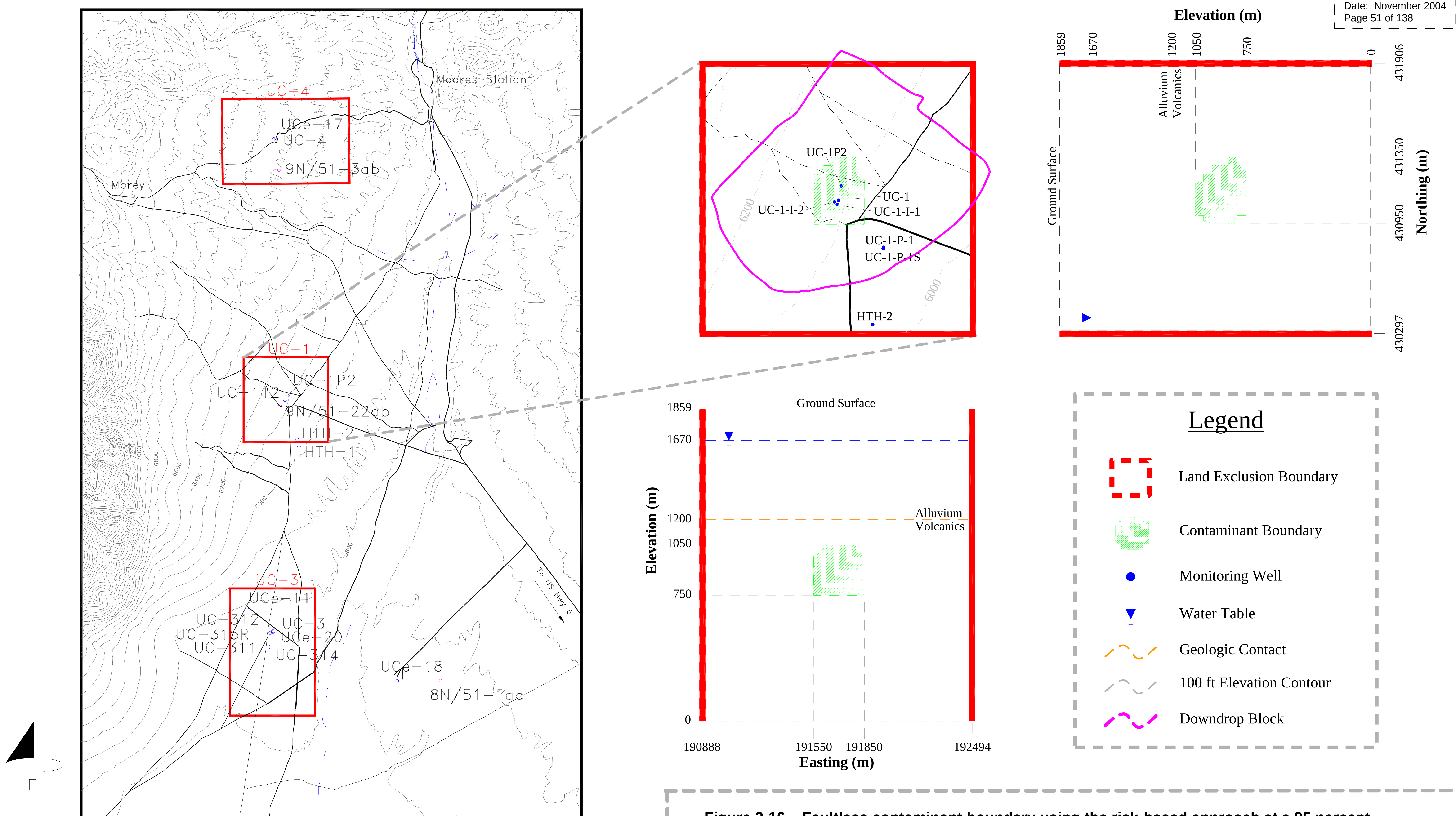


Figure 2-16 – Faultless contaminant boundary using the risk-based approach at a 95 percent significance level at 1,000 years after detonation. Modified from Pohll et al. (2003).

after the detonation is presented in Figure 2-17. The contaminant boundary using the risk-based calculation at a significance level of 95 percent for the cumulative 100-year period after the detonation is presented in Figure 2-18. The contaminant boundary region does not change significantly during the 1,000-year simulation period, principally because of the very slow groundwater velocity, and also due to the large number of radionuclides considered with their variety of half-lives.

Temporal changes in the boundary were also examined for a tritium-only boundary produced as requested by Liebendorfer (2001). That interim deliverable was designed to assist both NDEP and the DOE National Nuclear Security Administration/Nevada Operations Office (NNSA/NV) to prepare for the compliance boundary negotiation with a realistic frame of reference. The tritium boundary was calculated at 5, 10, 20, 50, 100, and 1,000 years after infill of the cavity. These boundaries are smaller than the composite boundary, and because they are based on a single radionuclide, remain classified (Pohll, 2003).

2.3 Compliance Boundary

The objective of the CAI process is to define boundaries around each CAU to establish areas that contain water that may be unsafe for domestic and municipal use. These are the "contaminant boundaries" defined by the FFACO (1996). The FFACO strategy requires the following to define the compliance boundary:

> "From the contaminant boundary predicted by the computer model, a compliance boundary will be negotiated between NDEP and DOE. The compliance boundary will define the area within which the radiological contaminants above the SDWA standards relative to background are to remain. DOE will be responsible for ensuring compliance with this boundary. The compliance boundary may or may not coincide with the contaminant boundary. If the predicted location of the contaminant boundary cannot be accepted as the compliance boundary, an alternate compliance boundary will be negotiated by both parties."

Monitoring compliance with the CAU boundaries will be accomplished by measuring appropriate physical and chemical parameters in wells within the modeled region.

A CAU flow and contaminant transport model was used to estimate the Faultless contaminant boundary. The boundary is composed of a perimeter and lower boundary. The accepted contaminant boundary and other considerations formed the basis for the negotiated compliance boundary, as

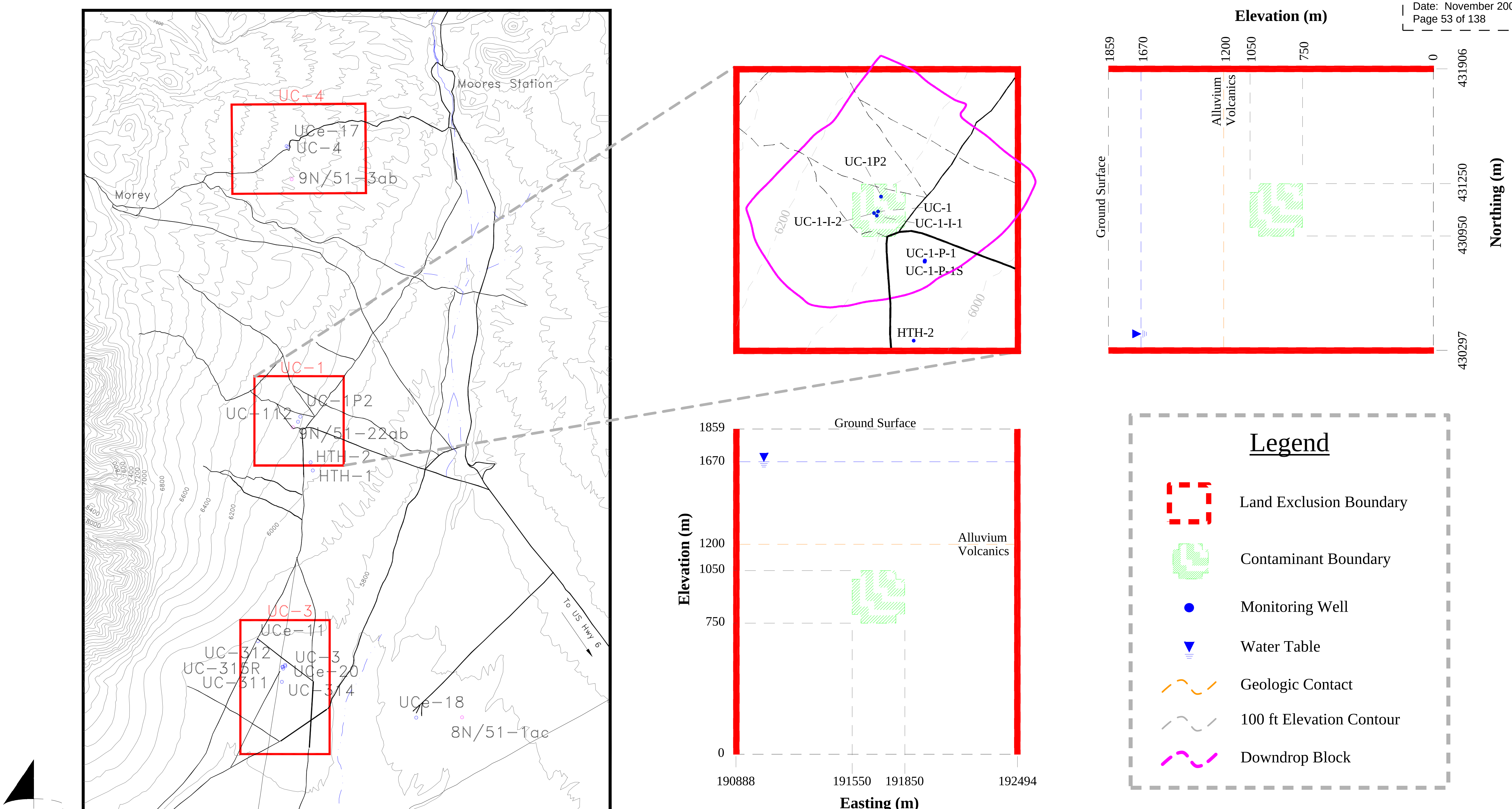


Figure 2-17 – Faultless contaminant boundary using the regulatory-based approach at a 95 percent significance level at 100 years after detonation. Modified from Pohll et al. (2003).

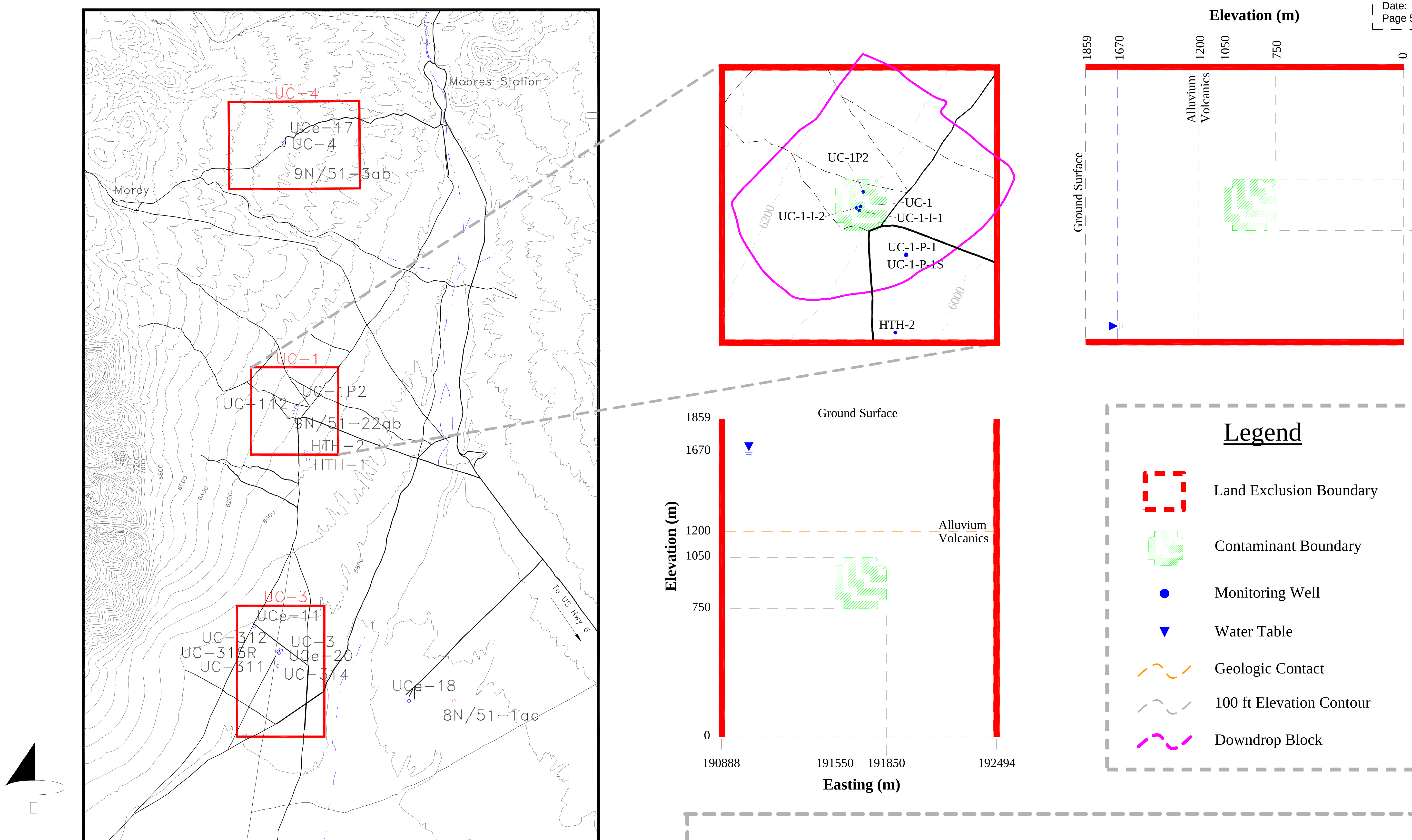


Figure 2-18 – Faultless contaminant boundary using the risk-based approach at a 95 percent significance level at 100 years after detonation. Modified from Pohll et al. (2003).

required per the dictionary for the UGTA process flow diagram in the FFACO. Although no spatial definition of the compliance boundary is provided in the FFACO, it seems logical that the compliance boundary would have similarly defined boundaries as the contaminant boundary. That is, the compliance boundary would consist of a defined perimeter and lower boundary. However, the compliance boundary provides the opportunity for consideration of factors not quantified in the calculation of the contaminant boundary.

As noted in Section 2.2.1, the contaminant boundary calculation is based upon ambient conditions, meaning in the case of UC-1, the absence of groundwater withdrawals in the area. Pumping to extract groundwater could have an impact on the rate and direction of contaminant migration. Control of groundwater use in a larger region than that encompassed by the contaminant boundary itself is necessary to protect against potential human exposure.

It has been recognized that the CNTA groundwater flow and transport model was constructed at an intermediate scale to the regional and local flow systems (Liebendorfer, 2000). The model is sub-regional in nature and deliberately expresses conditions unaffected by the Faultless test. As a result, data within the down-dropped block that may be affected by the test may not be accurately represented in the model. In addition, the model (published in 1999) is built on steady-state conditions whereas recovery of hydraulic head levels continued as of 1997, the date of the last water-level measurements in the post-test hole. These factors mean that the groundwater model accuracy will be lower in the region disturbed by the Faultless test.

The following four factors were considered in the development of the compliance boundary at CNTA:

1. The contaminant boundary is very small as a result of low groundwater velocities, so that the 1,000-year boundary does not extend very far from the cavity itself (between two and three cavity radii from the working point). There would be no added value in developing compliance boundaries on interim time periods.

2. Although the contaminant boundary includes all the uncertainty in the model, additional uncertainties exist regarding the near-field conditions not incorporated into the model. This means some additional conservatism is warranted, particularly in the down-dropped block region disturbed by the nuclear test.

3. There is no land area buffer surrounding CNTA, such as that likely to be present for CAUs on the NTS which may include portions of the NTS and/or military lands.

4. The DOE currently restricts extraction of subsurface materials for a horizontal distance of 3,300 ft from surface ground zero, for national security and public safety concerns.

The cavity radius for the Faultless test is estimated as 100 m, based on generic relationships with depth of burial (Glasstone and Dolan, 1977). Broad experience from nuclear testing indicates that fracturing due to nuclear tests can extend out to 5.2 times the cavity radius (Borg et al., 1976). In the case of Faultless, the extent of fracturing can be observed through surface fractures to extend beyond this distance to the northeast and southwest. A distance of five cavity radii, or 500 m (1,640 ft) from Faultless ground zero, extends to the boundary of the down-dropped fault block at the southern and northeastern edges (see Figure 2-19).

As a result of the need to monitor compliance in the modeled region and the limitations on the predictions of contaminant migration within the down-dropped block, the compliance boundary is best defined as the perimeter of the down-dropped block, as mapped after the Faultless test, extending vertically downward to the same lower boundary as the contaminant boundary (see Figure 2-20). The compliance region fits within the current exclusion zone maintained by the DOE, so that no additional restriction of groundwater resources results from the designation (Figure 2-19).

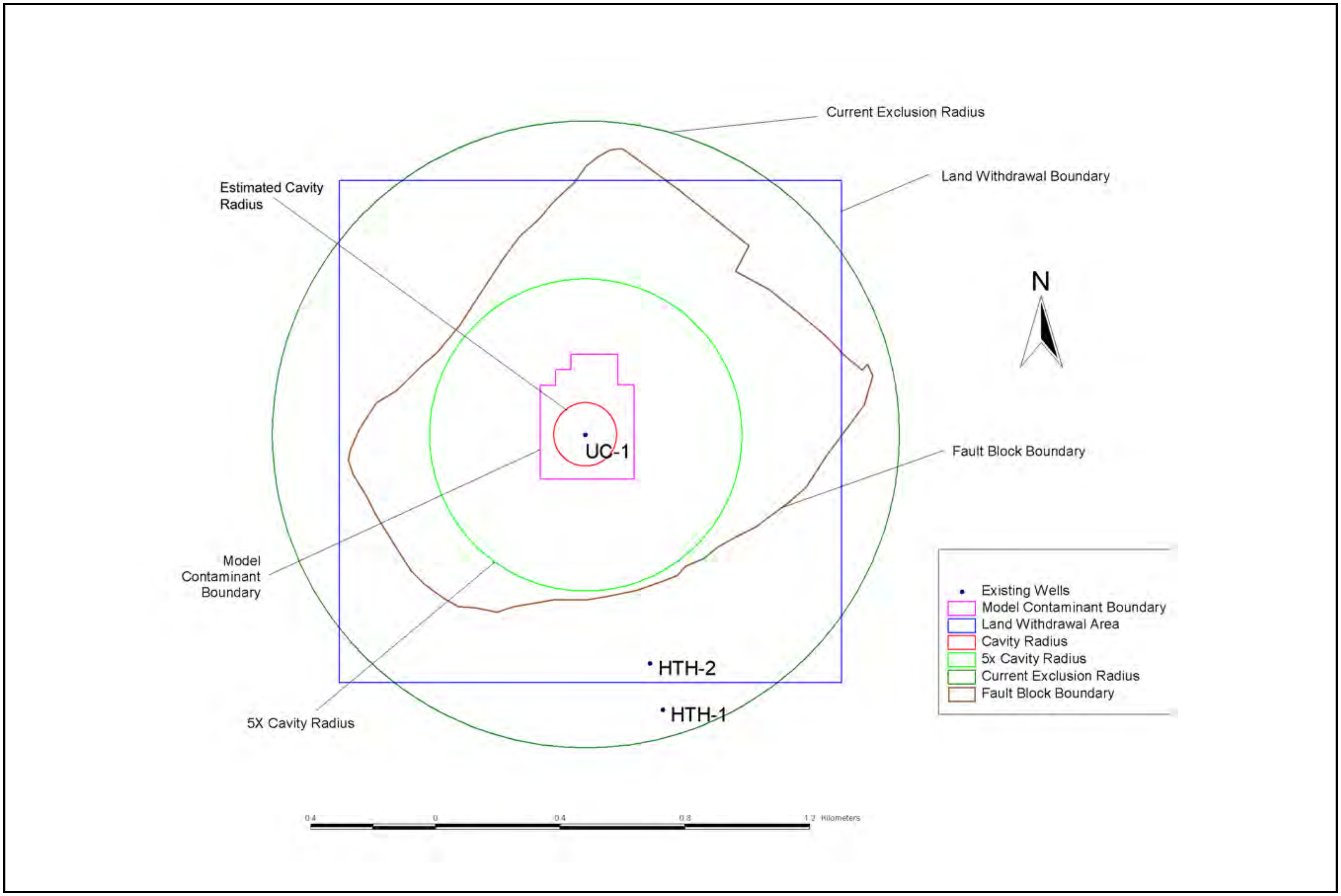


Figure 2-19
CNTA Compliance and Contaminant Boundaries, Land Withdrawal Boundary, and Estimated Cavity Radius

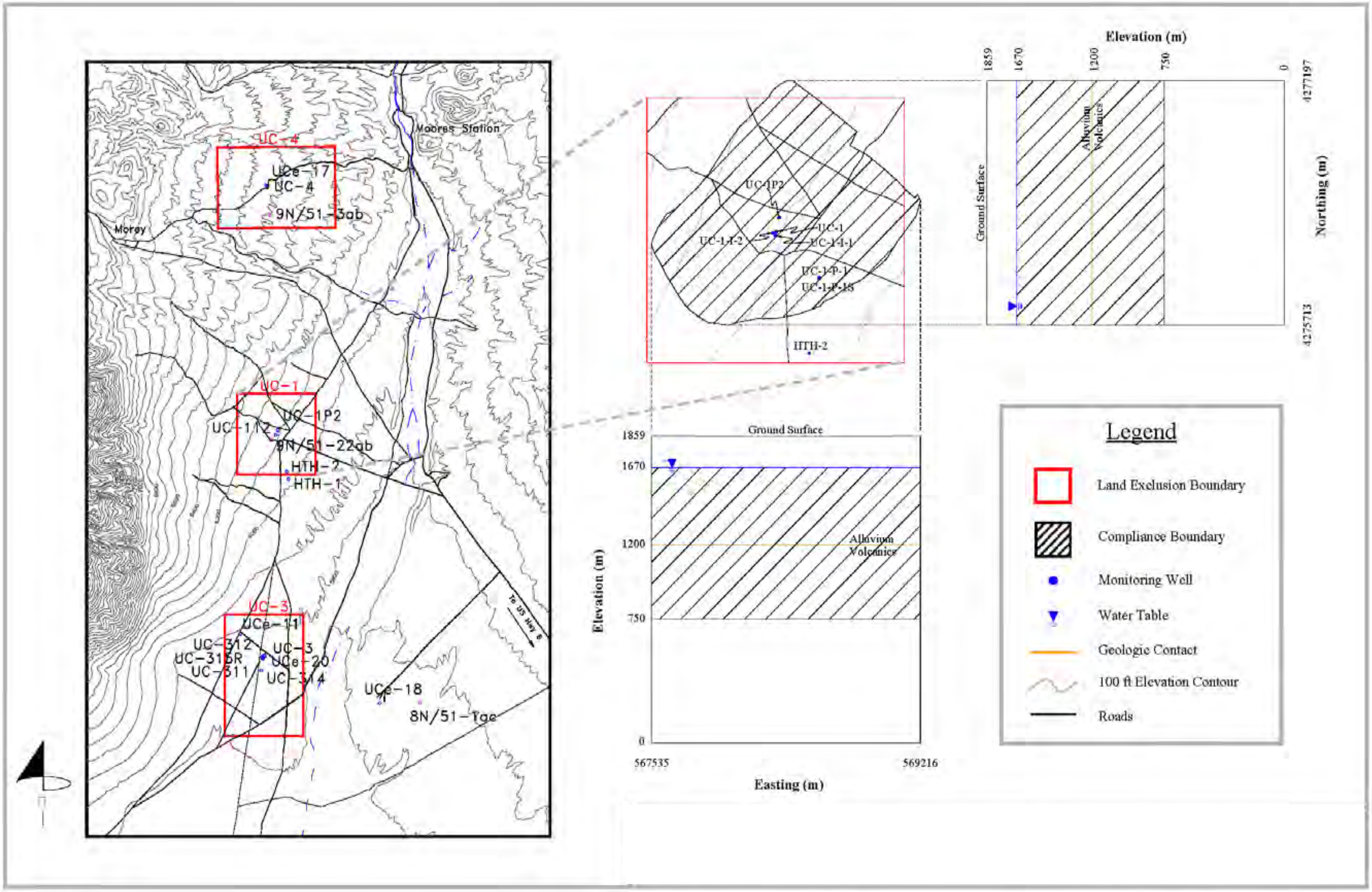


Figure 2-20
Faultless Compliance Boundary. Coordinates are in UTM, Zone 11 - NAD 27.

3.0 Evaluation of Alternatives

This section presents the corrective action objectives for CAU 443, describes the general standards and decision factors used to screen the corrective action alternatives, and develops and evaluates a set of corrective action alternatives that could be used to meet the corrective action objectives.

3.1 Corrective Action Objectives

The corrective action objectives are media-specific goals for protecting human health and the environment. Based on potential exposure pathways, the following corrective action objectives have been identified for CAU 443:

- Prevent or mitigate exposure to groundwater contaminants of concern at concentrations exceeding MCLs or risk-based levels
- Reduce the risk to human health and the environment to the extent practicable

3.2 Screening Criteria

The corrective action alternatives are evaluated based on the approach outlined in *Focused Evaluation of Selected Remedial Alternatives for the Underground Test Area – Preliminary* (DOE, 1998a). Although the site is not regulated under the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA), a CERCLA-style alternative (threshold criteria, primary balancing criteria, and modifying criteria) evaluation was performed. Each alternative is assessed against the following evaluation criteria developed to address the CERCLA requirements as mandated by the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (40 CFR 300.430[e][9]):

- Overall protection of human health and the environment
- Compliance with applicable or relevant and appropriate requirement(s) (ARARs)
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community acceptance

3.2.1 Evaluation Criteria

The following text describes the criteria used to evaluate the corrective action alternatives:

Overall Protection of Human Health and the Environment

Protection of human health and the environment is a threshold requirement under CERCLA (CFR, 2003e). This mandate requires that the corrective action include any protective measures that are needed to mitigate cancer risks and non-cancer toxicity. These measures may or may not be directly related to media cleanup, source control, or management of waste. The corrective action alternatives are evaluated for the ability to meet corrective action objectives as defined in Section 3.1.

Compliance with Applicable or Relevant and Appropriate Requirement(s) (ARARs)

Compliance with ARARs is a threshold requirement under CERCLA (CFR, 2003e). Each corrective action alternative must meet the proposed media cleanup standards as set forth in applicable state and federal regulations and as specified in the CAIP (DOE/NV, 1999). For CAU 443, the standard is the drinking water MCLs.

Long-Term Effectiveness and Permanence

Long-term effectiveness and permanence is a primary balancing criteria under CERCLA (CFR, 2003e). Each corrective action alternative must be evaluated in terms of risk remaining at the CAU after the corrective action alternative has been implemented. The primary focus of this evaluation is on the extent and effectiveness of the controls that may be required to manage risk posed by treatment residuals and/or untreated waste.

Reduction of Toxicity, Mobility, and/or Volume (Through Treatment)

Reduction of toxicity, mobility, and/or volume is a primary balancing criteria under CERCLA (CFR, 2003e). Each corrective action alternative must be evaluated for its ability to reduce the toxicity, mobility, and/or volume of the contaminated media. Reduction in toxicity, mobility, and/or volume refers to changes in one or more characteristics of the contaminated media by the use of corrective measures that decrease the inherent threats associated with that media. In regards to certain radiogenic nuclides that are included as COPCs in subsurface rock and groundwater, natural radioactive decay is the only way that toxicity of these substances is reduced. However, removal of radiogenic nuclides from subsurface rock and/or groundwater remains an alternative to reduce toxicity of the contaminated media.

Short-Term Effectiveness

Short-term effectiveness is a primary balancing criteria under CERCLA (CFR, 2003e). Each corrective action alternative must be evaluated with respect to its effect on human health and the environment during implementation of the corrective action. The following factors will be addressed for each alternative:

- Protection of the community from potential risks associated with implementation such as fugitive dusts, transportation of hazardous materials, and explosion
- Protection of remediation workers during implementation
- Environmental impacts that may result from implementation
- The amount of time until the corrective action objectives are achieved

Implementability

Implementability is a primary balancing criteria under CERCLA (CFR, 2003e). The implementability criterion addresses the technical and administrative feasibility of implementing a corrective action alternative and the availability of services and materials needed during implementation. Each corrective action alternative must be evaluated for the following criteria:

- **Construction and Operation -** refers to the feasibility of implementing a corrective action alternative given the existing set of waste and site-specific conditions.
- **Administrative Feasibility -** refers to the administrative activities needed to implement the corrective action alternative (e.g., permits, public acceptance, rights-of-way, off-site approval).
- **Availability of Services and Materials -** refers to the availability of adequate off-site and on-site treatment, storage capacity, disposal services, necessary technical services and materials, and prospective technologies for each corrective action alternative.

Cost

Cost is a primary balancing criteria under CERCLA (CFR, 2003e). Costs for each alternative are estimated for comparison purposes only. The cost estimate for each corrective action alternative includes both capital and operation and maintenance costs, as applicable.

The following is a brief description of each component:

- **Capital Costs** - these costs include both direct and indirect costs. Direct costs may consist of materials, labor, mobilization, demobilization, site preparation, construction materials, equipment purchase and rental, sampling and analysis, waste disposal, and health and safety measures. Indirect costs include such items as engineering design, permits and/or fees, start-up costs, and any contingency allowances.

- **Operation and Maintenance** - these costs include labor, training, sampling and analysis, maintenance materials, utilities, and health and safety measures.

State Acceptance

State acceptance is a modifying criteria under CERCLA (CFR, 2003e). Each corrective action alternative must be evaluated with respect to the potential for acceptance by NDEP. Such acceptance may be affected by prior agreements between DOE and state regulatory agencies concerning previous surface corrective actions, interim groundwater modeling results, contaminant flow and transport modeling results, or model validation results. State acceptance of the alternatives set forth here can more accurately be gauged subsequent to submission of this document.

Community Acceptance

Community acceptance is a modifying criteria under CERCLA (CFR, 2003e). However, the requirement for community acceptance as it applies to CNTA is governed by NEPA, and was addressed to a certain extent by the Nevada Test Site Environmental Impact Statement (NTS EIS). Each corrective action must be evaluated with respect to community acceptance and community perception of potential risk. Community acceptance of alternatives could potentially rely on the quality of public outreach and public education efforts as much as on the intrinsic risks or benefits associated with each alternative. The NTS EIS addressed public comment and acceptance for environmental remediation activities, although that document did not address the massive excavation activities discussed in Table 3-1 as part of Alternative 3b. Community acceptance of such a massive reclamation project would require additional public comment and acceptance.

3.3 Development of Corrective Action Alternatives

This section identifies and briefly describes the viable corrective action alternative technologies and the corrective action alternatives considered for the affected media. Based on the review of existing data, future use, and current operations at the CNTA, the following alternatives have been developed for consideration at CAU 443:

- Alternative 1 – No Further Action
- Alternative 2 – Proof of Concept and Monitoring with Institutional Controls
- Alternative 3 – Contaminant Control

3.3.1 Alternative 1 - No Further Action (Without Institutional Controls)

Under the No Further Action alternative, no activities would be implemented and current institutional and land-use controls would be discontinued. This alternative is a baseline case with which to compare and assess the other corrective action alternatives and their ability to meet corrective action standards. The baseline risk assessment evaluates the potential threat to human health and the environment in the absence of any remedial action or degradation of the contaminant source. This alternative does not meet the corrective action objectives because it does not protect human health and the environment. Under the No Further Action alternative, people could be exposed to the COPCs at unacceptably high levels through intrusion into the subsurface environment or drilling of water supply wells. This alternative will be compared to the other alternatives using the selection decision factors for the CAU.

3.3.2 Alternative 2 - Proof-of-Concept and Monitoring with Institutional Controls

Under Alternative 2, a model-directed network of monitoring and validation wells would be installed in the vicinity of UC-1 to monitor the CAU compliance boundary and to measure parameters necessary to determine that the model prepared in the CAI (Section 2.0) makes reasonable predictions with an acceptable level of confidence.

The corrective action strategy relies on the groundwater flow and transport model of the Faultless site to determine the compliance boundary. A proof-of-concept period would be used as a post-audit of the model and would test the model over a five-year time frame. During this period it would be determined if the model produces meaningful results with acceptable uncertainty. Periodic water sampling for radionuclides and water level measurements in the wells would confirm that contamination is not crossing the compliance boundary and that actual hydrologic conditions at the CAU have not evolved away from the conditions predicted by the model. Institutional controls would include restrictions on subsurface intrusion within the compliance boundary to protect the environment and the public from inadvertent release of contaminants.

3.3.3 Alternative 3 – Contaminant Control

As stated by the FFACO, the corrective action strategy for groundwater at CNTA will incorporate (on a limited scale) concepts being developed for the UGTA CAUs at NTS. Several alternatives for removing or controlling contaminant sources were analyzed for UGTA, and are presented in detail in the *Focused Evaluation of Selected Remedial Alternatives for the Underground Test Area* (DOE/NV, 1998a). These same alternatives could also be used for CAU 443 at the CNTA.

Therefore, as presented in the *Focused Evaluation of Selected Remedial Alternatives for the Underground Test Area* (DOE/NV 1998a), the following two alternatives for contaminant source control that were analyzed for UGTA sites were considered for active remediation of the Faultless site at CNTA:

3a - Pump and treat (with institutional controls)
3b - Excavation and disposal

3.4 Evaluation of Alternatives

The evaluation criteria described in Section 3.2 were used to conduct detailed and comparative analyses of each corrective action alternative. The advantages and disadvantages of each alternative were assessed to select a preferred alternative for CAU 443. Table 3-1 summarizes the detailed analysis of the alternatives.

Table 3-1
Detailed Evaluation of Alternatives
(Page 1 of 5)

Evaluation Criteria	Alternative 1 No Further Action	Alternative 2 Proof of Concept and Monitoring with Institutional Controls	Alternative 3 Contaminant Control
Overall Protection of Human Health and the Environment	Does not meet corrective action objective of preventing or mitigating exposure to subsurface soil containing COPCs. Does not prevent exposure to contaminated groundwater. Does not prevent spread of COPCs in the groundwater. No worker exposure associated with implementation.	Meets corrective action objectives. Prevents inadvertent intrusion into the contaminated zone. Prevents exposure to subsurface contamination. Prevents exposure to contaminated groundwater. Does not prevent spread of COPCs in the groundwater. No risk to workers associated with heavy equipment and potential contact with impacted media during excavation and transportation activities. Low risk to public due to remote location and controlled access to the CAU, subsurface soil, and groundwater.	3a - Pump and treat (with institutional controls): Potentially meets corrective action objectives if appropriate technology is found to mitigate tritium and other contaminants in the groundwater. Prevents inadvertent intrusion into the contaminated zone. Prevents exposure to subsurface. Prevents exposure to contaminated groundwater. Workers potentially exposed to radioactive contaminants in treatment residues. 3b - Excavation and disposal: Potentially meets corrective action objectives, although significant surface impact likely would require additional corrective action. Prevents spread of COPCs. High potential for worker exposure associated with implementation.
Compliance with Applicable or Relevant and Appropriate Requirements (ARARs)	Does not comply with ARARs because COPCs remain exposed to dissolution and migration in the groundwater and pathways remain for human exposure.	COPCs remain exposed to dissolution and migration in the groundwater. However, compliance with ARARs is achieved because exposure pathways are eliminated through land-use restrictions.	3a - Complies with ARARs because potentially mobile COPCs are removed from the groundwater, and exposure to immobile COPCs in the subsurface environment is eliminated by land-use restrictions 3b - Complies with ARARs by removing soil containing COPCs, but could create different pathways by creating dust contaminated with COPCs, and by relocating rock contaminated with COPCs from the subsurface to the surface, and increasing long-term stewardship responsibilities. Potential pathways to the accessible environment are not necessarily diminished by removing them from the deep subsurface environment.

Table 3-1
Detailed Evaluation of Alternatives
(Page 2 of 5)

Evaluation Criteria	**Alternative 1** **No Further Action**	**Alternative 2** **Proof of Concept and Monitoring with Institutional Controls**	**Alternative 3** **Contaminant Control**
Long-Term Effectiveness and Permanence	Long-term risk to public mitigated by low hydraulic conductivity resulting in slow contaminant migration rates. Potentially ineffective in isolating COPCs from the accessible environment due to lack of access controls, allowing inadvertent exposure to contaminated groundwater.	Long-term risk to public mitigated by low hydraulic conductivity resulting in slow contaminant migration rates. Institutional controls prevent inadvertent intrusion into, and exposure to remaining COPCs. Administrative controls must be maintained.	3a: Long-term risk to public eliminated by removal of mobile COPCs from groundwater and isolation of immobile COPCs by land-use restrictions. Long-term effectiveness is enhanced with the passage of time as the most mobile COPCs manifest relatively short radioactive half-lives. 3b: Moving contaminated bedrock from the subsurface environment to an appropriate on-site disposal facility compounds the problem of long-term isolation of long-lived radionuclides from the environment. The potential impact to surface environment from excavating the contaminated bedrock is enormous.
Reduction of Toxicity, Mobility, or Volume	Reduction in toxicity by natural radioactive decay only. Reduction in mobility by sorption on naturally occurring minerals only. No known volume reduction. Mobility of COPCs is extremely limited due to very low hydraulic conductivity values and the resultant low migration rates. However, enhanced mobility due to inadvertent intrusion is not prevented.	Reduction in toxicity by natural radioactive decay only. Reduction in mobility by sorption on naturally occurring minerals only. No known volume reduction. However, the mobility of COPCs is extremely limited due to very low hydraulic conductivity values and the resultant low migration rates. Enhanced mobility due to inadvertent intrusion prevented by administrative controls.	3a: Reduction in toxicity by radioactive decay only. Reduction in mobility and volume achieved by removal of mobile COPCs from groundwater. 3b: Reduction in toxicity by radioactive decay only. Mobility reduction by removing COPCs from subsurface environment, but surface isolation compounded by the need for active long-term stewardship. Volume increase in contaminated rock upon excavation.

Table 3-1
Detailed Evaluation of Alternatives
(Page 3 of 5)

Evaluation Criteria	Alternative 1 No Further Action	Alternative 2 Proof of Concept and Monitoring with Institutional Controls	Alternative 3 Contaminant Control
Short-Term Effectiveness	Effective in isolating COPCs from the accessible environment in the short term because of the remote location and low migration rate. Workers not exposed to radioactive contaminants.	Effective in isolating COPCs from the accessible environment in the short term because of low migration rate. Public protected by remote location, low migration rate, and site access controls. Workers not exposed to radioactive contaminants. Environmental impacts limited to a few drill pads that would have to be reclaimed. Implementation would not require an extended period of time, but institutional controls would be in effect for an extended period of time.	3a: Effective in isolating COPCs from accessible environment by removing mobile COPCs from the groundwater, assuming that an effective way of treating tritiated water is employed during the initial 30 years of treatment. 3b: Not effective in isolating COPCs from accessible environment in the short-term because COPCs are removed from inaccessible subsurface environment and moved to more accessible surface environment. High risk to workers associated with potential contact with impacted media during excavation activities as well as the physical hazards of open pit mining. Serious environmental impacts are anticipated due to implementation. Implementation would require an extended period of time. Short term risks to the community would be high because of the dangers associated with dust control in excavating large volumes of contaminated rock and soil. Environmental impacts would be high.

Table 3-1
Detailed Evaluation of Alternatives
(Page 4 of 5)

Evaluation Criteria	Alternative 1 No Further Action	Alternative 2 Proof of Concept and Monitoring with Institutional Controls	Alternative 3 Contaminant Control
Implementability	Easily implemented. Technical feasibility is high. Administrative feasibility is high. All of the services and materials are readily available.	Easily implemented. Coordination of all entities is necessary to ensure compliance with administrative controls to prevent intrusion into and exposure to contaminated soil and groundwater. Technical feasibility is high. Administrative feasibility is high. All of the services and materials are readily available.	3a: Difficult to implement due to a number of deep extraction wells that need to be drilled, the treatment of tritiated water, and the handling of water and treatment residues after treatment. Technical feasibility is low and services are not readily available for the treatment of tritium in the water. 3b: Extremely difficult to implement due to the enormous volume of overburden to be removed, the large volume of contaminated bedrock to be excavated and isolated, the volume of contaminated groundwater to be pumped from the excavation and treated, and the long-term stewardship of the contaminated material. Technical feasibility is low and the availability of services is inadequate. Workers likely to be exposed to high radiation doses.
Cost	$0	Estimated cost ranges from $1,500,000 to $5,000,000.	3a: Estimated cost ranges in the tens of millions of dollars if tritium is allowed to naturally decay in the groundwater. Cost likely to be in the hundreds of millions of dollars if tritium can be removed from the groundwater. 3b: Estimated cost ranges from many hundreds of millions of dollars to billions of dollars.
State Acceptance	State acceptance is unlikely and can be gauged better following submission of CADD/CAP.	State acceptance is likely and can be gauged better following submission of CADD/CAP.	3a: State acceptance unknown but likely and can be gauged better following submission of CADD/CAP. 3b: State acceptance unknown, but unlikely because of the massive impact to the surface environment. Acceptance can be gauged better following submission of CADD/CAP.

Table 3-1
Detailed Evaluation of Alternatives
(Page 5 of 5)

Evaluation Criteria	Alternative 1 No Further Action	Alternative 2 Proof of Concept and Monitoring with Institutional Controls	Alternative 3 Contaminant Control
Community Acceptance	Community acceptance is unlikely, although actual acceptance is probably related to the perceived community threat.	Community acceptance likely, although actual acceptance probably related to perceived community safety.	3a: Community acceptance likely because of the perceived public health safety in removing contaminated groundwater, and in the future lack of restrictions to access for this parcel of public land. However, additional public involvement activities would likely be necessary to support this option. 3b: Community acceptance very unlikely because of the massive impact to the surface environment resulting from excavation of COPCs from a depth of 1,000 m.

4.0 Recommended Alternative

Based on the results of the corrective action investigation discussed in Section 2.0 and the detailed and comparative analysis of the potential corrective action alternatives presented in Section 3.0, the preferred corrective action alternative selected for implementation at CAU 443 is Alternative 2, Proof-of-Concept and Monitoring with Institutional Controls. This alternative (along with Alternative 3a) meets the requirement of Protection of Human Health and the Environment. Alternative 2 was superior to Alternative 3a in Implementability and Cost. The rationale for selecting Alternative 2 is described below:

- Health risks are minimized by preventing worker exposure and public access to the contaminated groundwater by administrative controls.
- Only minimal waste from drilling and sampling will be generated. If groundwater in the monitoring wells is not contaminated these wastes will not be hazardous or radioactive.
- It is easily implemented, although coordination of all entities is necessary to ensure compliance with administrative controls. The required services and materials are readily available.
- It provides a cost-effective method to protect human health and the environment and to meet closure requirements.

4.1 Proof-of-Concept

The proof-of-concept approach relies on the groundwater flow and transport model of the Faultless site at the CNTA. The model was developed to provide a predictive tool for groundwater flow in the alluvial and volcanic aquifers in the vicinity of the Faultless test, and for radionuclide transport by groundwater away from the test cavity. Numerical flow and transport models are effective tools for predicting migration of contaminants through the subsurface, where lithologic and hydrologic data are sparse relative to the natural heterogeneity of the systems. The variability in lithologic characteristics and hydraulic conductivity can be simulated through numerous model runs. These results define a range of predicted values for the variables that control the fate and transport of contaminants in the groundwater, and provide statistically testable results for contaminant plume migration. Model validation entails placing wells at locations within the modeled volume at CNTA and confirming flow directions, presence or absence of welded tuff, range of hydraulic conductivity values, and contaminant transport predictions.

4.2 Monitoring

Monitoring well(s) will be placed down-gradient from the nuclear test emplacement point. The distance between the monitoring well(s) and ground zero is predicated on the need to provide adequate early warning while simultaneously avoiding near field effects, which were not accounted for in the model. Periodic water sampling and testing of the monitoring well(s) will confirm that contamination is confined within the compliance boundary.

4.3 Institutional Controls

The original CNTA area (now known as UC-1) is withdrawn per Public Land Order 4338, as noted in *Federal Register,* Vol. 32, No. 241 (December 14, 1967) (*Federal Register*, 1967). The land is withdrawn from all forms of appropriation under public land laws, including mining laws (30 *United States Code*, Ch. 2) and mineral leasing laws, and reserved for use of the AEC (now DOE) for experimental purposes. The withdrawal does not alter the applicability of public land laws governing the use of the lands under lease, license, or permit or governing the disposal of their mineral or vegetative resources other than under the mining and mineral leasing laws, as long as the activities do not interfere with the project.

Restrictions will be addressed in the closure report for the CNTA subsequent to monitor well installation, testing, and proof-of-concept monitoring. Restrictions to subsurface intrusion within the compliance boundary will be instituted to protect the environment and the public from inadvertent release of contaminants to the accessible environment while maintaining public access to surface activities. Such restrictions will include, but not be restricted to, access to subsurface mineral rights and subsurface water rights.

Subsurface use restrictions in the vicinity of CNTA are to remain in place in perpetuity. These restrictions are described on the permanent monument located at the SGZ (surface ground zero) at UC-1:

> "No excavation, drilling, and/or removal of materials is permitted without U.S. Government approval within a horizontal distance of 3,300 feet from the surface ground zero location (Nevada States coordinates N1,414,340 and E629,000, Nye County, Nevada). Any re-entry into U.S. Government drill holes within this horizontal restricted area is prohibited."

5.0 Implementation of the Corrective Action Plan

The preferred corrective action alternative for the Faultless site is to leave the Faultless nuclear cavity in place, monitor groundwater conditions, and control activities impacting the subsurface in the area through long-term stewardship (and deed restrictions). The strategy for the Faultless monitoring network is presented in the following sections. The framework for forming the post-closure stewardship activities is presented in Section 7.0.

With a large radionuclide source being left in place, and given the uncertainties inherent in modeling the behavior of groundwater systems, monitoring of the Faultless site is an important component of assuring the effectiveness of the corrective action. Monitoring can be viewed as the final step in addressing the uncertainty present in the Faultless closure. Groundwater monitoring not only serves to build confidence that the system is performing as predicted, it acknowledges the uncertainties inherent in the modeling process and the possibility, however remote, of unexpected outcomes.

Monitoring of groundwater conditions is one of two major actions recommended in this alternative. The second action is long-term site stewardship. The need for effective stewardship of the site is dictated by the dynamic groundwater system containing the contaminants. The contaminant boundary calculated to preserve public health and the environment is based on current hydrologic conditions. The extent of harmful contaminants migrating from the Faultless site could be dramatically changed by certain resource extraction activities, principally large-scale groundwater pumping. As a result, effective controls on activities involving the subsurface will be needed in the region outside the contaminant boundary. Stewardship of the site will also entail evaluating natural changes in the hydrologic system that could affect the closure decision, and protecting the national security aspects of the site from willful or inadvertent intrusion.

5.1 Monitoring Objectives

The objectives of groundwater quality monitoring are generally divided into four categories: (1) ambient monitoring, (2) detection monitoring, (3) compliance monitoring, and (4) research monitoring (Todd et al., 1976). Long-term monitoring for CNTA combines the second and third objectives. Detection monitoring provides early indication of the migration of radionuclides from the test cavity to the downgradient direction. At the same time, these data also fall under the requirement for compliance monitoring in the FFACO.

Appendix VI of the FFACO specifies a five-year proof-of-concept monitoring network during the corrective action phase. "*This phase of monitoring will use groundwater wells in a monitoring network to determine if the monitoring network design will provide adequate CAU surveillance. Measurements of field parameters will be used to demonstrate that the model is capable of making reasonable predictions that fall within an acceptable level of confidence*" (FFACO, 1996). Using the results of the proof-of-concept monitoring and model validation, the long-term monitoring requirements for the CAU are developed in the Closure Report (FFACO, 1996).

The objectives of the CNTA proof-of-concept monitoring network are to (1) provide a means to evaluate the groundwater transport model and its predictions through the validation process, (2) provide a system with high detection probability that takes into account uncertainty in the migration pathways, (3) provide a system for early detection of radionuclide migration rates in excess of what has been predicted by the CNTA model, (4) assure the public and the regulators that public health is not compromised, (5) provide compliance monitoring of physical parameters to demonstrate that groundwater conditions have not significantly changed from those simulated in the model, (6) achieve site closure and minimize long-term risk of public exposure to contaminated groundwater and (7) achieve all of these objectives while providing the best value to the tax payers.

The validation process is necessary in developing an effective detection monitoring system. The detection system is based on the model results. Validation of the model, and reduction of uncertainty in the model predictions in the process, is a priority for detection monitoring. In addition, validation also meets FFACO requirements regarding proof-of-concept monitoring.

When a monitoring program has multiple objectives, it is possible the objectives can be conflicting. For example, objectives such as low cost, high detection probability, and early detection can be conflicting. These objectives conflict because an increase in the detection probability is accomplished by either installing more wells (increasing cost) or by placing the wells further from the source, thereby increasing time to detection (Storck et al., 1997). Another example is conflict between the validation and detection objectives whereby the optimum location for obtaining validation data may not coincide with the most-likely transport direction. Because of this conflict, one optimal solution does not exist, and the trade-offs among these objectives must be considered.

5.2 Monitoring Network

Development of the monitoring network uses the hydrogeologic approach (background on the various approaches to monitoring network design can be found in Hassan, 2003) combined with the simulation and probability-based approaches to select the monitoring well locations. The purpose is to place wells in locations likely to encounter fast migration pathways.

Pre- and post-event monitoring of milk, water and air occurred at the time of the Faultless event and was conducted by the EPA (formerly US Public Health Service), the US Geological Survey, and Teledyne Isotopes. The Atomic Energy Commission (AEC) initiated a long-term surveillance plan for CNTA at the time of site demobilization and restoration (U.S. AEC, 1973). Implementation of this plan was included in the Long-Term Hydrologic Monitoring Program (LTHMP) established by the AEC and operated by the EPA. The objectives of the program were to: (1) assure public safety, (2) inform the public, media, and scientific community if the need arose, (3) document compliance with anti-pollution requirements, and (4) improve pre-event prediction capabilities (U.S. AEC, 1973). More recently, LTHMP reports state the goal is to measure radioactivity concentrations in water sources near the sites of former underground nuclear explosions (U.S. EPA, 1999).

The LTHMP program was based on using existing wells. The original LTHMP network included three domestic wells and one spring, all in excess of 8 miles distant from Faultless, and two site exploration wells, HTH-1 and HTH-2. As described by AEC (1973), the network was predicated on the assumption that the southward groundwater gradient in the alluvium units would govern contaminant transport from the nuclear test located in the deeper volcanic units (an assumption contradicted by the Corrective Action Investigation [CAI]). Through the decades, the locations monitored have varied as function of condition and access. The analyses have consistently found tritium concentrations to be below the minimum detectable concentration.

An evaluation of the LTHMP recommended that the program increase the use of hydrogeology in placement of monitoring wells (Chapman and Hokett, 1991). The inception of the DOE Environmental Management Program and development of the FFACO in Nevada provided a framework for rigorously evaluating the potential for contaminant transport from the Faultless test. As a result of the CAI, the understanding of the potential for contaminant migration from Faultless has changed from the conceptual model upon which the LTHMP was based. In particular, contaminant transport is believed to take place through the deeper volcanic units with a horizontal hydraulic gradient to the north, rather than southward in the alluvium.

As a result of the improved understanding of contaminant migration, and as a result of a desire to provide early detection and demonstrate compliance with the compliance boundary, the monitoring network used by the LTHMP for the Faultless test will be replaced by the network described in the following sections. A higher level of protection for the public and the groundwater resource can be provided by a monitoring network focused closer to the source of potential contamination, as opposed to many miles away, and by monitoring in the direction of migration. As wells HTH-1 and HTH-2 are located close to the site, special attention is given below to the decision not to include them in the revised monitoring program.

Even before the Corrective Action Investigation (CAI), logging and sampling results from HTH-1 and HTH-2 raised questions regarding their effectiveness as monitoring wells (Mihevc et al., 1996). HTH-1 is unsuitable for monitoring purposes due to its construction. HTH-1 was drilled during site investigations before the Faultless test to a depth of 1,129 m. The purpose of the well was to investigate the hydraulic properties throughout the geologic section. The well was cased and cemented throughout its length, after which 10 zones were shot perforated. The perforated horizons include zones in the alluvium, tuffaceous sediments, and welded tuff. Hydraulic testing at the time the well was drilled revealed differing hydraulic head values in the various perforated intervals, and the presence of vertical flow in the borehole. The well was left in this condition, allowing communication throughout its length through the 10 perforations. Logging and testing during the 1990s showed continuing vertical flow in the borehole (Mihevc et al., 1996). Hydraulic head measurements in the well represent a composite head from which discrete head values cannot be extracted and to which the CAU model cannot be compared.

Well HTH-2 was also drilled during site investigations before the Faultless test, to a depth of 304.7 m. There is blank casing to 152 m, and slotted casing from 152 to 304.7 m. The casing was hung in the borehole, allowing circulation of fluids between the casing and annulus. Initial hydraulic head measurements in the well represent head in the upper aquifer system in the alluvium, and were used for CAU model calibration. Through time, the vertical flow of groundwater facilitated by HTH-1 may have created a hydraulic mound that affects the water level at HTH-2 (Mihevc et al., 1996), such that it may be perturbed from the *in situ* hydraulic head for groundwater in the alluvium.

Presented below is the basis for the long-term monitoring network design for the Faultless test. First the approach used in the design is presented, followed by a detailed description of the application of that approach to CAU 443. The recommended network is then summarized. The monitoring frequency, the monitoring analytes and parameters, and the reporting requirements are presented in separate sections. The monitoring description concludes with discussion of how the data will be evaluated and the possibility for change in the network in the future.

5.2.0 Network Design

5.2.0.1 Monitoring Design Approach

The monitoring design relies on the simulation approach (using the existing CNTA model) combined with hydrogeologic expertise and probabilistic design methodology. For illustration purposes, we hypothesize the problem of the monitoring network design (selection of the well locations) as shown in Figure 5-1. The radionuclide plume emanating from the source is predicted by the model to migrate to the north and one would normally place the monitoring wells to intercept the plume. The distance along the flow direction between the working point (center of the cavity) and the CP passing through each monitoring well is denoted as x_k. Massmann and Freeze (1987a and b) and Meyer and Brill (1988) consider the failure of a monitoring network to occur when the monitoring network does not detect the contaminant before it reaches a compliance boundary. In fact, the probability of failure in year t, $P_f(t)$, is simply the probability that the time of contaminant release plus the travel time of the plume through the hydrogeological environment lies within year t (Massmann and Freeze, 1987a). If these components of failure are independent, Massmann and Freeze (1987a) write

$$P_f(t) = \sum_{t^l=0}^{t-t_{op}} \left\{ P(t' = t^l)\, P(t'' = t - t_{op} - t^l) \right\} \qquad (5\text{-}1)$$

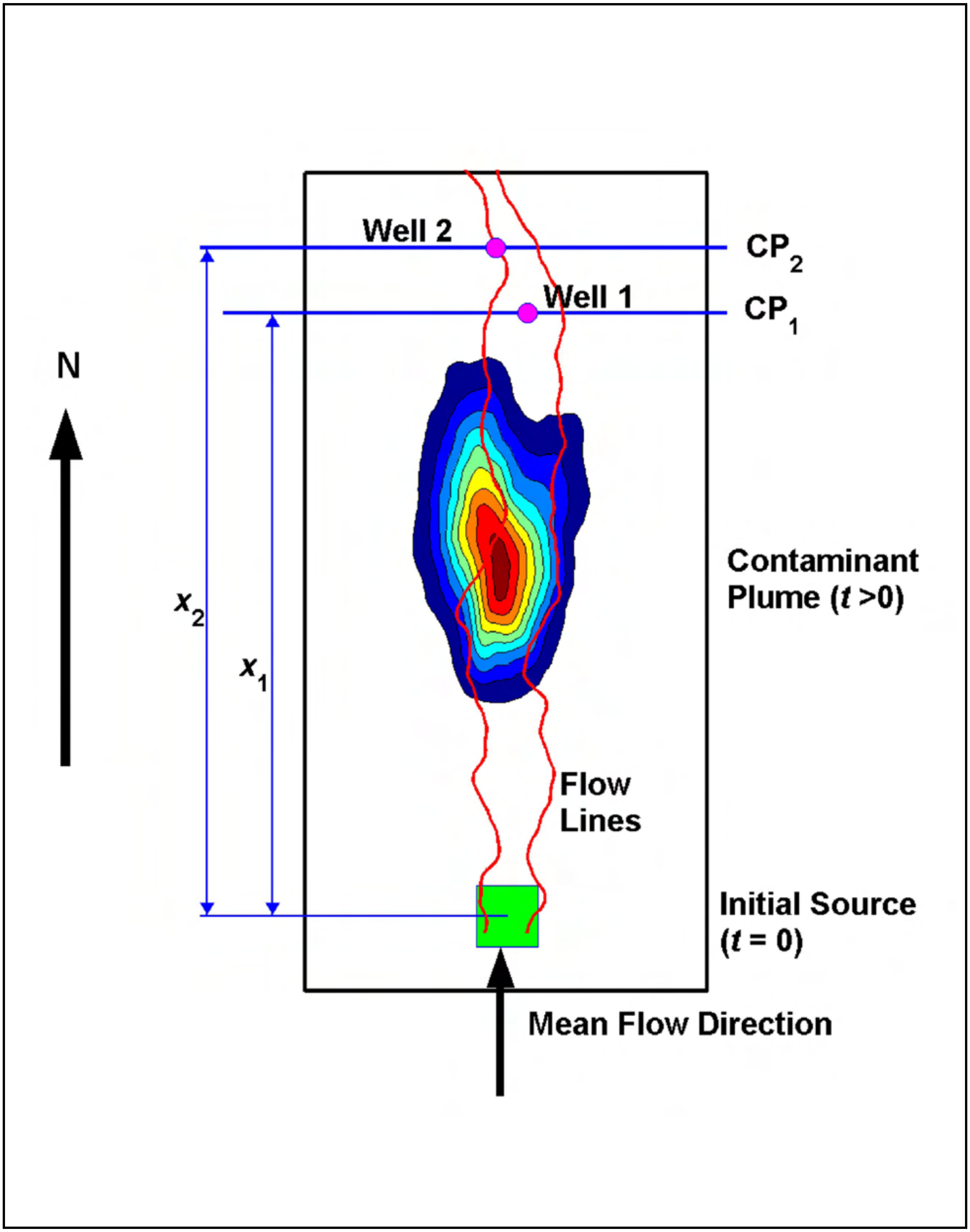


Figure 5-1
Schematic Diagram Showing the Location of Contaminant Plume, Monitoring Wells, and the Distances and Definitions Used in Equations (5-1) through (5-3)

where t is the time for which the calculations are carried out (year), t_{op} is the time at which the facility is put into operation (year), t' is the time until containment is breached (year), and t'' is the time of travel for the contaminant plume to migrate from the containment structure to the compliance surface (year). Massmann and Freeze (1987a) define the probability in Equation (5-1) as the failure probability of the unmonitored facility. For the monitored facility, they define the failure probability as

$$P_f^m(t) = P_f(t)\,(1 - P_d) \tag{5-2}$$

where $P_f^m(t)$ is the failure probability of the monitored facility at year t (*i.e.,* the probability that contaminant is released and contaminants travel through the system to the compliance boundary within year t without detection), and P_d is the probability of detection by the monitoring network.

For the CNTA case, we assume that a monitoring well fails if (1) an arbitrary percentage (e.g., 20 percent) of the plume mass crosses a CP normal to the mean flow direction, with the CP also passing through the well, and (2) the well does not detect the presence of contaminants. It is important to note that the "arbitrary percentage" is an important value that can be negotiated. Using the multiplication rule of the conditional probability theory, one can define the probability of failure in year t for a monitoring well located at $\boldsymbol{x}_j = (x_j, y_j, z_j)$, as

$$P_f(t;\mathbf{x}_{jk}) = P\left(\frac{1}{M_{total}}\int_0^t Q(\tau; x_k)\,d\tau \geq \alpha\right)\left(1 - P_{dj}\right) \tag{5-3}$$

where $P_f(t; \mathbf{x}_{jk})$ is probability that the well located at $\mathbf{x}_j$ will not detect the plume when α percent of its mass crosses the CP located at distance x_k from the center of the source along the mean flow direction (to the north for the CNTA model) in a time frame less than or equal to t years, $\int_0^t Q(\tau; x_k)d\tau$ is the cumulative mass arrival to the CP located at x_k, M_{total} is the total mass of contaminant available in the aqueous phase, and P_{dj} is the probability of detection by the monitoring well located at $\mathbf{x}_j$, given that α % or less of the plume mass has crossed the CP. For example, if the schematic plume shown in Figure 5-1 splits along the two flowpaths shown, Well 1 may not detect the plume, giving a false negative. This will give a zero value for P_{d1}, which in turn leads to a high failure probability as shown from Equation (5-3). Analogously, we can define

$$P_s(t;\mathbf{x}_{jk}) = P\left(\frac{1}{M_{total}} \int_0^t Q(\tau; x_k)\, d\tau \le \alpha \right) P_{dj} \qquad (5\text{-}4)$$

where $P_s(t;\mathbf{x}_{jk})$ is the success probability, that is, the probability that the monitoring well will detect the plume in year t if α % of its total mass or less arrives at the CP of the monitoring well by year t. It can be seen that for individual wells, the time-dependent probability of failure, the probability of success, and the probability of a plume reaching the CP are zero at early times and then they all start to increase as the plume moves toward the CP. If the predefined percentage of the plume mass (α %) crosses the CP before the monitoring well detects any contaminants, then P_{dj} is zero and the success probability is zero. If the well detects contaminants before α % of the mass crosses the CP, then P_{dj} is 1.0 and the failure probability becomes zero. This binary decision point provides a tangible measure of success, which can be expanded to multiple wells.

The value of P_{dj} can be estimated from the plume migration analysis. A plume will be detected by a monitoring system only if the groundwater flow lines passing through the cavity also pass through the screened interval of the monitoring well (Massmann and Freeze, 1987a). This probability of detection by a monitoring well can be estimated from Monte Carlo simulations used to predict plume migration. The detection occurs when particles representing the contaminant mass (using a particle tracking approach for modeling the transport processes) pass through any of the vertical cells where the well screen is located. However, to account for the element of time, to overcome the issue of the classified initial source mass, and to compare different well locations, the area of the t-z distribution of the normalized masses (particle masses) for a monitoring well is used as an indicator of the likelihood of detection. Thus the detection probability for a monitoring well j can be obtained using the Monte Carlo simulations as

$$P_{dj} = \sum_{i=1}^{NMC} \frac{W_{ji}}{NMC} \tag{5-5}$$

where NMC is the number of Monte Carlo realizations used in the analysis (500 in the CNTA model) and W_{ji} can be obtained as

$$W_{ji} = \int_{0}^{t} \int_{z=z_b}^{z=z_t} M_{ji}(\tau, z)\, dz\, d\tau \tag{5-6}$$

$M_{ji}(\tau, z)$ is the resident mass in the monitoring well cell located at elevation z and time τ, z_b is the bottom elevation of the lowest cell that can be sampled by the well, and z_t is the top elevation of the uppermost cell that can be sampled.

The above analysis is implemented through the following steps (see Figure 5-2). The first step is to identify the number of possible candidate locations, J, for the monitoring wells. The second step is to select a time frame for the analysis, which is represented by the simulation time scale, T, and the time, t, at which probabilities are to be obtained. The simulation time scale T will be selected such that the wells will be able to detect (or have a high chance of detecting) the plume. In other words, the total simulation time should be large enough compared to the time at which probabilities are computed, to enable the computation of the first term on the right-hand side of Equations (5-3) and (5-4). The purpose of selecting a simulation time, T, that is less than the 1,000-year time scale of the model, is to reduce computational time and allow for using a sufficient number of particles to represent the initial mass.

The third step is to run Monte Carlo simulations and record for each realization the t-z distribution of the resident mass ($M_{ji}(\tau, z)$ in Equation 5-6) within the cells occupied by each monitoring well. The integration of this mass distribution gives W_{ji} for each realization i = 1 to NMC and each well j. The fourth step is to compute for each candidate well location the probability that α % of the total plume

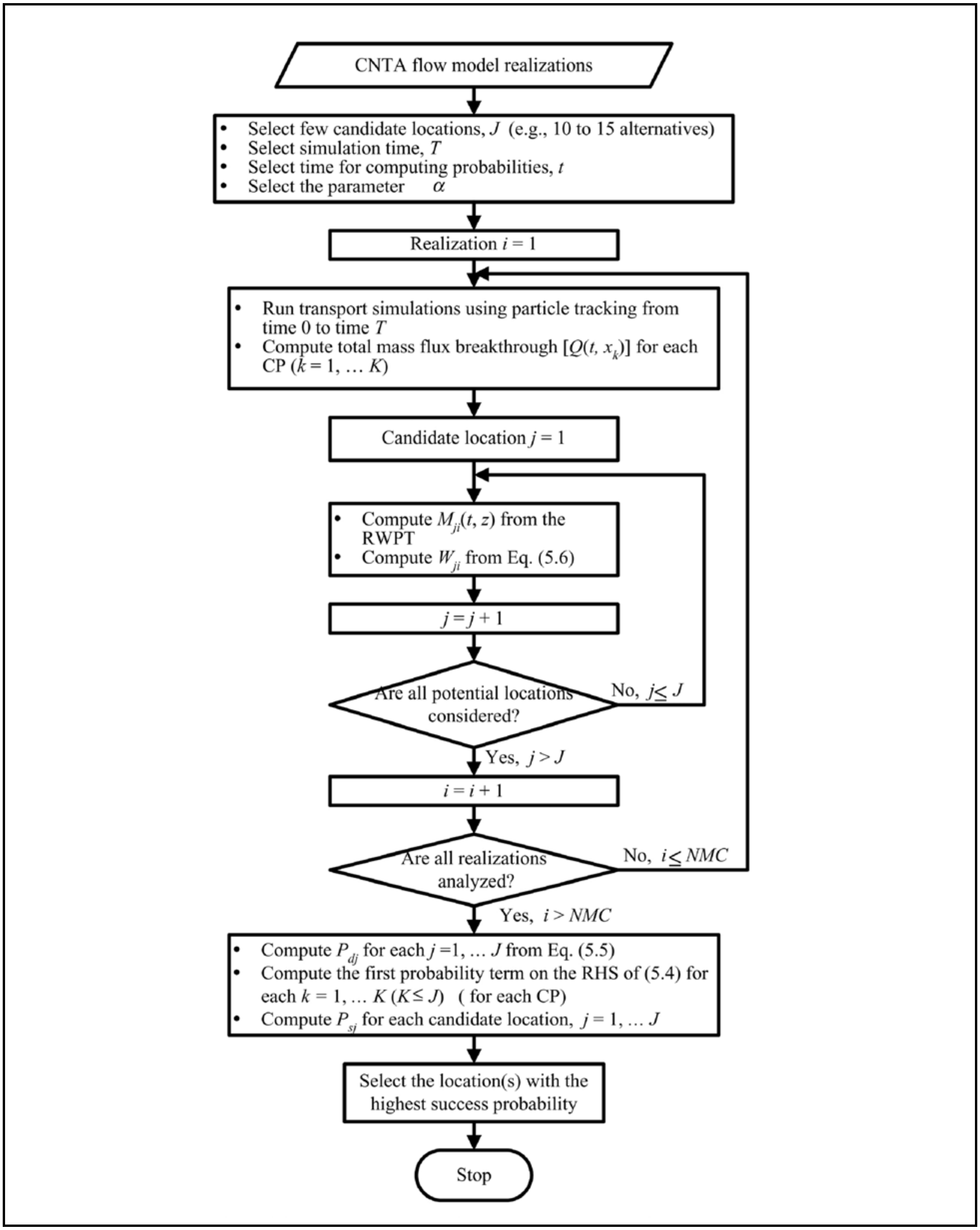


Figure 5-2
A Step-by-Step Description of the Design Methodology

mass crosses the CP, k, passing through that location in time t or less. This can simply be obtained by integrating the total mass flux breakthrough curve for each CP ($k = 1, \ldots K$ with $K \leq J$) from time zero to time t. The fifth step is to use Equation (5-4) to compute the success probability for each candidate well location (due to the computational burden, only a finite number of candidate locations will be evaluated). Locations with the highest success probability will then be selected as potential well locations.

Although computationally demanding, the approach described above is simple in nature and relies on the simulation approach combined with hydrogeologic expertise and site knowledge. Several reasons lead to using this simplified design approach as opposed to automated optimization techniques. First, the underlying model structure is generally uncertain to justify an elaborate search for "optimal" designs that may actually be no better than *ad hoc* strategies proposed based on site familiarity. Second, optimization approaches are sought when designing a monitoring network that consists of many wells and the question becomes where the optimum locations are for these wells. For the CNTA case, the great depth of the wells limits the number of wells drilled. The probabilistic analysis dictates how many wells one should place and where to place them. This is presented in the following section.

5.2.0.2 Design Implementation

This section presents the analysis for the Faultless groundwater monitoring network. It begins with a presentation of the model simulation and probability-based approaches and concludes with a presentation of the hydrogeologic approach.

5.2.0.2.1 Model Simulation and Probability-Based Approaches

The detection-monitoring objective is achieved by placing a well in a location with high likelihood of detecting the migration of radionuclides according to flow and transport model predictions. The probabilistic analysis performed is based on the focused Faultless model as described in Pohll et al. (2003).

The simulation layout is shown schematically in Figure 5-3 through Figure 5-5. Figure 5-3 shows a to-scale, 3-D view of the simulation domain, the cavity location and five CPs located at 200, 250, 300, 350, and 400 m from the working point normal to the northwardly flow direction. The figure also shows a zoom-in view showing the source and the five CPs, with the y-axis scale exaggerated to clearly show the five CPs. A plan view is also presented to show the numbering sequence of the CPs, which will help in tying the results to this schematic picture. This plan view is also exaggerated in terms of the y-scale. Figure 5-4 is similar to Figure 5-3 except that it shows the other five CPs that are located at 450, 500, 600, 700, and 800 m from the working point. The last CP located at 800 m from the working point coincides with the northern boundary of the UC-1 land withdrawal area. The (0, 0, 0) origin in the 3-D views of Figure 5-3 and Figure 5-4 corresponds to the coordinates 189,875 m East, 429,275 m North, and 295 m elevation.

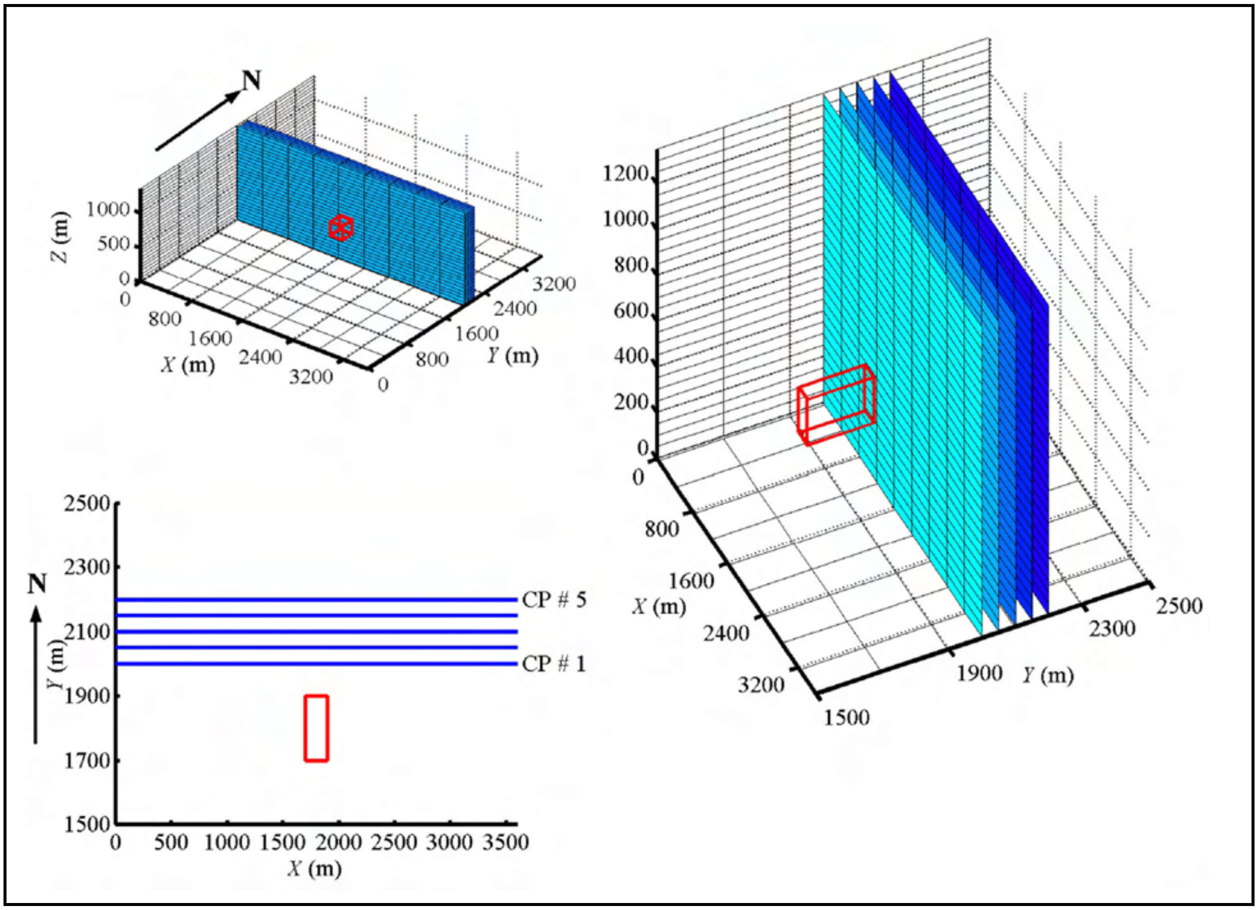


Figure 5-3
A 3-D view (top - to scale) showing the model domain, the cavity and the five CPs (CP #1 through CP #5), a zoom-in around the cavity and the CPs (right - exaggerated scale in the y-direction to allow distinction between CPs), and a 2-D plan view showing the location of the five CPs relative to the cavity (bottom - again with exaggeration in the y-scale).

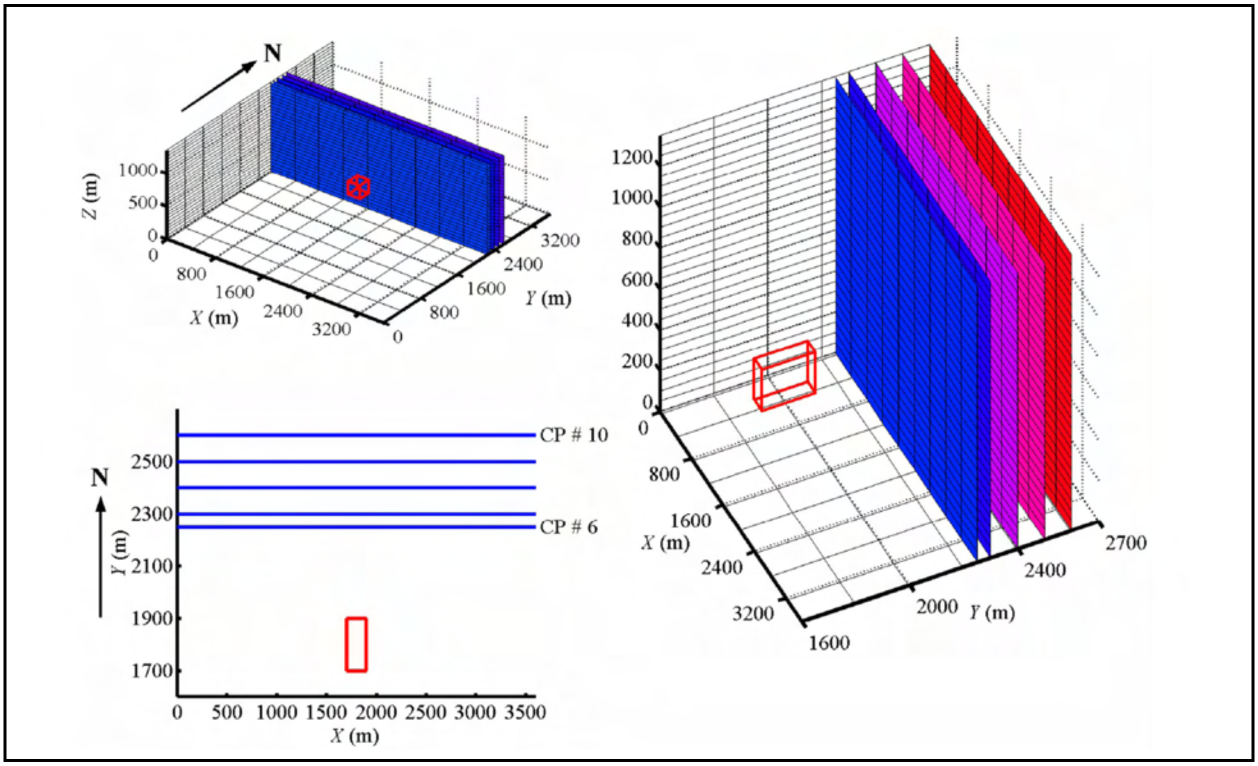


Figure 5-4
A 3-D view (top - to scale) showing the model domain, the cavity and the five CPs (CP #6 through CP #10), a zoom-in around the cavity and the CPs (right - exaggerated scale in the y-direction to allow distinction between CPs), and a 2-D plan view showing the location of the five CPs relative to the cavity (bottom - again with exaggeration in the y-scale).

Transport simulations were conducted for the 1,000-year regulatory time frame, as specified in the FFACO (FFACO, 1996). Particles representing the radionuclide source are tracked in the space-time domain for the total simulation time of 1,000 years, ignoring the retarding processes of matrix diffusion and radioactive decay. At every time step and for each CP, dimensions of the plume as it crosses a particular CP are obtained and recorded. Figure 5-5 shows how the plume width, height, and centroid (or center of mass) location are obtained for a certain CP. Therefore, for each CP, the plume width, height, and (X, Z) coordinates of the plume center of mass are recorded for every time step. This output is subsequently analyzed at times 100, 200, 500, and 1,000 years after detonation. For any of these four times, the maximum plume width and the maximum plume height that were ever attained from time zero until this time are selected for plotting the histograms discussed shortly. For the center of mass of the plume as it crosses the different CPs, the average value of the center of mass location is obtained by averaging the non-zero values from time zero to the current time. The

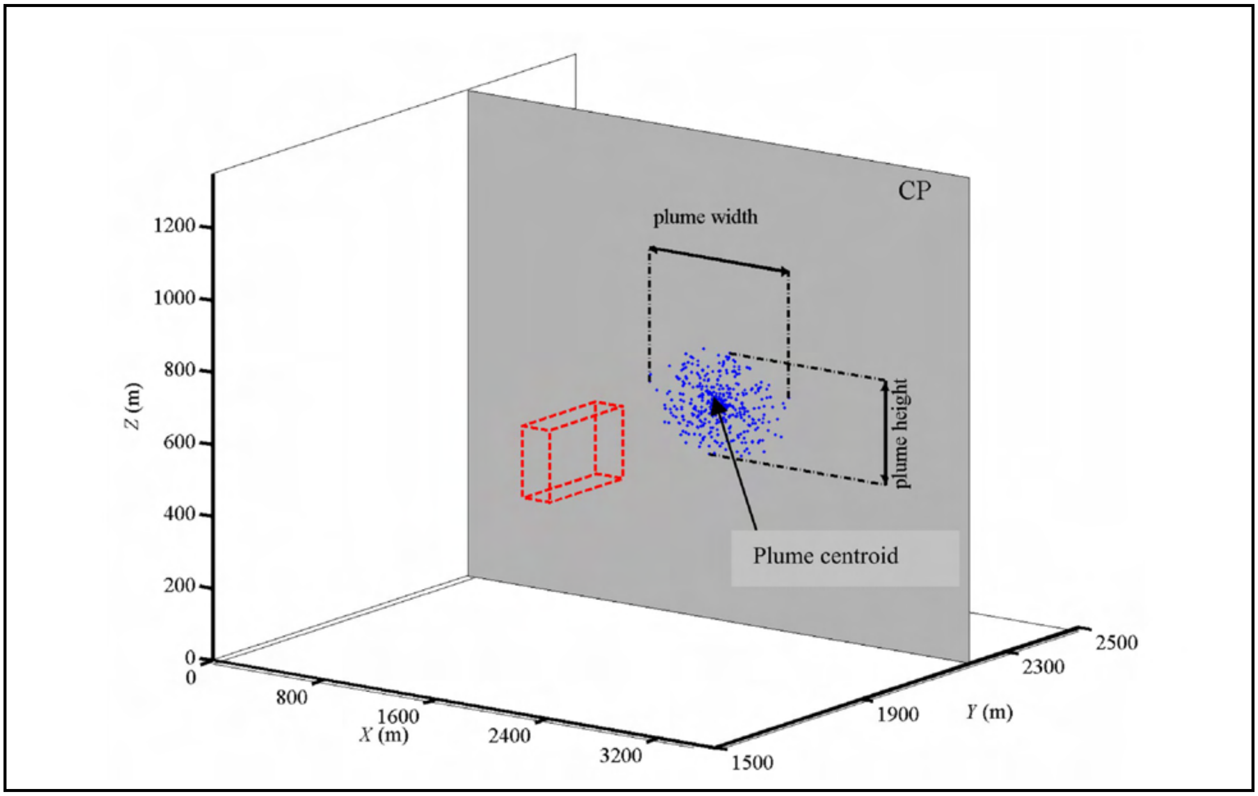


Figure 5-5
Schematic Representation of the Plume Width and Height as Particles Cross the CP

zero values of the center of mass of the plume are attained when no particles exist in the vicinity of the CP at the current time step. This occurs due to the dispersion of particles and the fact that they do not migrate in a continuous manner.

Figure 5-6 and Figure 5-7 show the distribution of the percentage of total mass that crossed each of the 10 CPs at the specific times considered. The number of realizations with mass crossing the control plane is presented on the figures as N_{tot} for each case. For t = 100 years from detonation, only 54 realizations (out of 500) had mass arriving at CP # 1, and the fastest migration rate among these realizations only led to about 12 percent breakthrough. Again this is based on ignoring matrix diffusion, and no radioactive decay is considered. For CP # 10 that is aligned with the UC-1 land withdrawal area, only seven realizations exhibit a breakthrough, with a maximum of less than 2 percent. After 1,000 years, the number of realizations showing breakthrough values at CP # 1 becomes 163 and at CP # 10 becomes 95, with a maximum mass arrival of about 50 percent in both cases.

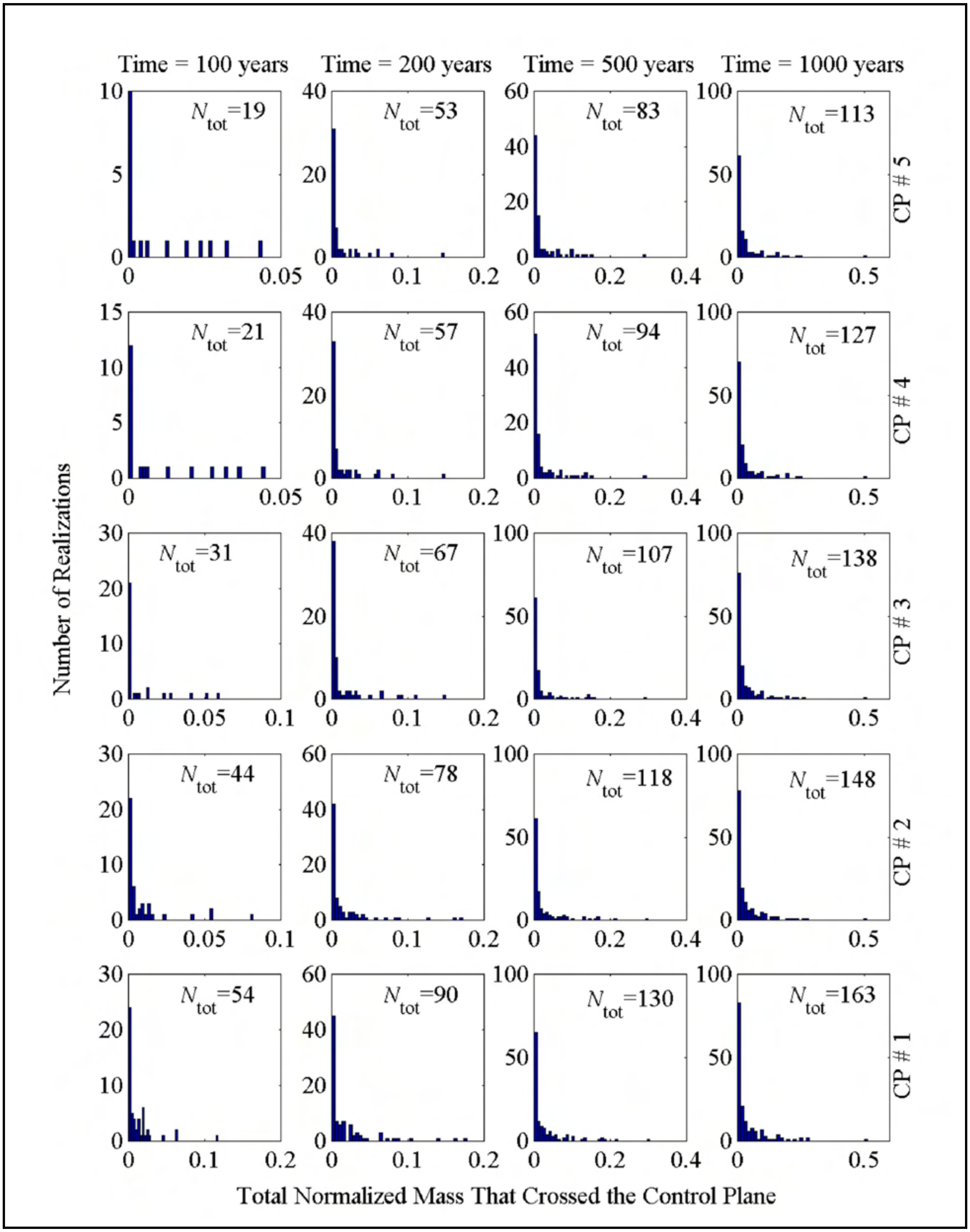


Figure 5-6
Distribution of the Total Mass Crossing CP #1 through CP #5 at Different Times

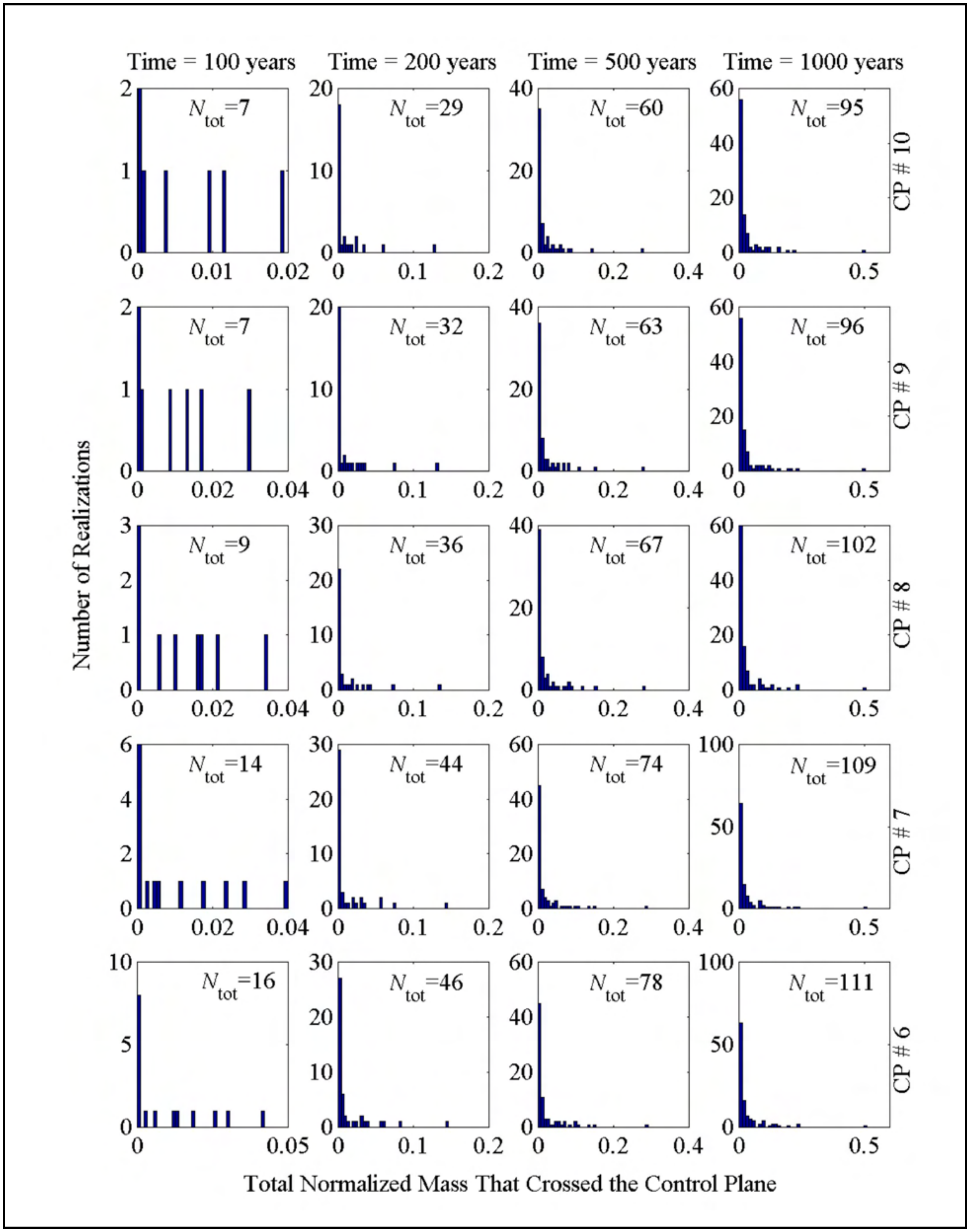


Figure 5-7
Distribution of the Total Mass Crossing CP #6 through CP #10 at Different Times

Based on these results, it can be seen that the likelihood of migration (and thus the likelihood of plume detection) away from the Faultless cavity is very low. For the nearest CP located only 200 m north of the working point, only one third of the realizations show breakthrough values within the 1,000-year regulatory time frame. This number will decrease if one accounts for matrix diffusion and radioactive decay. The farther away one gets from the working point the lower the likelihood of detection becomes. Therefore, although the location of a monitoring well is based on the physical and geometric characteristics of the predicted plume, it is actually very unlikely that any radionuclide migration will be detected. However, it is also important to note that the monitoring well may provide valuable information for the validation process of the CNTA model.

In Figure 5-8 through Figure 5-11, the distribution of the plume width and plume height as defined in Figure 5-5 is plotted for the different times and the different CPs. It is seen that the plume width is in many realizations between 100 and 200 m and the plume height is also around 100 to 200 m in many realizations. Only in a few realizations does the plume width exceed 500 m. With the fractured nature of the hypothesized densely welded tuff unit that accounts for most of the northern migration, the actual width and height of the plume may in fact be smaller than predicted by the model. This is because the model applies a continuum approach to this problem, and for realizations involving flow through fractured tuffs this may overestimate dispersion.

Figure 5-12 through Figure 5-15 show the distribution of the X and Z location of the plume center of mass when it crosses the CPs. The figures show that the center of mass in many realizations is at about X = 1,800 m from the domain origin, which coincides with the longitudinal centerline of the domain. In the Z direction, the plume center of mass is more or less normally distributed with a central tendency around Z = 500 m (recall this is relative to the domain origin at an elevation of 295 m). This is about 100 m below the working point elevation. The distribution in the vertical Z direction provides guidance for where to sample the monitoring well for concentration measurements. Note, however, that the variability of the Z location between realizations is partly a result of the uncertainty in the existence and location of the densely welded tuff unit that is built into the CNTA model. Therefore, it is important to realize that most of the lateral flow to the north occurs through this hypothesized welded tuff unit. The location of the sampling interval in any well should be tied to the location of the densely welded tuff unit if it is encountered in the field at or below the nuclear

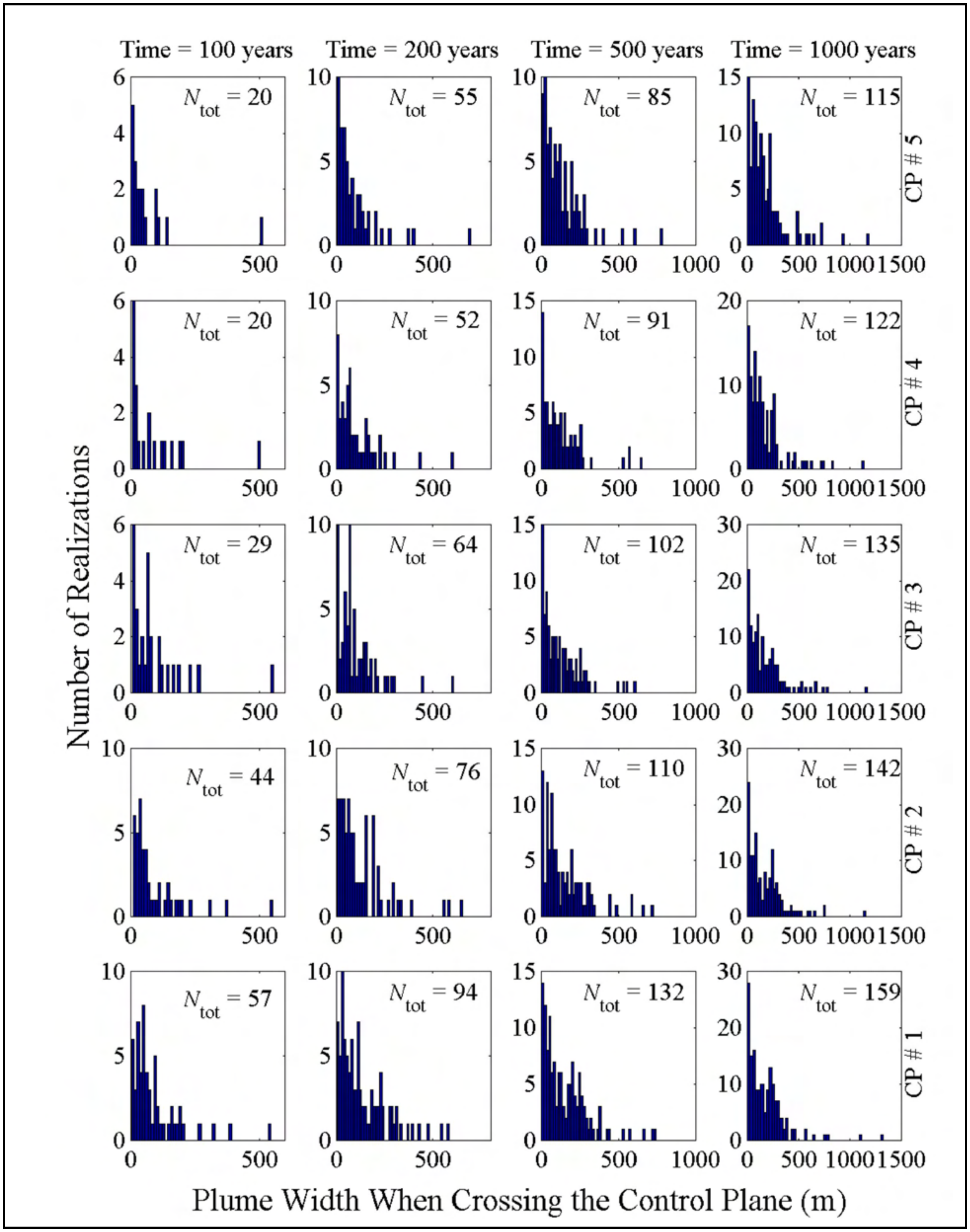


Figure 5-8
Plume Width Distribution for CP #1 through CP #5 at Different Times

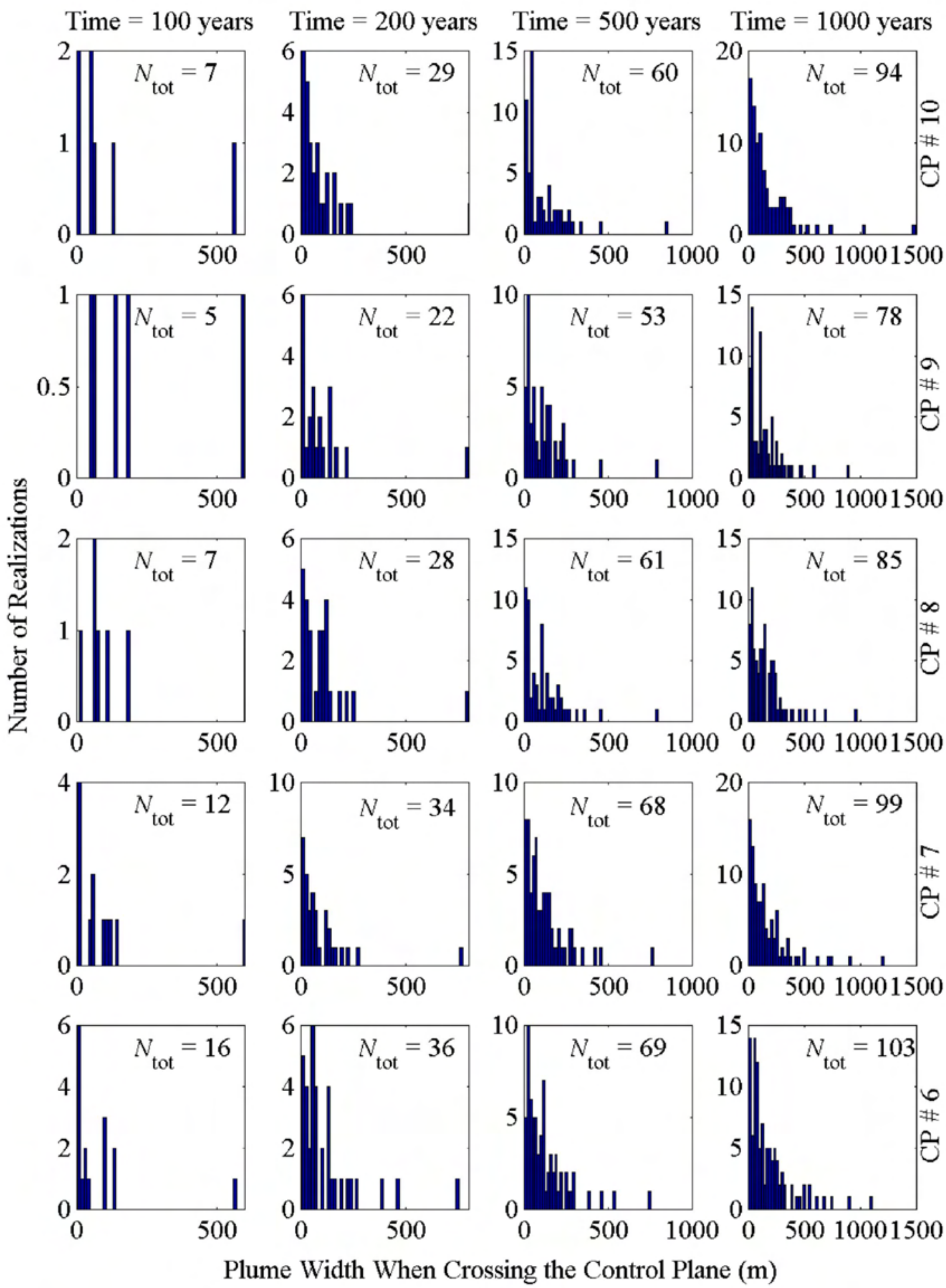


Figure 5-9
Plume Width Distribution for CP #6 through CP #10 at Different Times

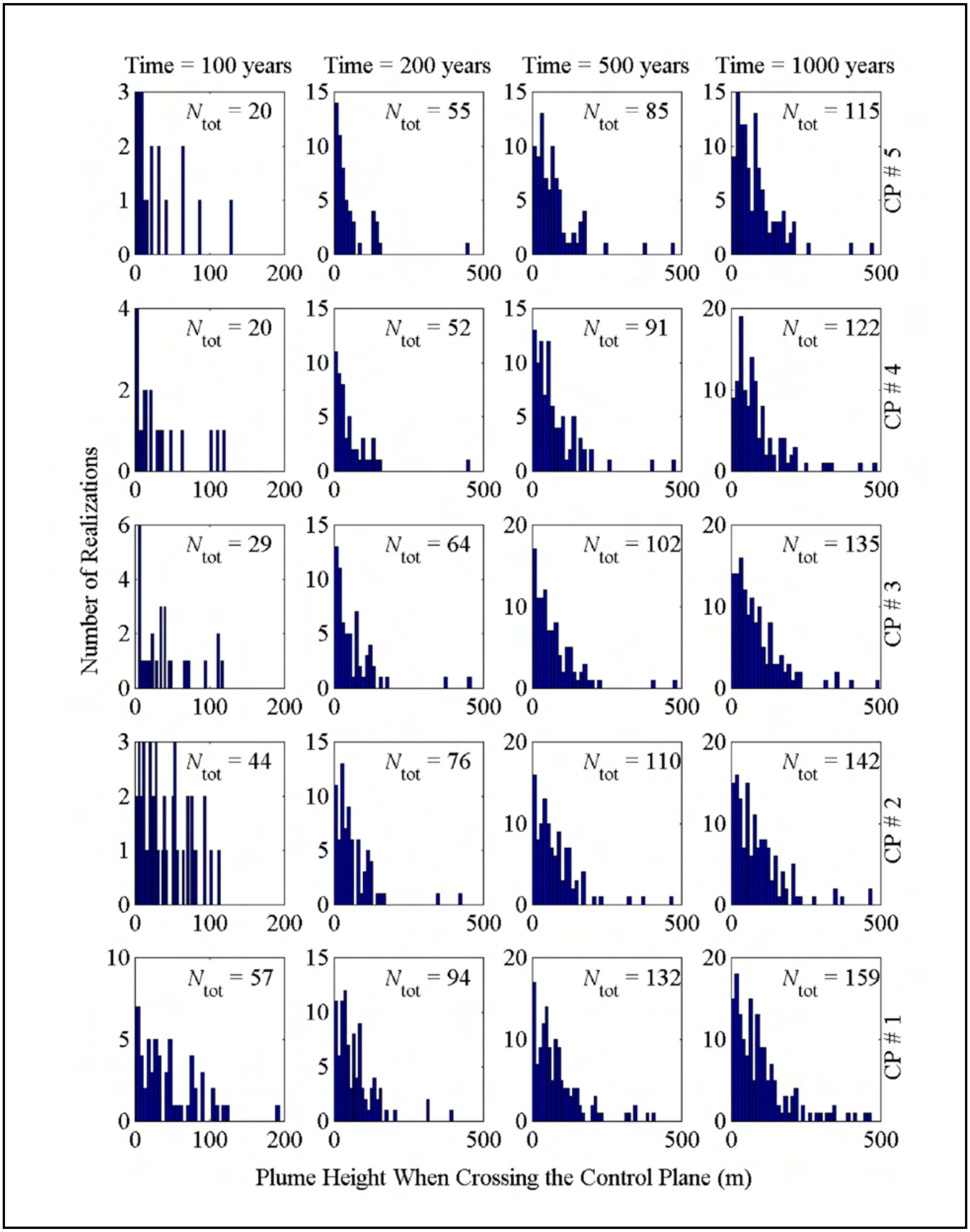


Figure 5-10
Plume Height Distribution for CP #1 through CP #5 at Different Times

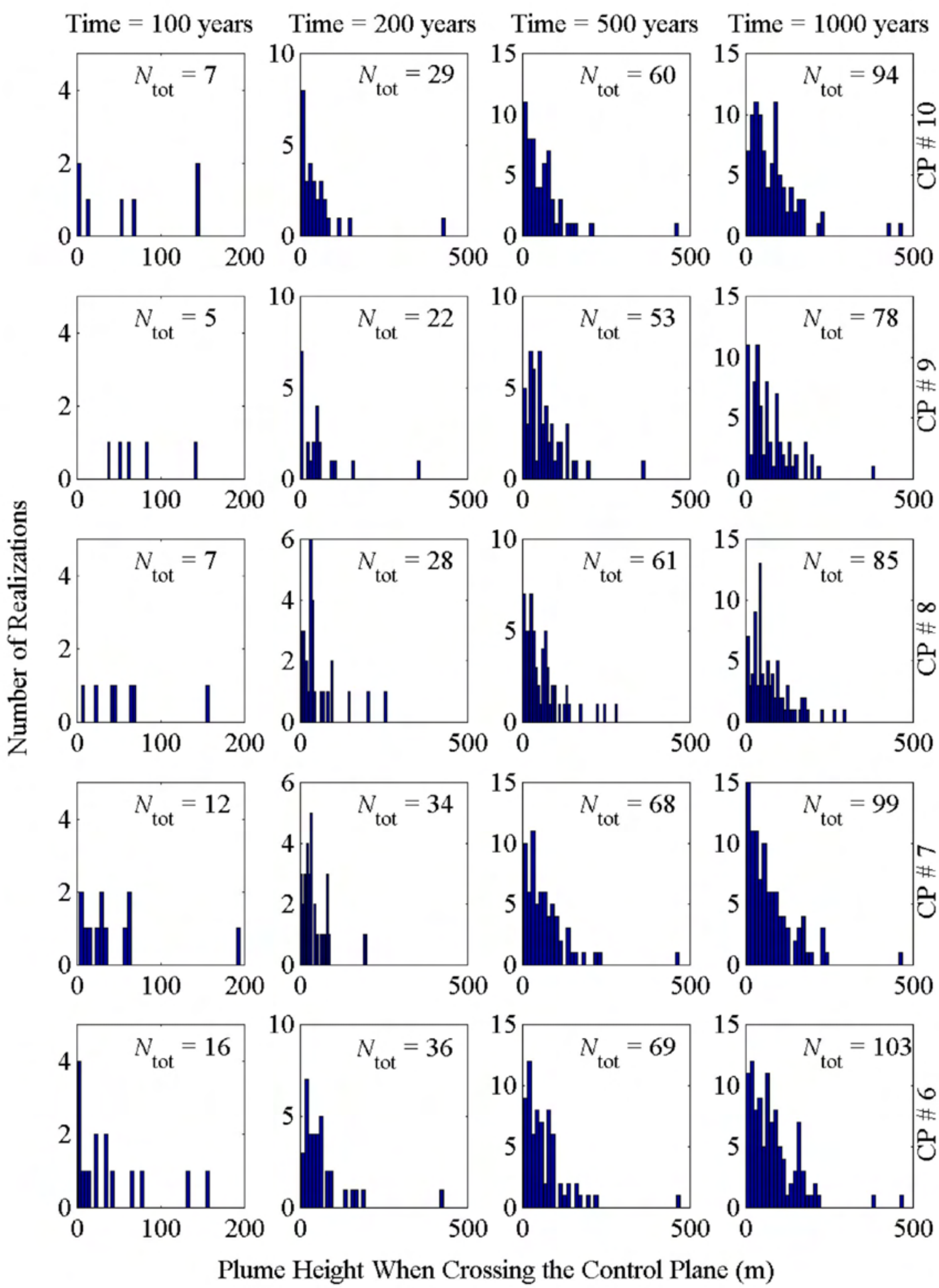


Figure 5-11
Plume Height Distribution for CP #6 through CP #10 at Different Times

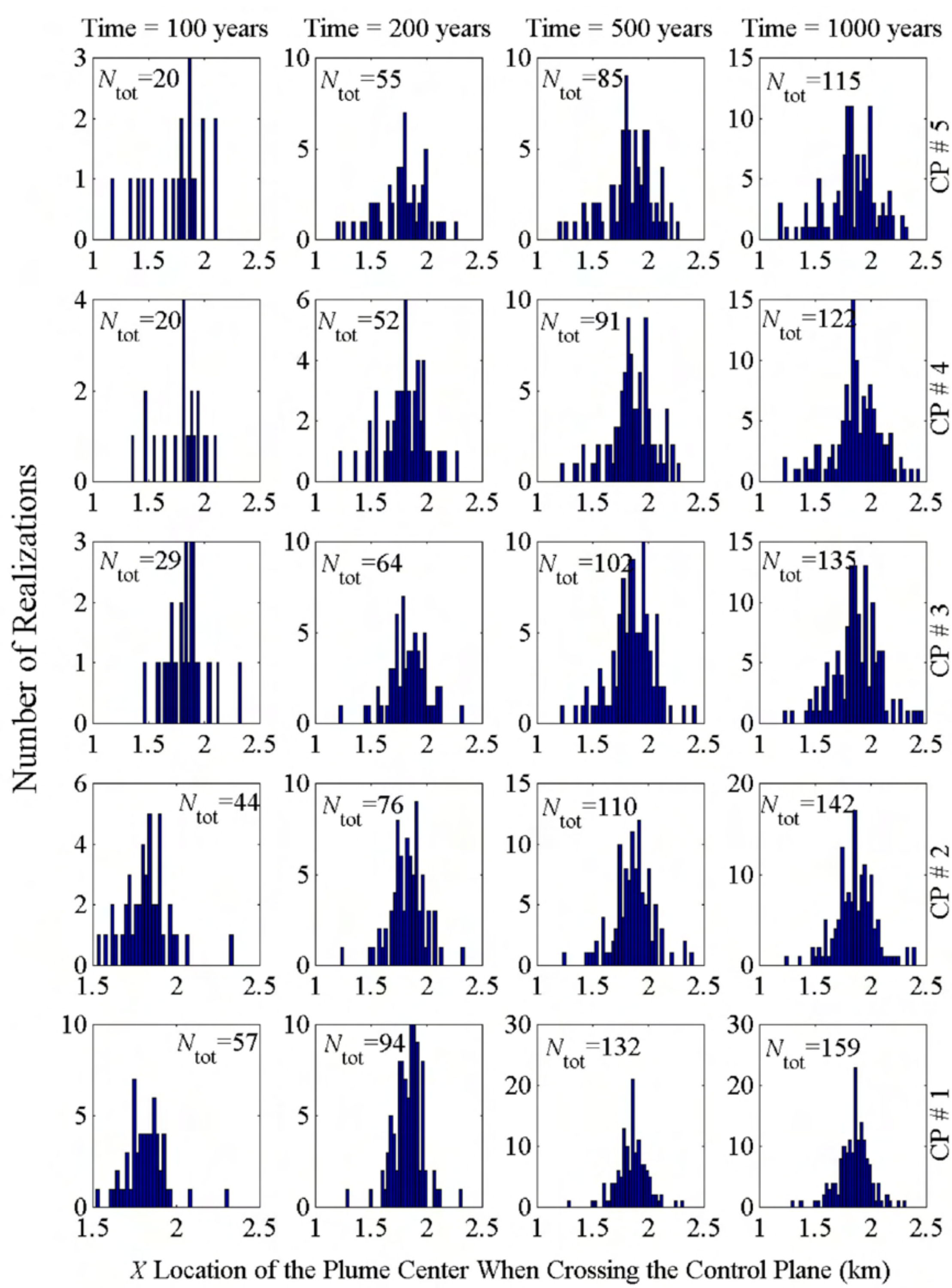


Figure 5-12
Distribution of the X Location of the Plume Center of Mass When Crossing CP #1 through CP #5 as Average Values from Time Zero to the Given Times

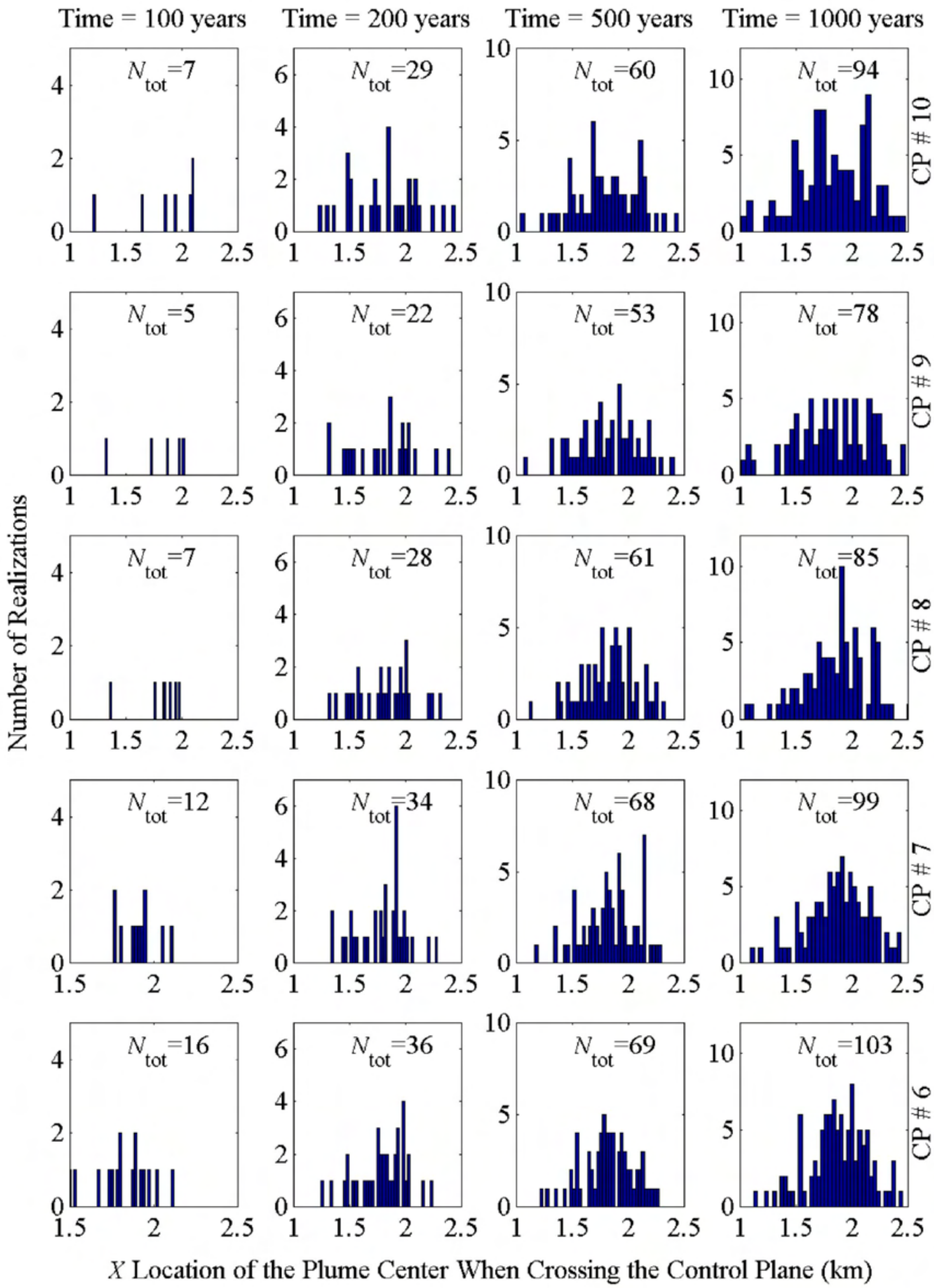


Figure 5-13
Distribution of the X Location of the Plume Center of Mass When Crossing CP #6 through CP #10 as Average Values from Time Zero to the Given Times

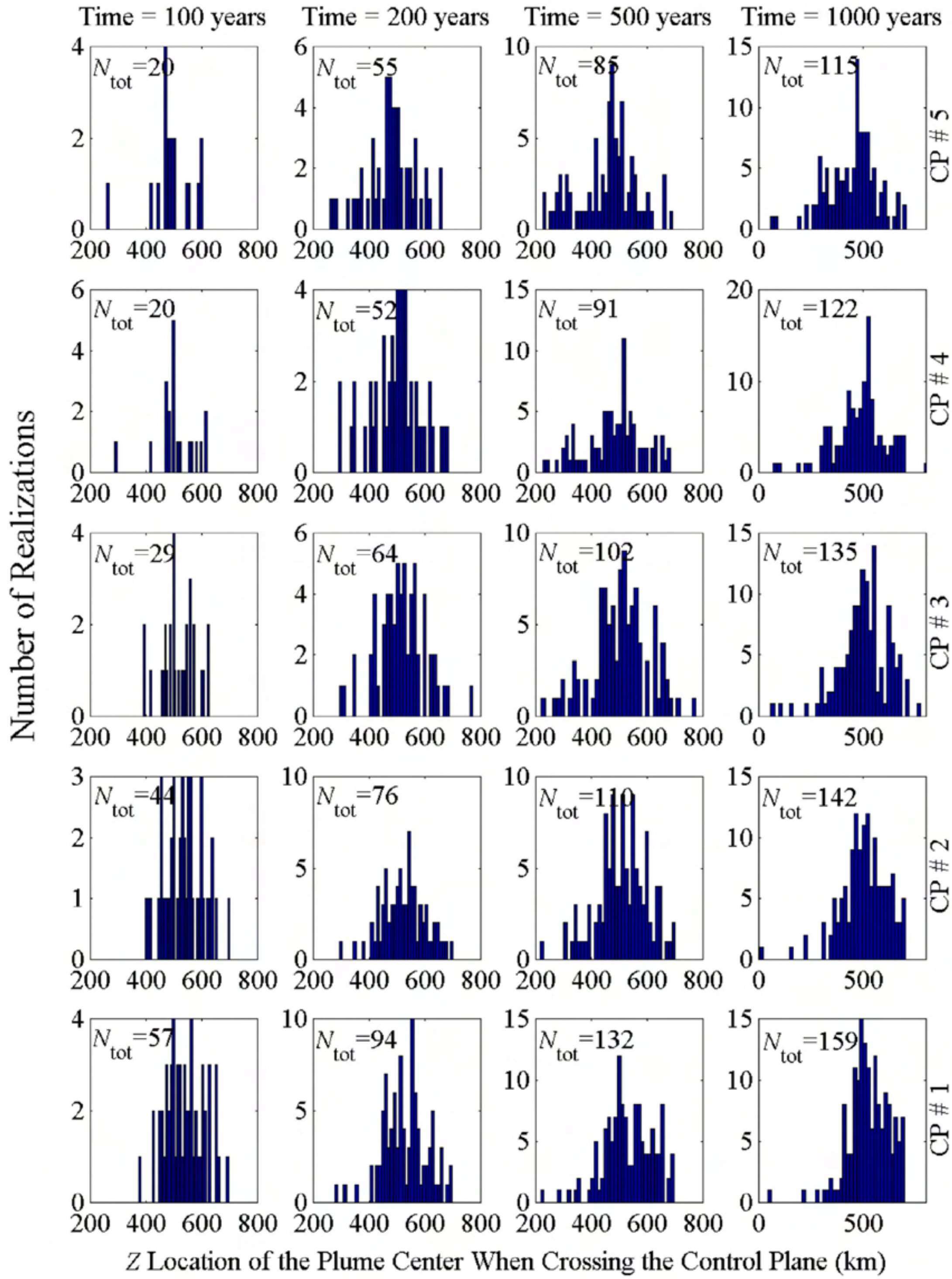


Figure 5-14
Distribution of the Z Location of the Plume Center of Mass When Crossing CP #1 through CP #5 as Average Values from Time Zero to the Given Times

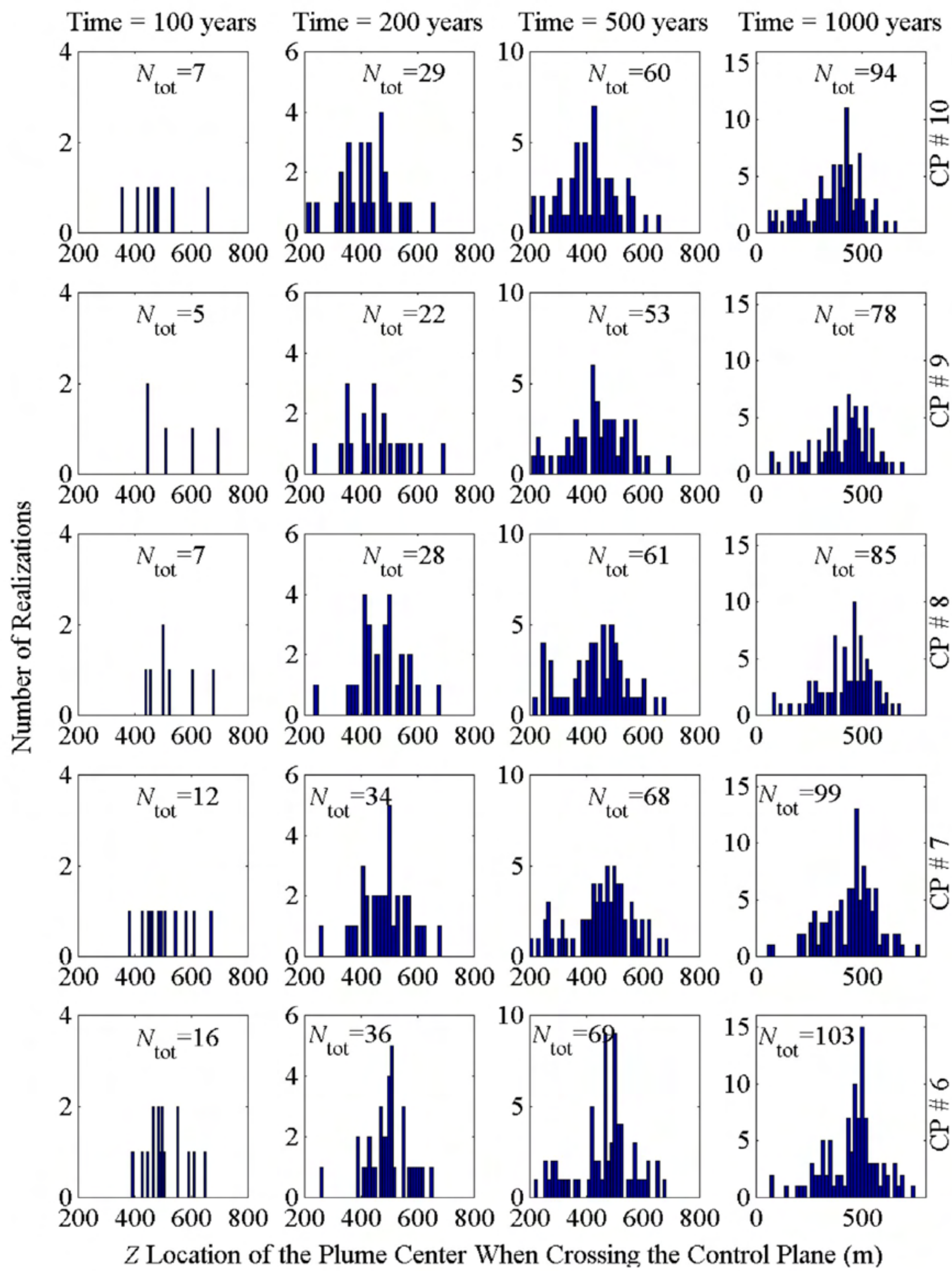


Figure 5-15
Distribution of the Z Location of the Plume Center of Mass When Crossing CP #6 through CP #10 as Average Values from Time Zero to the Given Times

cavity horizon. If the unit is not encountered during drilling, one would place the sampling intervals according to the guidance provided by the distributions in Figure 5-14 and Figure 5-15.

The small cross-sectional size of the plume and the limited distribution of the center of mass location in multiple realizations suggest that an optimum placement can be realized by a single well (although even this well will have a low likelihood of plume detection due to the low likelihood of migration, as previously discussed). A greater degree of spreading, either through dispersion of the plume or variation in plume location from realization to realization, would require more wells for adequate coverage. Results also indicate that the location likely to encounter plume migration is along the longitudinal centerline of the domain downstream of the cavity.

For early detection of fast migration pathways, one would place the monitoring well as close to the cavity as practically possible. Several reasons limit the practicality of being close to the cavity. The first is the increased worker risk incurred by drilling into, or very near, nuclear cavities where radionuclides can be injected by the blast. The second is that the Faultless model was constructed using hydrogeologic conditions undisturbed by the nuclear test. This means that features specific to effects from the nuclear test, such as faults and collapse structures, were not included in the model because it was assumed that radionuclide migration in the long term would be dominated by the characteristics of the natural groundwater system. Thus, the accuracy of the model can be expected to be higher at greater distances from the cavity outside the area disturbed by the test. In addition, use of the monitoring data must be considered in terms of well placement. Even if detection probability is greater close to the cavity, confirming contamination within the contaminant boundary may not serve a useful long-term management function for the site. Balancing these factors leads to a target location for the detection monitoring well, MV-3, of approximately 640 m north of Faultless surface ground zero (Figure 5-16).

5.2.0.2.2 Hydrogeologic Approach

The monitoring well selection process described above relies on multiple simulations of the Faultless numerical model to identify locations with the highest probability of detecting contaminant migration. The model itself is built upon all available hydrogeologic data and also incorporates hydrogeologic analysis and intuition applied during the data analysis and calibration stages. Thus the hydrogeologic approach is incorporated within the model simulation approach.

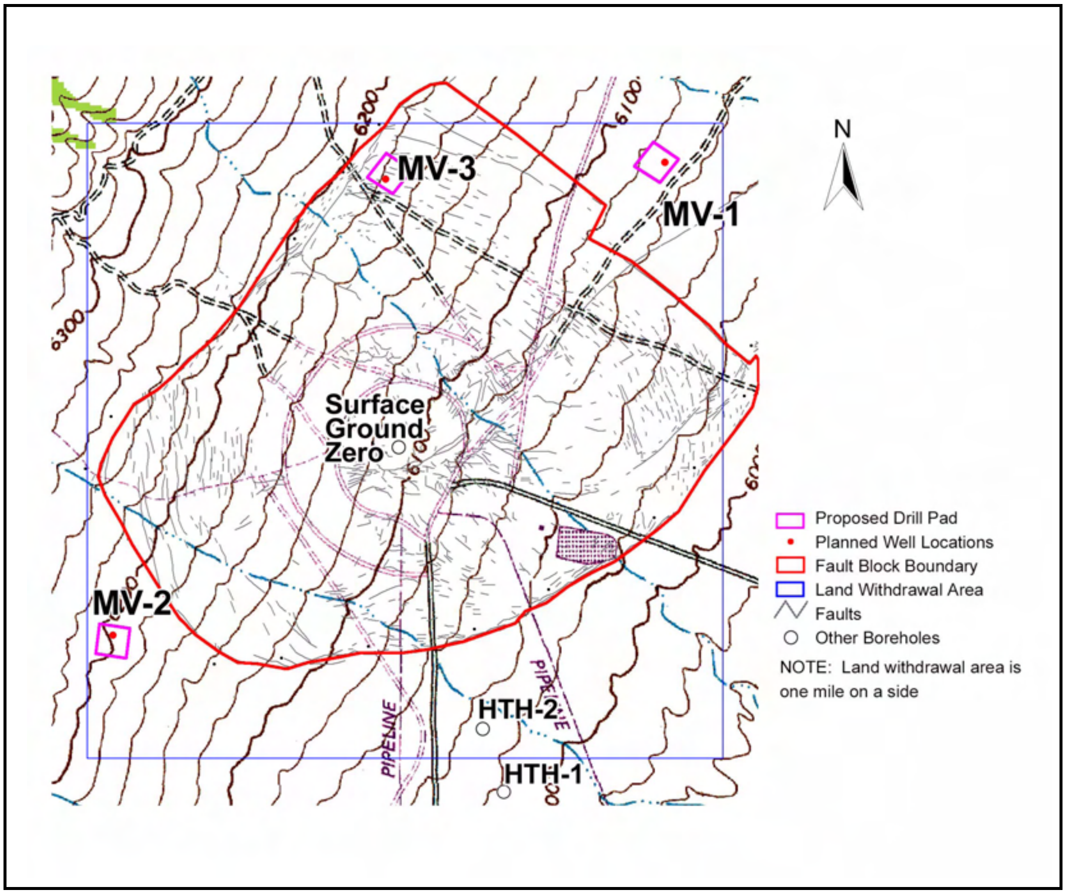


Figure 5-16
Map of the UC-1 Land Withdrawal (dashed line), Showing Faultless Surface Ground Zero and Locations of the Three New Wells

Though the quantitative analysis concluded that optimum detection monitoring can be realized by a single well, the FFACO also states that compliance monitoring will include measurement of physical parameters to demonstrate that they remain within the range of measurements used in the flow model as "an indication that the conditions have not significantly changed." In the case of Faultless, this can be met by monitoring the quasi steady-state condition of the groundwater system using hydraulic head measurements. Multiple monitoring points are desirable for monitoring hydraulic head, particularly because the hydraulic gradient at the testing horizon is the parameter of concern and determining a gradient requires spatially distributed measurements. For this reason, and also to satisfy the demands of model validation described in Section 5.5, two wells will be included in the network for system monitoring, in addition to the one detection monitoring well (Figure 5-16), distributed so that the hydraulic gradient at the nuclear test horizon can be monitored.

In addition to the application of hydrogeologic knowledge through the modeling, development of the monitoring network for CNTA will also be subject to the hydrogeologic approach during implementation. Insight developed from knowledge of the hydrogeologic environment will directly affect the final well completions. For example, transport through fractures in welded tuff is known to present a possible fast pathway. Although the simulation and probability-based approaches indicate that the best vertical location to sample is about 100 m below the working point, if a welded tuff unit is identified near or below the cavity horizon during drilling, it is likely to present a desirable location for a well screen, whether or not it is at that exact vertical location. Other factors that will be considered during drilling and testing any monitoring well are the hydraulic heads encountered and the identification of faults or other significant hydrogeologic features. As this information will only be available during the fieldwork, it is likely to be incorporated in the monitoring well design through the use of the hydrogeologic approach, although it is possible that some additional numerical simulations could be performed as data are collected.

5.2.0.2.3 Summary of Monitoring Network Design

Three wells are included in the monitoring network for CAU 443, all of which will be drilled as part of this Corrective Action. One of these wells has a primary function for detection monitoring (MV-3), while the other two have system monitoring and model validation (described in Section 5.5) as their primary functions (MV-1 and MV-2). All of the wells will be monitored for hydraulic head and will also have groundwater samples collected for radionuclide analysis (see Section 5.2.2 for monitoring analytes and parameters).

The depth of all the new wells is targeted to be between 1,200 and 1,400 m below land surface because the primary transport pathway is directed downward from the nuclear test horizon. Two well completion diagrams (Figure A.1-1 and Figure A.1-2 in Appendix A) have been prepared reflecting two possible conditions in the subsurface. A third condition, absence of welded tuff throughout the drilled section, is also possible. Figure A.1-1 demonstrates a completion where welded tuff is encountered relatively high in the lithologic section, but no welded tuff is encountered near the nuclear test horizon. A piezometer is targeted for the mid-section tuff, and the well screen is placed according to the optimum transport horizon predicted by the model (100 m below the test horizon, at an elevation of 785 m). Figure A.1-2 shows a completion for the case where the well screen is targeting a welded tuff encountered deep within the section as a possible transport pathway. Final completion details will be specified for each well individually taking into account the particular geologic and hydrologic conditions encountered during drilling. In addition to the well screen near the total depth of the borehole, up to two piezometers will be installed in the annular space. These are designed to provide hydraulic head data.

5.2.1 Monitoring Frequency

Monitoring will occur annually. The frequency of data collection should correspond to contaminant transport times as predicted by the flow and transport models. However, in the case of CNTA, very slow groundwater velocities compounded by contaminant retardation processes during transport would result in long intervals between monitoring. Such long monitoring intervals contrast with practical needs for maintaining active knowledge of the monitoring system, for surveillance of activities in the region around the site, and for generating data to support the proof-of-concept determination. These needs are best met with a monitoring interval of once a year. The monitoring of some system parameters, such as hydraulic head, may need to occur more frequently than once a year, depending on whether equilibrium conditions are regained rapidly after well installation. These conditions will be reported to NDEP as specified in Section 5.2.3.

5.2.2 Monitoring Analytes and Parameters

Monitoring analytes and parameters include tritium, carbon-14, iodine-129, and hydraulic head, as summarized in Table 5-1. Tritium will be the primary radiochemical analyte. This selection is based on the mobility of tritium, its abundance in the source term for the first hundred years, and the low detection limits available. Due to the relatively short half-life of tritium, longer-lived radionuclides will gain in importance during post-closure monitoring. Carbon-14 and iodine-129 are selected as long-lived radionuclides for the monitoring program because of their importance in defining the contaminant boundary (Pohll et al., 2003). Although carbon-14 and iodine-129 are selected to address post-closure monitoring, data collected preclosure can be used to establish background conditions.

The system parameter selected for proof-of-concept monitoring is hydraulic head. It is selected based on the sensitivity of hydraulic head to changes in a hydrologic system.

Table 5-1
Monitoring Analytes and Parameters

Analyte/ Parameter	Measurement Method	Container Type	Preservative	Filtration	Holding Time	Required Detection Limit
Tritium	Scintillation counting	1-liter glass	None	Nonfiltered	180 days	300 pCi/L
Carbon-14	Accelerator mass spectrometry	2-liters glass	None	Nonfiltered	180 days	5 pCi/L
Iodine-129	Accelerator mass spectrometry	1 liter amber glass	None	Nonfiltered	180 days	0.1 pCi/L
Hydraulic Head	Wireline, transducer, electric tape	NA	NA	NA	NA	± 0.1 ft

*Monitoring of hydraulic head may need to be more frequent than annually at the beginning of the proof-of-concept period until post-drilling equilibration is reached.

5.2.2.1 Quality Assurance/Quality Control Processes

The quality of the monitoring results depends on establishment and implementation of effective sampling, analysis, and support processes. Plans and procedures governing data collection are developed in accordance with the UGTA QAPP (DOE/NV, 2003a). The fundamental aspects of this plan are presented below.

Collecting the water samples in accordance with established processes will ensure sample quality. Plans and procedures are developed to ensure that appropriate sampling controls are planned and implemented. Representative samples are achieved by pumping the well and purging to the point of collecting representative groundwater. Groundwater will be considered representative only after at least one well volume has been purged and the field-measured parameters of temperature, electrical conductivity (EC) and pH have stabilized. Electrical conductivity (EC) and pH are measured to establish the representative nature of the groundwater sample, and not as empirical parameters within the monitoring program.

Analytical quality will be ensured through laboratory and field quality assurance/quality control (QA/QC) systems to include the use of established processes and standards for calibration. Trip blanks, laboratory blanks, field blanks, and duplicate samples will be included in the routine monitoring to determine the effectiveness and precision of sampling processes. Although the contaminant boundary is based on SDWA levels that equate to 20,000 pCi/L for tritium, 2,000 pCi/L for carbon-14, and 1 pCi/L for iodine-129, the quality requirement for the monitoring will be the detection levels as given in Table 5-1. The detection requirements for carbon-14 and iodine-129, in particular, are low because these analyses will be used to establish background conditions for comparison during post-closure monitoring.

Comparison of hydraulic head between the flow model and field measurements is complicated by issues of scale. The model reports head averaged through 50 cubic meter (m^3) blocks, whereas the well screen is limited at least in the x and y directions. This reduces the information to be gained from very precise head measurements for proof-of-concept. Nonetheless, subtle variations in hydraulic head may be useful indicators of change in the overall hydrologic system in response to climatic or anthropogenic causes. Thus, the ability to detect trends with a precision of plus or minus a tenth of a foot (three centimeters) is the quality requirement for the hydraulic head measurements. Absolute accuracy of the measurement is dependent on well deviation and is not necessary for monitoring trends in head within a single well. Data quality will be obtained through the use of calibrated field equipment (wirelines, transducers or water level probes), and a standard operating procedure requiring three repetitive measurements within the acceptable precision.

5.2.2.2 Sampling Methods

Groundwater samples will be obtained using submersible pumps installed in the new wells and will be used for model validation and proof-of-concept analysis, as well as monitoring. It is also possible that samples will be collected with a wireline and discrete sampler, or a submersible pump, from existing site wells and piezometers in the new wells, as part of the validation and proof-of-concept analysis.

Samples from the new wells will be collected with a submersible pump. The drilling contractor will develop the wells before the first sample collection. An aquifer test will then be conducted to obtain hydraulic parameters, but also to purge the borehole of drilling fluid so that representative samples can be obtained. This initial purging will be conducted until pH, EC, and temperature stabilize, and any chemical tags added to drilling fluids are reduced to acceptable levels. Subsequent sample collection from the new wells and any other well sampled using a pump, will be conducted after one well volume is purged and pH, EC, and temperature stabilize.

Conditions that require validation or proof-of-concept samples to be collected with a discrete sampler are likely to prohibit purging. In these cases, it is proximity of the sampler to the screened horizon that is relied on for providing representative groundwater, but these samples will be designated of lower reliability than those collected after purging. An example is a sample which may be collected from the existing post-shot well on the site.

Table 5-2 lists additional analytes that may be used for the validation and proof-of-concept analysis.

Table 5-2
Additional Analytes

Analyte	Analytical Method	Container Type	Preservative	Filtration	Holding Time	Required Detection Limit
Cations						
Calcium	SW-846 6010B	1 liter[a], amber glass or polyethylene	HNO_3 to pH<2[a], Cool/Ice to 4°C	Filtered	6 months[a]	1,000 (µg/L)[b]
Magnesium						
Potassium						
Sodium						
Anions						
Bicarbonate	EPA 310.1[d]	1 liter[a] polyethylene	Cool/Ice to 4°C	Nonfiltered	14 days[a, d]	1,000 (µg/L)[c]
Carbonate						
Chloride	EPA 300.1[e]			Filtered	28 days[a, e]	250 (µg/L)[c]
Sulfate	EPA 300.1[d]					1,000 (µg/L)[c]
Age and Migration Parameters						
$^{18/16}$Oxygen	Mass spectrometry	125-mL glass	None	Nonfiltered	180 days	+/- 0.2 per mil (precision)
Deuterium/ Hydrogen	Mass spectrometry	10-mL glass Polyseal lids	None	Nonfiltered	Indefinitely	+/- 1.0 per mil (precision)

[a]U.S. EPA Test Methods for Evaluating Solid Waste, 3rd Edition, Parts 1-4 (EPA, 1996)
[b]USEPA Contract Laboratory Program Statement of Work for Inorganic Analysis, Multi-Media, Multi-Concentration, ILM04.0, EPA/540/R-95/121. Washington, DC. (EPA, 1995)
[c]Laboratory-specified detection limit
[d]Methods for Chemical Analysis of Water and Waste, EPA/600/4-79/020. 1983. Washington, DC. (EPA, 1983)
[e]Determination of Inorganic Anions in Drinking Water by Ion Chromatography, EPA/600/R-98/118. 1997. Cincinnati, Ohio. (EPA, 1997)

µg/L = Micrograms per liter

5.2.3 Reporting Requirements

Reporting frequency for results from the Faultless monitoring program will vary during the initial stages of the program. It is envisioned that the reporting frequency will eventually stabilize to match the annual frequency of actual monitoring events. An initial report will be completed and submitted to NDEP after completion of the monitoring wells and will discuss findings that resulted from drilling, well completion, and well development. Hydraulic head measurements initially will likely occur more frequently than once a year, as discussed in Section 5.2.1. However, two or more episodes of hydraulic head measuring will be necessary to establish post-development trends in the immediate vicinity of the new monitoring wells, so an annual reporting frequency will suffice to provide NDEP with useful data within the local and regional context of CNTA. If noteworthy or unexpected results are discovered during the period of time that the new monitoring wells are equilibrating with local hydrologic conditions, these would be reported to NDEP as special reports. Once the monitoring wells are completed, developed, and have achieved equilibration within the context of the local hydrology, an annual reporting frequency in conjunction with the annual testing frequency will be observed. These data will be reported to NDEP in the form of a letter report, and will include any charts and/or data tables necessary to accurately represent monitoring results.

5.2.4 Evaluation and Evolution of Monitoring Network through Time

Data collected from the monitoring network will be used to determine compliance with the CAU compliance boundary in terms of contaminant concentrations, and to monitor the hydraulic system relative to the steady-state assumption. Analysis of the data relative to the range of values used in the groundwater modeling is part of the validation and proof-of-concept work, described in detail in Section 5.5.

The data evaluation for monitoring the compliance boundary will entail comparison of radionuclide concentrations measured in groundwater samples from the wells to regulatory limits. The range of values expected for each analyte from the numerical modeling are all below the detection limits. Water produced during drilling, development, and hydraulic testing will be monitored and reported as part of the Fluid Management Plan. Trends will be tracked in the long-term monitoring data to reveal systematic changes in radionuclide concentration in the monitoring wells, in addition to comparison to regulatory limits.

Hydraulic head will be used to monitor the quasi steady-state condition of the groundwater system; i.e., to determine if mean hydraulic head values remain constant through time, given fluctuations caused by natural temporal stresses and stresses related to well drilling, construction, and testing. This requires first determining when heads have stabilized following drilling and testing activities, then quantifying the natural mean and temporal variation in hydraulic head, and finally comparing subsequent monitoring measurements to that range. The frequency of measurement will be dictated by the recovery behavior. As recovery progresses, the stabilized hydraulic head in the wells will be estimated using methods described in ASTM D 4750. Determining the mean and variation will encompass data collection during and after recovery from the drilling and testing operations and evaluation of well efficiency at responding to the periodic stresses of earth tides and barometric pressure fluctuations over a period of at least one year. Once the data indicate that heads have reached quasi steady-state and the range of head variation is determined, the third phase will begin and entail comparison of subsequently collected head data to the range identified in the second step.

The range of hydraulic head predicted by the model at the well locations is shown in Figure 5-17. The mean head predicted at the planned completion elevation of 785 m is approximately 1660 m above mean sea level at MV-1 and MV-3, and 1663 m above mean sea level at MV-2. Evaluation of the measurements relative to these distributions is part of the model validation process and is described in detail in Section 5.5. The fluctuations encountered in a well while the groundwater system is at quasi steady-state are distinct from the range in hydraulic head predicted by the model, with the model range resulting from heterogeneity and uncertainty in the modeling process.

The periodic fluctuations relevant for defining quasi steady-state are due to earth tides and barometric pressure changes, with measurement precision also playing a role. In addition, there are sporadic impacts from seismic events. As defined in Table 5-1, a precision of ± a tenth of a foot (3 cm) will be achieved for the hydraulic head measurements. Water wells in Frenchman Flat at NTS experienced hydraulic head fluctuations on the order of 0.4 ft due to earth tides and 1 ft due to barometric effects (Bright et al., 2001). Barometric effects can be larger in response to especially strong storms. The range in periodic fluctuation will be reported to NDEP with the quasi steady-state mean value for each well, based on observations during the first year (assuming steady-state is obtained in a year). Future monitoring data outside of that range will trigger investigation of external causes (e.g., earthquakes) and trend analysis.

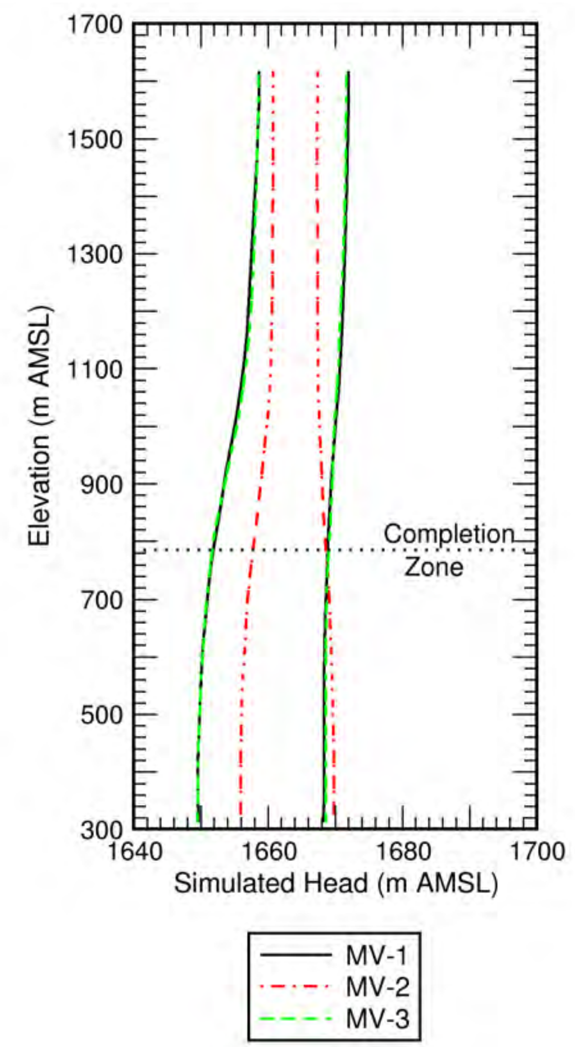


Figure 5-17
Hydraulic head range predicted by the flow model for the proposed well locations. (Note that predictions for MV-1 and MV-3 are virtually identical.) The mean plus and minus 2 standard deviations is shown (95% confidence internal). Head values represent hydraulic head for a 50 m^3 cell of the model. The elevation of the planned completion interval for the wells is also shown.

Because the monitoring network is based on the groundwater model, evaluating the network through time involves continued validation of the model. This post-closure validation will be provided by the hydraulic head measurements. Evolution of the monitoring network through time is expected in terms of the analytical suite. Once baseline values for carbon-14 and iodine-129 are established, analysis of these nuclides may be deferred for several decades. In later time, tritium with its short half-life, will cease to be a useful target and monitoring will shift to the longer lived nuclides of carbon-14 and iodine-129. Significant changes to the monitoring system will be presented for NDEP concurrence.

5.3 Waste Management

Activities that may generate investigation-derived waste (IDW) include the drilling and construction of new wells, sampling and monitoring of new and existing wells, well development, geophysical logging, and hydrologic/aquifer testing. Management of IDW will be based on regulatory requirements, field observations, process knowledge, and the results of laboratory analysis of CNTA investigation samples. Sanitary, hazardous, radioactive, and/or mixed waste, if generated, will be managed and disposed of according to DOE Orders, U.S. Department of Transportation regulations, *Resource Conservation and Recovery Act* (RCRA) regulations, applicable state regulations, and agreements and permits between the DOE and NDEP. Applicable waste management regulations and requirements are listed in Table 5-3.

Table 5-3
Waste Management Regulations and Requirements

Waste Type	Federal Regulation	Additional Requirements
Solid (nonhazardous) NTS Landfill Permit SW13.097.04[c] NTS Landfill Permit SW13.097.03[d] Tonopah Landfill for sanitary waste.	NA	NRS 444.440 – 444.645[a] NAC 444.570 – 444.7499[b]
Hazardous	RCRA[e]	NRS 459.400 – 459.600[a] NAC 444.850 – 444.8746[b] POC[f]
Low-Level Radioactive	NA	DOE Orders and NTSWAC[g]
Mixed	RCRA[e]	NTSWAC[g] POC[f]
Hydrocarbon	NA	NAC 445A.2272(b)[b]

[a] *Nevada Revised Statutes* (NRS, 1998a, b, c, d)
[b] *Nevada Administrative Code* (NAC, 2002a, b, c, d, e)
[c] *Nevada Test Site, Area 23, Nevada Division of Environmental Protection* (NDEP, 1997a)
[d] *Nevada Test Site, U10c Crater Located in Area 9, Nevada Division of Environmental Protection* (NDEP, 2001)
[e] *Resource Conservation and Recovery Act* (40 CFR 260-282) (CFR, 2003a)
[f] *Performance Objective for the Certification of Nonradioactive Hazardous Waste* (BN, 1995)
[g] *Nevada Test Site Waste Acceptance Criteria* (NTSWAC), Revision 5 (DOE/NV, 2003b)

5.3.1 Waste Minimization

Corrective action investigation activities have been planned to minimize IDW generation. All IDW will be segregated to the greatest extent possible. Use of hazardous materials will be minimized to limit unnecessary generation of hazardous and/or mixed wastes. Decontamination activities will be planned and executed to minimize the volume of rinsate.

5.3.2 Potential Waste Streams

Depending on the contaminants of potential concern (COPC), the types of IDW that may be generated include low-level radioactive waste (LLW), mixed wastes (LLW and hazardous waste), hydrocarbon waste, hazardous waste, and sanitary waste. IDW typically generated during investigation activities may include one or more of the following:

- Environmental media (e.g., groundwater, drilling fluids and cuttings, soil)
- Decontamination rinsate
- Development and sample purge water
- Personal Protective Equipment (PPE) and disposable sampling equipment (e.g., plastic, paper, sample containers, aluminum foil, spoons, bowls)
- Field-screening waste (e.g., groundwater, rinsate, spent solvent, disposable sampling equipment, and PPE contaminated by field-screening activities)

All waste from CNTA investigative areas will be evaluated against radiological standards as no RCRA constituents have been identified. However, should hazardous waste be generated from field sample kits, fuel spills, or waste brought onto the site, it will be managed according to RCRA, NDEP, and internal procedures. Each waste stream generated will be segregated to the greatest extent possible. Waste will be traceable to its source and to associated media samples.

5.3.3 Fluid Management

Fluids will be managed according to a CNTA Fluid Management Plan (FMP) that is approved by NDEP. Fluids found to meet fluid management criteria (i.e., less than or equal to five times the SDWA MCLs) may be released to the ground surface. Fluids that do not meet fluid management criteria will be managed according to applicable regulatory requirements and DOE Orders. If fluid is encountered that contains radionuclides approaching established health and safety or air quality limits (such as those listed in the National Emissions Standards for Hazardous Air Pollutants), drilling will stop until a management strategy is developed.

5.3.4 Personal Protective Equipment/Equipment

Disposable sampling equipment, PPE, and rinsate are considered potentially contaminated waste only by virtue of contact with potentially contaminated media (e.g., drill cuttings) or potentially contaminated water. PPE, disposable sampling equipment, and debris will be visually inspected for gross contamination (e.g., clumps of soil/sludge) and will be segregated as it is generated. Grossly contaminated PPE/equipment that comes in contact with hazardous waste, should any be encountered, will be managed as potentially "characteristic" hazardous waste. This segregated waste will either (1) be assigned the characterization of the contaminated material that was sampled, (2) be sampled directly, or (3) undergo further evaluation using the contaminated media sample results to determine how much contaminated media would need to be present in the waste to exceed regulatory levels. Waste that is determined to be hazardous will be entered into an approved waste management system (i.e., any appropriate facility used for the storage, treatment, or disposal of hazardous IDW generated during FFACO site investigations) where it will be managed and disposed of according to the requirements of RCRA or subject to agreements between NNSA/NSO and NDEP. The PPE/equipment that is not visibly stained, discolored, or grossly contaminated will be managed as it is generated as nonhazardous waste and disposed of as sanitary or LLW depending on the concentration of radioactive contamination, if present.

5.3.5 Rinsate

Decontamination activities will be performed according to approved contractor procedures specified in the contractor field instructions and as appropriate for the COPCs at CNTA. Decontamination rinsate will initially be evaluated using analytical results for samples associated with the rinsate (i.e., soil sample results from borehole or sampling activities associated with the generation of rinsate). Decontamination rinsate at this site will not be considered hazardous waste unless there is evidence that it displays a RCRA characteristic. Evidence may include such things as hazardous constituents in associated samples, the presence of a visible sheen, pH, or association with equipment/materials used to respond to a release/spill of a hazardous waste/substance. The regulatory status of the rinsate may also be determined through direct sampling. If determined to be hazardous, the rinsate will be entered into an approved waste management system where it will be managed and disposed of according to the requirements of RCRA or subject to agreements between NNSA/NSO and NDEP.

5.3.6 Soil

This waste stream consists of cuttings produced during drilling. This waste stream is considered to have the same COPCs as the material remaining in the ground. Regardless of the COPCs at the site (i.e., listed or not listed), the preferred method for managing this waste stream is by berming and covering the material next to the excavation pending contouring and/or revegetation, or by placement in a container(s). If containerized soil is determined to be hazardous, it will be managed and disposed of according to the requirements of RCRA or subject to agreements between NNSA/NSO and NDEP.

5.3.7 Investigation-Derived Waste Management

Process knowledge indicates that the drilling locations within the CNTA investigative area may (but are not expected to) be contaminated with radioactive constituents. To allow for the segregation of radioactive and “nonradioactive” waste and materials, radiological swipe and/or direct surveys may be conducted on reusable sampling equipment, PPE, and disposable sampling equipment waste streams exiting from within the controlled area. Removable contamination limits, as defined in Table 4-2 of the current *NV/YMP RadCon Manual* (DOE/NV, 2000a), shall be used to determine if such materials may be declared “nonradioactive.” Management requirements for sanitary, low-level, hazardous, or mixed wastes are discussed further in the following sections.

5.3.7.1 Sanitary Waste

Sanitary waste will be packaged in plastic bags or an appropriate receptacle and will be transported to a solid waste management unit. The IDW generated within a radioactive controlled area will be swiped and/or surveyed, as appropriate to determine if the removable contamination is under the limits defined in Table 4-2 of the current *NV/YMP RadCon Manua*l (DOE/NV, 2000a). IDW will be characterized as radioactive or nonradioactive based on these results.

5.3.7.2 Hydrocarbons

The action level for soil contaminated with hydrocarbons is 100 milligrams per kilogram (mg/kg) in the State of Nevada, as specified in *Nevada Administrative Code* 445A.2272 (NAC, 2002). Soils and associated IDW with hydrocarbon levels above 100 mg/kg, provided other regulated constituents are below regulatory limits, shall be managed as hydrocarbon waste and disposed of in accordance with all applicable regulations.

5.3.7.3 Hazardous Waste

Hazardous waste accumulation areas (HWAAs) and/or satellite accumulation areas (SAAs) will be established to accumulate waste that may be hazardous. The HWAAs will be properly controlled for access and will be equipped with spill kits and appropriate spill containment. All containers in HWAAs will be managed consistent with the requirements of 40 CFR 265 Subpart I (CFR, 2003c). A "Hazardous Waste Pending Analysis" marking will be placed on the waste containers until waste characterization is complete. Once the waste is characterized, containers of waste determined to be hazardous will be clearly marked or labeled as "Hazardous Waste." The HWAAs will be inspected weekly and will be covered under a site-specific emergency response plan until the waste is determined to be nonhazardous or all containers of hazardous waste have been removed from the accumulation area. The SAAs, if established, will be managed in accordance with 40 CFR 262.34(c) (CFR, 2003b). The SAAs may be employed to temporarily accumulate waste associated with field-screening methods (e.g., field test kits]) or for IDW pending characterization. These waste management methods will be appropriate for the amount of waste being accumulated.

5.3.7.4 Low-Level Waste

Investigation-derived waste may be characterized incorporating the use of process knowledge, analytical results of direct or associated samples, visual examination, radiological surveys, and swipe results. Radiological swipe surveys and/or direct scan surveys may be conducted on reusable sampling equipment and the PPE and disposable sampling equipment waste streams exiting a radiologically controlled area. This allows for the immediate segregation of radioactive waste from waste that may be unrestricted regarding radiological release. Removable contamination limits, as defined in Table 4-2 of the current version of the *NV/YMP RadCon Manual* (DOE/NV, 2000a), may be used to determine if such waste may be declared unrestricted regarding radiological release versus being declared radioactive waste. Direct sampling of the waste may be conducted to help determine if a particular waste unit (e.g., drum of soil) contains LLW, as necessary. Waste that is determined to be below the values of the RadCon Manual, Table 4-2, by either direct radiological survey/swipe results or through process knowledge will not be managed as potential radioactive waste, but will be managed in accordance with the appropriate section of the site-specific documents. Waste in excess of *NV/YMP RadCon Manual*, Table 4-2 values (DOE/NV, 2000a), will be managed as a potential radioactive waste. Suspected LLW will be managed in accordance with the contractor-specific waste certification program, contractor-specific procedures, and the Nevada Test Site Waste Acceptance Criteria (NTSWAC) (DOE/NV, 2003b). The IDW will be staged at a designated Radiological Controlled Area or Radioactive Materials Area pending certification and disposal under NTSWAC requirements (DOE/NV, 2003b). Waste drums will be labeled "Radioactive Material Pending Analysis."

5.3.7.5 Mixed Wastes

Mixed waste, if generated, shall be managed in accordance with RCRA (CFR, 2003a) and State of Nevada requirements. These regulations, as well as DOE requirements for radioactive waste, are interpreted as follows. Where there is a conflict in regulations or requirements, the most stringent shall apply. For example, weekly inspections per RCRA regulations will be applied to mixed waste even although it is not required for radioactive waste. In general, mixed waste shall be managed in the same manner as hazardous waste, with additional mandatory radioactive waste management program requirements. Mixed waste shall be transported via an approved waste transporter to the NTS transuranic waste storage pad for storage pending treatment or disposal. Mixed waste with hazardous waste constituents below land disposal restrictions may be disposed of at the NTS Area 5 Radioactive Waste Management Site, if the waste meets the NTSWAC requirements (DOE, 2003b). Mixed waste not meeting land disposal restrictions will require development of a treatment plan under the requirements of the Mutual Consent Agreement between DOE and the State of Nevada (NDEP, 1995).

5.3.7.6 PCB and Radioactive PCB Wastes

Polychlorinated biphenyls (PCBs) are governed by the *Toxic Substances Control Act* and its implementing regulations in 40 CFR 761 (CFR, 2003d). No PCB contaminated waste is anticipated during this project. PCB contamination may be found as a sole contaminant, or in combination with any of the types of waste discussed in this section. For example, PCBs may be a co-contaminant in soil that contains a RCRA “characteristic” chemical constituent such as lead, resulting in a PCB/hazardous waste. PCBs may also be a co-contaminant in radioactive wastes (PCB/radioactive waste), in sanitary or hydrocarbon waste (PCB waste), in RCRA “characteristic” waste (PCB/hazardous waste), or even in mixed waste (PCB/radioactive/hazardous waste). The IDW will initially be evaluated using analytical results for media samples from the investigation. If any type of PCB waste is generated, it will be managed according to 40 CFR 761, or subject to agreements between NNSA/NSO and NDEP.

5.4 Required Authorizations, Notifications, and Permits

Several State of Nevada and Federal permits and studies must be completed before drilling begins at the CNTA. The surface activities in different parts of the CNTA are administered variously by the BLM and the U.S. Forest Service (USFS), both of which are required to administer the *Endangered Species Act* and the *National Antiquities Act*. These acts, and NEPA, require that a biological surface survey and an archeological surface survey respectively be completed before any surface disturbing activities, such as the construction of the access roads, drill pads, and containment ponds that will be necessary for installing monitoring wells. The State of Nevada Division of Water Resources requires a “Request for Waiver to Drill Observation or Monitoring Well” to be completed before drilling any water quality monitoring well. The Water Resources Board also requires an “Affidavit of Intent to Abandon a Monitoring Well” to be completed and submitted with each waiver for a monitoring well. Any well that is abandoned must be plugged and abandoned in accordance with Nevada Administrative Code (NAC) 534.4365 (NAC, 1998). If a public water source, such as a well located on or near the CNTA, is intended to be used for either drilling purposes or for dust abatement measures, then a temporary water use application form must also be completed. Nye County does not require any specific permits to be completed in order to drill and complete groundwater quality monitoring wells located within the county.

5.5 Proof-of-Concept

The recommended corrective action for the Faultless site is based in large part on the results of numerical models of groundwater flow and radionuclide transport. Many uncertainties are inherent in these models, and most stem from the inability to precisely know the conditions everywhere in the subsurface. In response to these uncertainties, the FFACO prescribes a validation and proof-of-concept period for groundwater models used in closing underground nuclear test sites.

The description of the proof-of-concept process is given in Appendix VI of the FFACO in the process flow diagram dictionary for the UGTA CAUs. It is as follows:

> A 5-year proof-of-concept monitoring network will be developed in accordance with the CAP. This phase of monitoring will use groundwater wells in a monitoring network to determine if the monitoring network design will provide adequate CAU surveillance. Measurements of field parameters will be used to demonstrate that the model is capable of making reasonable predictions that fall within an acceptable level of confidence.
>
> Model validation, to ensure fidelity of the model to the physical system, will use a ten-step protocol to demonstrate that a model has been developed which meets user needs. These ten steps 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 analysis, 7) model verification, 8) predictive simulations, 9) presentation of model results, and 10) postaudit.
>
> The validation postaudit step tests whether the model can predict future system behavior. The five-year proof-of-concept is the model postaudit to establish, within a longer time frame, that the model is capable of producing meaningful results with an acceptable degree of uncertainty. Model validation is substantiated once all ten steps are shown to have been acceptably completed.

In their acceptance of the CAU model, NDEP expressed concern regarding the degree of verification and validation of the model. Specifically, NDEP states "*Though the DDA constitutes a partial verification of the flow and transport model, NNSA/NV has not presented a model that has been fully verified by an independent set of data. Based on the information presented to date, NDEP will concur with the model conditioned on a commitment for future model verification.*" (Liebendorfer, 2001). Two conditions are specified in the letter:

> NNSA/NV must create a validation plan, which addresses conditions downgradient of the Faultless cavity, north of ground zero. The validation plan may be developed in conjunction

> with the monitoring plan. If the CADD concludes that monitoring is the appropriate course of action, dual-purpose monitoring wells (model validation and long-term monitoring) should be thoroughly evaluated.
>
> The validation plan must include clearly defined trigger mechanisms for revisiting the model; such as the presence of tritium above background levels in downgradient areas or a significant thickness of the high hydraulic conductivity densely welded tuff at shot cavity depths. Key elements of the validation plan, including the particulars of trigger mechanisms, should be discussed with NDEP as development of the plan progresses (Liebendorfer, 2001).

Based on these requirements, the proof-of-concept phase for Faultless focuses on model validation, which will also serve to evaluate the basis of the monitoring network and demonstrate that it provides adequate surveillance of the CAU. The NDEP requirements for model validation will be met during the proof-of-concept phase. This is consistent with the post-audit specified in the FFACO, which is to establish, within a longer time frame, that the model is capable of producing meaningful results with an acceptable degree of uncertainty. Given the steady-state nature of the flow model and the extremely limited transport predicted for the site, the model's ability to predict future system behavior must be tested based on its ability to represent the subsurface. The requirement to present mechanisms for revisiting the model is also consistent with the validation strategy presented in the FFACO, which is based on the iterative approach to developing and improving models recommended by Anderson and Woesner (1992).

5.5.1 Strategy

The proposed approach to validate the CNTA model relies on using both multi-response data and diverse statistical tests to evaluate model performance. The approach follows a systematic step-by-step adaptive strategy and is aimed at building confidence in the model predictions (Hassan, 2003 and 2004a). Even the simplest deterministic subsurface model is very difficult to evaluate (Hassan, 2004b). The proposed plan accounts for the stochastic nature of the CNTA model and aims to reduce the uncertainty inherent in the large number of realizations considered in the Monte Carlo analysis (Hassan, 2004a).

The focus of the proposed validation methodology is centered around the following three main themes: (1) testing how predictions of numerical groundwater flow and transport models of CNTA and the underlying conceptual models and assumptions are robust and consistent with regulatory purposes, and (2) reevaluating and refining model predictions and reducing the uncertainty level based on data collected in the proposed field activities for model validation.

5.5.1.1 Proposed Step-by-Step Procedure for CNTA Model Validation

Figure 5-18 describes the steps of the process to validate the model predictions. There is one clearly defined point in the validation process where a significant revision of the model can be triggered. This trigger point occurs at Step 7, where the results may be determined to not meet regulatory objectives. All of the validation steps are described below.

Step 1: Identify the data needed for validation, the number and location of the wells, and the type of experiments needed. Well locations can be determined based on the existing model and should favor locations likely to encounter fast migration pathways, such as fractured tuffs. The monitoring strategy (see monitoring section) was implemented to help select these locations with the result that one well should be placed due north of the cavity. Additional wells should be located around the cavity in such a way to enable verification of lateral and vertical head gradients and flow directions in the model. Other factors such as safety issues associated with radioactive contamination and the cost of drilling and collecting data have to be considered. Sequencing of data collection is also important and the ability to adjust the plan as information is gathered.

Step 2: Carry out the fieldwork to install the wells and obtain the largest amount of data possible from the wells. The data should include geophysical logging, resistivity logs, head measurements, concentrations of contaminants in groundwater (e.g., checking for tritium), and other information that can be used to test the model structure, input, or output (e.g., temperature logs, conductivity measurements).

Step 3: Evaluate the model calibration accuracy for each individual realization using the calibration data only (pre-validation data; the data used to construct the original model). This has already been performed using the generalized likelihood uncertainty estimator (GLUE) (Freer and Beven, 1996; Franks and Beven, 1997; Pohlmann et al., 2004), as reported in Pohll et al. (2003). Other tools such as linear regression analysis and hypothesis testing might be used to provide additional objective measures to evaluate the relative strength of each realization in terms of reproducing the original field calibration data.

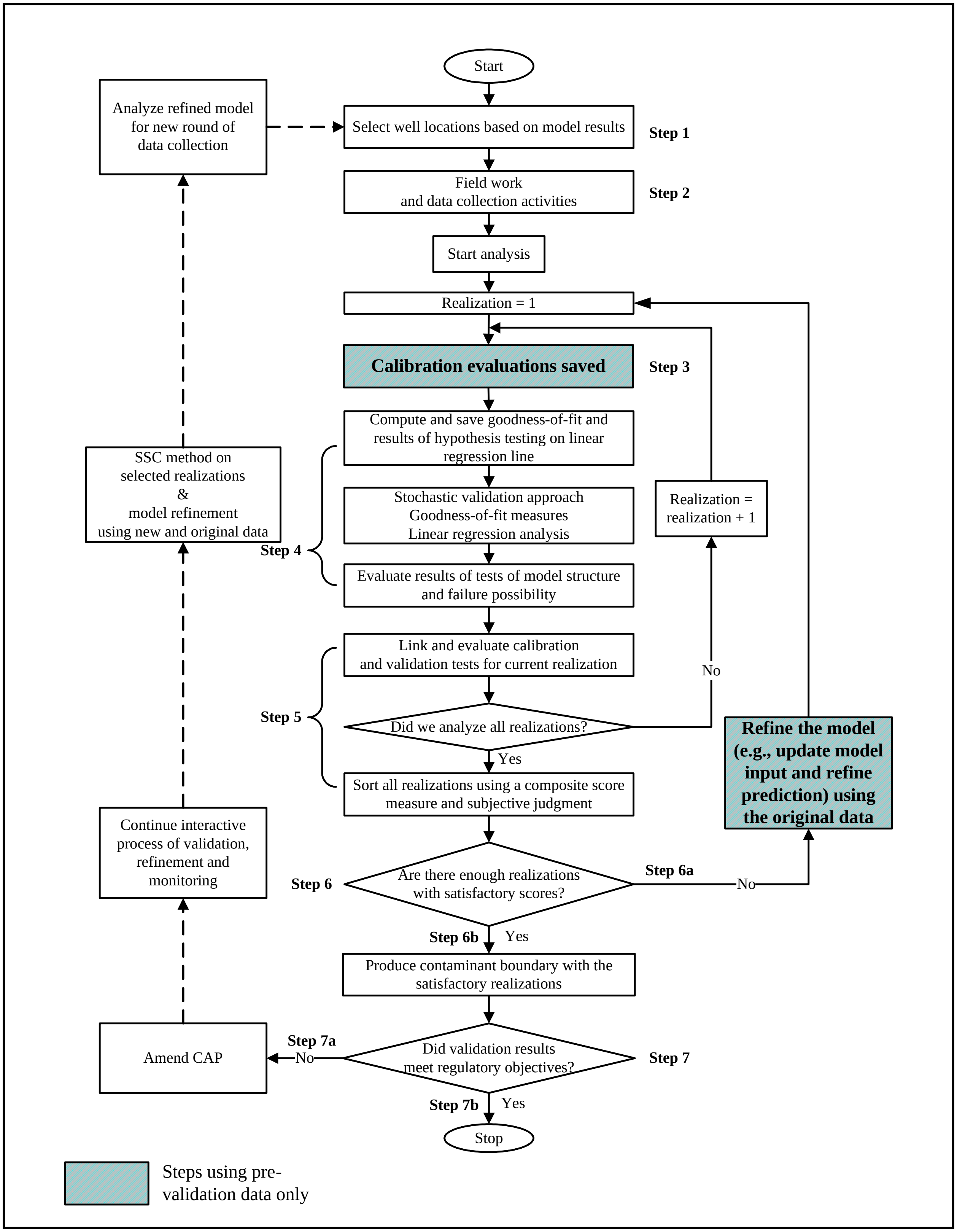


Figure 5-18
Proposed Validation Approach. The Dashed Pathway from Step 7a Presumes the Original Strategy is Deemed Sound

Step 4: Perform the different validation tests that will help evaluate the different submodels and components of the model. The stochastic validation approach proposed by Luis and McLaughlin (1992) can be adapted and used to test the flow model output (heads) under saturated conditions. Other objective tests (e.g., goodness-of-fit tests) using the validation data (previously it was calibration data) can be used for the heads to complement this stochastic approach that is based on hypothesis testing. Some data will be used to check the occurrence or lack thereof of failure scenarios (e.g., whether tritium exists much farther from the cavity than is predicted by any realization of the stochastic CNTA model). The philosophy here is to test each individual realization with as many diverse tests (in terms of the statistical nature of the test and the tested aspect of the model) as possible and have a quantitative measure of the adequacy of each realization in capturing the main features of the modeled system.

Step 5: Link the results of the calibration accuracy evaluations (Step 3) and the validation tests (Step 4) for all realizations and sort the realizations in terms of their adequacy and closeness to the field data. A subjective element may be invoked in this sorting based on expert judgments and hydrogeologic understanding. The objective here is to filter out the realizations that show a major deviation or inadequacy in many of the tested aspects and focus on those that “passed” the majority of the tests and evaluations. By doing so, the range of output uncertainty is reduced and the subsequent effort can be focused on the most representative realizations/scenarios.

Step 6: Step 5 results will determine the forward path and guide the decision as to whether there is a sufficient number of realizations that attained a satisfactory high score (thus building confidence in the original model) and are considered sufficient for further analysis or whether this number of realizations is not sufficient in comparison to the realizations with low scores indicating that the original model needs adjustment.

> **6a.** If the number of realizations with low scores is very large compared to the total number of model realizations, it could be an indication that the model has a major deficiency or conceptual problem or it could be that the input is not correct. In the latter case, it may be that the model is conceptually good, but the input parameter distributions may be skewed one way or another. Generating more realizations and keeping those that fit the validation criteria can shift the distribution to the proper position. This can be done using the existing model without conditioning or using any of the new validation data. If the model has a major deficiency or conceptual problem, generating additional realizations will not correct it and continued failure per the validation criteria will be obvious.

6b. If the number of realizations with high scores is found sufficient, this indicates that the model does not have any major deficiencies or conceptual problems. This determination will be made according to a number of metrics as detailed in the validation criteria section. These metrics are tested and supported by statistical hypothesis testing and provide good evaluation criteria for the model realizations. Based on the realizations retained in the analysis and deemed acceptable, a contaminant boundary will be calculated and compared to the original contaminant boundary. This comparison will be presented for reference by decision makers in Step 7.

Step 7: Once the model performance has been evaluated per the acceptance criteria, the model sponsors and regulators have to answer the last question in Figure 5-18. This question will determine whether the validation results meet the regulatory objectives or not. This is the trigger point that could lead to significant revision of the original model.

7a. If the answer to the question posed is no, then the left-hand side path in Figure 5-18 begins with an evaluation of the investigation strategy, consistent with the process flow diagram in Appendix VI of the FFACO. If the original strategy is deemed sound, a new iteration of model development will begin, using the data originally collected for validation, and steps 1 to 6 will be eventually repeated. If the original strategy is deemed unsound, a new strategy will be developed. Whatever strategy is selected, the CADD/CAP will be amended before execution.

7b. If the answer to the question posed is yes, validation is deemed sufficient and the model is considered adequate or robust.

Numerical groundwater models, and in particular stochastic models, are very complex and modifying or changing any aspect of the model may produce unanticipated consequences in a different aspect of the model. To get the best outcome of the validation process, one needs to both consider the different details separately and take the broader view of the entire model while working step-by-step through the different decisions and trade-offs.

It can be seen and expected that the process of validating a site-specific groundwater model is not an easy one. Throughout the structured process described above, there may be a desire to confirm that the work is on the right track. The way to this confirmation is the cumulative knowledge gained from the different stages of the validation process. That is, a set of independent tests and evaluations will provide knowledge about the model performance, and the test results will provide some incremental, but additive, pieces of information that will be of paramount importance. While there are no guarantees of success (attaining a conclusive outcome about model performance), the combined presence of these different results and evaluations sharply improves the odds that one can make a good decision about the model performance.

5.5.1.2 Implementation of Steps 1 and 2 in the Procedure for CNTA Model Validation

The aspects of the Faultless flow and transport models selected for validation constitute those that were key in development of an effective monitoring network and in development of the contaminant boundary. The recommended validation targets are:

1. Hydraulic head
2. Presence or absence of welded tuff near emplacement location
3. Contaminant transport predictions (confirming absence of transport above MCLs)
4. Hydraulic conductivity range

These are presented in priority order. Comparing hydraulic head values to confirm flow directions is vital to the effectiveness of groundwater monitoring. Determining whether or not the welded tuff exists near the emplacement horizon is also important because only those simulations with welded tuff resulted in any significant transport. Confirming the transport predictions (essentially ruling out fast pathways) is desirable, despite the low probability of detectable transport predicted by the model. Comparing the range of hydraulic conductivity in new wells with that used in the model will confirm a major parameter leading to the slow predicted velocities.

The corresponding approach proposed for each target is summarized below.

1. Hydraulic head: Measure hydraulic head in units distributed both laterally and vertically around the test. In particular, the confirmation of downward-directed vertical gradients at the test horizon is critical. These measurements will be performed in the well bore and in piezometers installed in the annular space.

2. Welded tuff: Log (including geophysical logs) the lithologic section in boreholes distributed around the emplacement hole.

3. Contaminant transport: Collect and analyze groundwater samples for Faultless-related contaminants, principally tritium. These samples will be collected from the well bore following purging. General groundwater characteristics will also be determined to confirm

conditions used in the transport model. These will include major ions, silica, pH, EC, temperature, and stable isotopes of oxygen and hydrogen.

4. Hydraulic conductivity: Perform aquifer tests in the wells. If hydraulic conditions allow it, tests may also be attempted in the piezometer tubes.

   Each well should be able to provide information on all the targets.

The monitoring analysis (Section 5.2.0.2) determined that an optimum monitoring-well placement can be realized by a single well due to the small cross-sectional size of the plume and the limited distribution of the center of mass location in multiple realizations. Three monitoring wells will be drilled to provide data for model validation and to be part of the long-term monitoring network for the site, consistent with NDEP's statement "If the Corrective Action Decision Document concludes that monitoring is the appropriate course of action, dual-purpose monitoring wells (model validation and long-term monitoring) should be thoroughly evaluated" (Liebendorfer, 2000). Only one well, however, is expected to be in the path of any potential radionuclide migration away from the Faultless cavity. Preliminary well locations are shown on Figure 5-16. The first well to be drilled (MV-1) will be located northeast of Faultless ground zero and have a primary validation objective. The second well, MV-2, will be southwest of ground zero and also have a primary validation objective. The locations of MV-1 and MV-2 were selected to obtain data from areas around the nuclear test where no wells are currently located, and to distribute the head data for gradient determination. The well location based on the monitoring analysis is located due north of ground zero and is designated MV-3. This well will also provide validation information, although its location within the down-dropped block and the model's basis on hydrogeologic conditions undisturbed by the nuclear test may complicate the validation use. Details of the well completions are described in Section 5.2.0.2.3 and presented in Appendix A.

5.5.2 Evaluation Criteria

According to the validation plan shown in Figure 5-18, the first set of analyses using the field data collected for validation purposes will yield results that will be evaluated to determine the path forward. The first "if" statement in the validation approach pertains to whether a sufficient number of realizations attained satisfactory scores on how they represent the field data used for calibration (old) and used for validation (new). The determination of whether a sufficient number exists will be based on five criteria with the decision made in a hierarchical manner as will be discussed later. The five criteria are summarized below.

1. Individual realization scores (S_j, j = 1, …, number of realizations) obtained based on how well each realization fits the validation data will be evaluated. The first criterion then becomes the percentage of these scores, P_1, that exceeds a certain reference value.

2. The number of validation targets where field data fits within the inner 95 percent of the probability density function (pdf) of these targets as used in the model (P_2) is the second criterion.

3. The results of hypothesis testing to be conducted using the stochastic perturbation approach of Luis and McLaughlin (1992) that decomposes the differences between measured and observed heads, identifies those attributed to the model, and statistically evaluates the hypothesis that those differences are negligible (i.e., the model is valid) (P_3). This approach is described in detail in Appendix B.

4. The results of linear regression analysis and other hypothesis testing (e.g., testing error variance based on calibration data and based on validation data) that could be feasible (depending on the size of data set obtained in the field), P_4.

5. The results of the correlation analysis where the log-conductivity variance is plotted against the head variance for the targeted locations and the resulting plot for the model is compared against the field validation data (P_5).

The hierarchical approach to making the above determination is described by a decision tree. This decision tree for the acceptance of the realizations and for passing the first decision point on the validation approach is shown in Figure 5-19. The process starts with evaluating S_j and determining whether the percentage of realizations with scores above the reference value, P_1, is more than 40 percent, between 30 and 40 percent, or less than 30 percent. If the number is more than 40 percent, it is deemed sufficient. If it is between 30 and 40 percent or less than 30 percent, then the second criterion, P_2, is used as shown in Figure 5-19. The second criterion represents the number of validation targets where the field data point lies within the inner 95 percent of the pdf for that target as used in (input) or produced by the CNTA model. Then if P_1 is between 30 and 40 percent and P_2 is between 40 and 50 percent or if P_1 is less than 30 percent but P_2 is greater than 50 percent, the number of realizations is deemed sufficient. If P_1 is less than 30 percent and P_2 is less than 40 percent, then the remaining three measures, P_3, P_4, and P_5, are used to determine whether the model needs revision or whether more realizations can be generated to replace some of the current realizations. In this

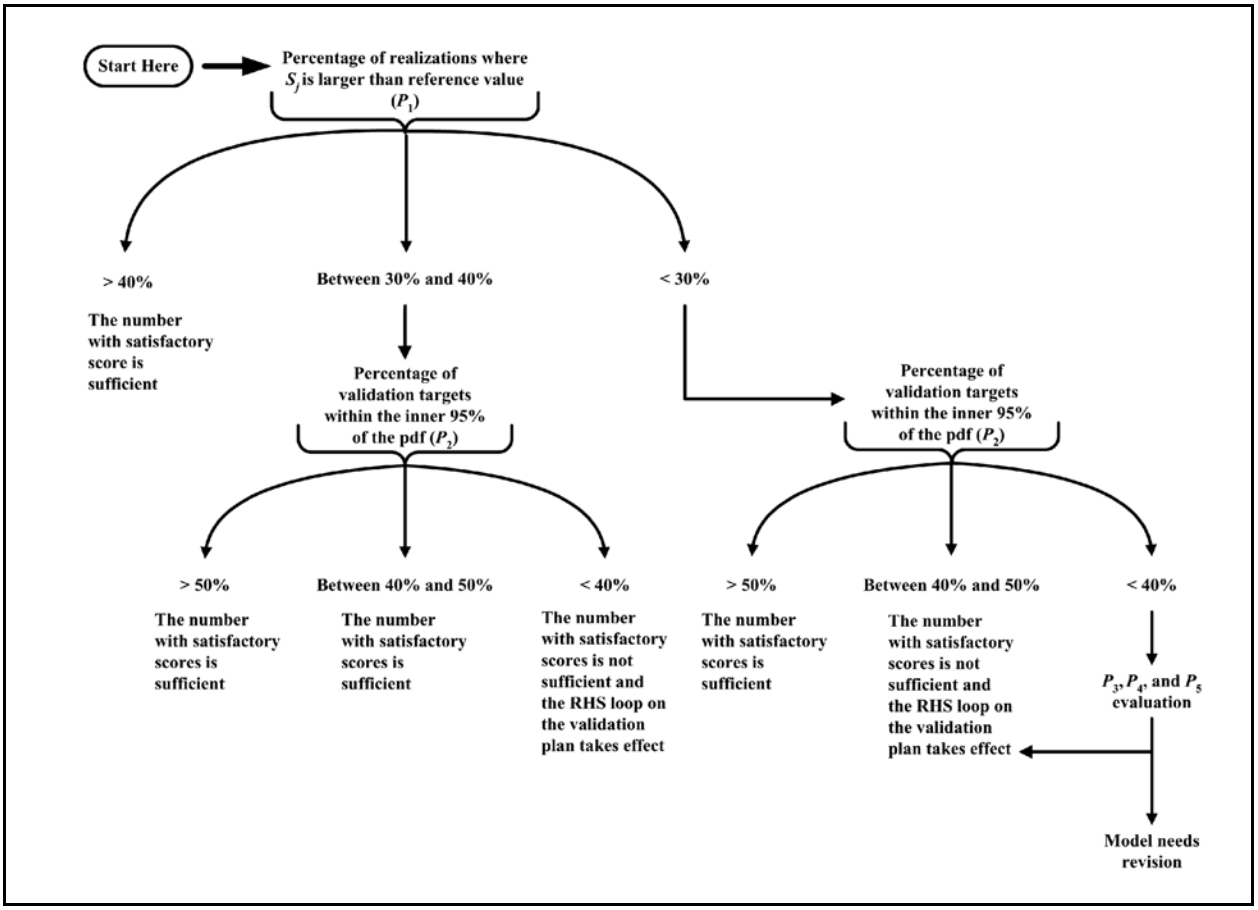


Figure 5-19
A Decision Tree Chart Showing How the First Decision (Step 6) in the Validation Plan Will be Made and the Criteria for Determining the Sufficiency of the Number of Acceptable Realizations

latter case, it may be that the model is conceptually good but the input parameter distribution is skewed one way or another and by generating more realizations and keeping the ones that fit the above criteria, the distribution attains the proper position. This can be done using the existing model without conditioning or using any of the new validation data (i.e., no additional calibration). The rationale for selecting the above thresholds (30%-40% for P_1 and 40%-50% for P_2) is described through an example and as these metrics are evaluated with statistical hypothesis testing in Appendix B. The appendix contains specific details and examples of the application of the validation criteria to the Faultless flow and transport model.

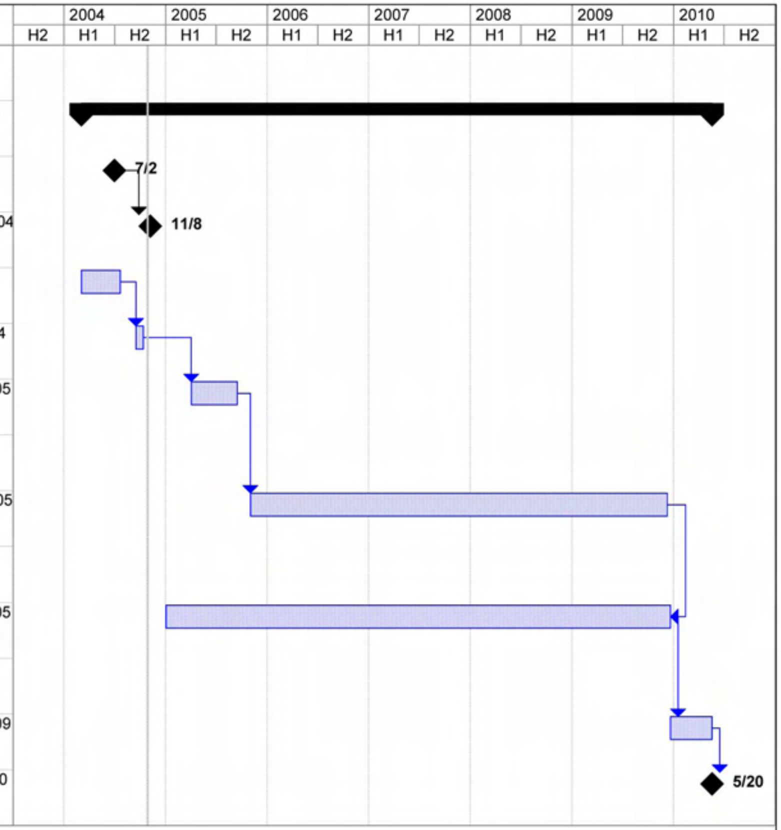
5.5.3 Reporting

Several milestones will occur during the proof-of-concept process. The first major milestone will be the completion of well installation and initial data collection. The results of the drilling and well completion will be communicated to NDEP through a well completion report. Validation data collection will also continue with measurement of water levels and tritium concentrations as part of the monitoring network. This ongoing data collection will be transmitted through annual monitoring program reports. The validation analysis will begin upon initial completion of the wells, with its exact course through the sequence shown in Figure 5-18 dependent on the match between the data and the model. The results of the validation analysis will be communicated to NDEP at Step 7 in Figure 5-18, as a major decision point in the process. It is anticipated that validation of the model can be achieved within the first two years of the proof-of-concept period.

6.0 Schedule

Figure 6-1 shows the schedule for the CNTA corrective action, through the proof-of -concept period and Closure Report.

ID	Task Name	Duration	Start
1			
2	**CNTA Corrective Action**	**1620 days**	**Fri 3/5/2004**
3	CNTA CADD/CAP to NDEP	0 days	Fri 7/2/2004
4	Final CNTA CADD/CAP to NDEP	0 days	Mon 11/8/2004
5	Monitoring Wells Prefield Planning	100 days	Fri 3/5/2004
6	Surface Prep	19 days	Fri 9/17/2004
7	Monitor Wells Field Work	120 days	Mon 4/4/2005
8			
9	Annual Monitoring Data Evaluation	1071 days	Thu 11/3/2005
10			
11	Proof of Concept Analysis	1296 days	Mon 1/3/2005
12			
13	Prepare Closure Document	108 days	Tue 12/22/2009
14	Issue Closure Report	0 days	Thu 5/20/2010



Project: CADDrilling05
Date: Tue 10/26/2004

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

Figure 6-1
Schedule

7.0 Post-Closure

Activities necessary to ensure protection of human health and the environment following CNTA subsurface closure are collectively known as long-term stewardship activities. At CNTA, stewardship will be designed to prevent exposure to the contamination left in place in the Faultless test cavity. Stewardship activities will include record keeping, inspections, groundwater monitoring, and controls on subsurface access and resource extraction. DOE is committed to long-term stewardship of the Faultless site, as evidenced by baseline budget planning documents that outline 50 years of stewardship activities and the funding for those activities.

As prescribed in Appendix VI of the FFACO, the Closure Report will establish the long-term monitoring requirements for the CAU, develop technical and administrative contingency plans for actions to be taken if long-term monitoring results are not acceptable, and define future land-use restrictions. These requirements and plans will build upon the findings and experience of the proof-of-concept monitoring. Anticipated activities are briefly described below, with details to be submitted in the Closure Report.

7.1 Inspections and Monitoring

The purpose of inspections and monitoring is to protect human health and the environment from the radionuclide hazard left in place in the Faultless cavity. Activities anticipated are as follows:

- Groundwater monitoring, and accompanying well inspections
- Land and resource use monitoring and accompanying site inspections
- Records management

These activities are expected to continue in perpetuity, commensurate with the time span through which the Faultless cavity presents a hazard. Monitoring and inspection frequency may be decreased from the annual schedule conducted during proof-of-concept. Groundwater monitoring frequency is generally tied to transport velocities, and given the very slow velocities currently predicted for radionuclide transport from the Faultless cavity, the system is not expected to require frequent monitoring. The experience gained during the proof-of-concept will be used to determine the optimum frequency for maintaining adequate site knowledge and surveillance.

A key component of the long-term site stewardship will be institutional controls. Institutional controls can minimize the potential for human exposure and protect the integrity of the CNTA closure decision by limiting resource use and providing information to modify or guide human behavior at the site. An institutional control plan will be included in the Closure Report and will include the legal and practical limits of available tools, identification of the parties responsible for the necessary activities, and cost estimates for the stewardship activities.

The contaminant boundary presented as part of this CADD/CAP will be important in guiding the development of institutional controls for CNTA. However, the boundary is based upon ambient (non-stressed) groundwater conditions. Pumping for groundwater outside the contaminant boundary has the potential to alter the hydrologic conditions that in turn can alter contaminant migration behavior. Thus, there is a need to control certain types of groundwater development activities beyond the contaminant boundary. Resource management tools will be developed as part of the closure process so that responsible parties can make permit decisions based on the knowledge developed during the CADD and validation processes. These tools evaluate whether a proposed groundwater extraction activity is consistent with the site closure, is clearly inconsistent, or whether additional evaluation must be conducted to make a determination.

7.2 Maintenance of Monitoring System

The baseline shows maintenance and monitoring from 2010 through 2069. The wells will be inspected annually and repaired as necessary to perform monitoring. Long term monitoring requirements will be developed in the Long-Term Surveillance and Monitoring Plan following completion of the Closure Report. The budget is based on an average of one replacement well every 25 years.

7.3 Re-Evaluation of Model and Monitoring System

The monitoring network will continuously add to the state of knowledge about the groundwater system in the Faultless area. The new information will either support the closure decision, thus reducing the uncertainties associated with the decision, or indicate conditions that may call into question the ongoing validity of the closure decision. Essentially, the post-audit validation of the flow and transport model will continue as long as site data are collected. Data collection objectives shift from primarily model validation with attendant site monitoring during proof-of-concept, to primarily site monitoring with attendant model validation during long-term closure.

Assuming that indicator radionuclide concentrations and hydraulic head values are the primary analytes and parameters monitored, trigger mechanisms for re-evaluating the model and monitoring strategy for possible revision will be upward trends in radionuclide concentrations not predicted by the model, and significant deviations in hydraulic head outside the steady-state range upon which the model is based. Unanticipated radionuclide concentrations may indicate a failure of the model to accurately represent flow and transport processes. Hydraulic head variations may signal a shift in the hydraulic system away from the previous steady-state conditions. Either occurrence will trigger re-evaluation of the modeling predictions and revision if necessary. Changes in resource use in the region (e.g., groundwater development) may also trigger reevaluation of the closure conditions, even in advance of discernible impacts on hydraulic head, in order for management options to be considered in a proactive rather than reactive timeframe.

8.0 References

ASTM D 4750, "Standard Test Method for Determining the Liquid Levels in a Borehole or Monitoring Well (Observation Well)," ASTM International.

AEC, see U.S. Atomic Energy Commission

Anderson, M.P., and W.W. Woessner. 1992. *Applied Ground Water Modeling: Simulation of Flow and Advective Transport.* New York, NY: Academic Press.

BLM, see U.S. Bureau of Land Management.

Beven, K.J. and A.M. Binley. 1992. The Future of Distributed Models: Model Calibration and Uncertainty Prediction. In *Hydrological Processes*, 6:279-298.

Borg, I.R., R. Stone, H.B. Levy, and L.D. Rampspott. 1976. *Information Pertinent to the Migration of Radionuclides in Ground Water at the Nevada Test Site, Part I: Review and Analysis of Existing Information*, Report UCRL-52078. Livermore, CA: Lawrence Livermore National Laboratory.

Bright, D.J., S.A. Watkins, and B.A. Lisle. 2001. *Analysis of Water Levels in the Frenchman Flat Area, Nevada Test Site*, Report 00-4272, 43p. U.S. Geological Survey Water-Resources Investigations.

CFR, see *Code of Federal Regulations*

Chapman, J.B., and S.L. Hokett. 1991. *Evaluation of Groundwater Monitoring at Offsite Nuclear Test Areas*, DOE/NV/10845-07. Desert Research Institute, Water Resources Center Publication #45085, 82p.

Code of Federal Regulations. 2003a. Title 40 CFR Parts 260, "Hazardous Waste Regulations (260-282)." Washington, DC: U.S. Government Printing Office.

Code of Federal Regulations. 2003b. Title 40 CFR Part 262.34(c), "Accumulation Time." Washington, DC: U.S. Government Printing Office.

Code of Federal Regulations. 2003c. Title 40 CFR Part 265 Subpart I, "Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities." Washington, DC: U.S. Government Printing Office.

Code of Federal Regulations. 2003d. Title 40 CFR Part 761.61, "PCB Remediation Waste." Washington, DC: U.S. Government Printing Office.

Code of Federal Regulations. 2003e. Title 40 CFR Part 300.430, "Remedial Investigation/Feasibility Study and Selection of Remedy." Washington DC: U.S. Government Printing Office.

Cvetkovic, V. and G. Dagan. 1994. Transport of Kinetically Sorbing Solute by Steady Random Velocity in Heterogeneous Porous Formations. In *Journal of Fluid Mechanics*, 265:189-215.

Cvetkovic, V., J.O. Selroos, and H. Cheng. 1999. Transport of Reactive Tracers in Rock Fractures. In *Journal of Fluid Mechanics*, 378:335-356.

Davis, M.G. 1999. *Annual Water Sampling and Analysis Calendar Year 1999: Rulison, Rio Blanco, Faultless, Shoal, Gasbuggy, Gnome Test Site Areas*, EPA-402-R-90-012, 21p.

Deutsch, C.V. and A.G. Journel. 1998. *GSLIB Geostatistical Software Library and User's Guide, Second Edition*. Oxford University Press.

Dinwiddy, G.A., and J.L. Schroder. 1971. *Summary of Hydraulic Testing in and Chemical Analyses of Water Samples from Deep Exploratory Holes in Little Fish Lake, Monitor, Hot Creek, and Little Smoky Valleys, Nevada*. USGS-474-90. Denver, CO: U.S. Geological Survey.

DOE, see U.S. Department of Energy.

EPA, see U.S. Environmental Protection Agency.

FFACO, see *Federal Facility Agreement and Consent Order.*

Federal Facility Agreement and Consent Order. 1996 (as amended). Agreed to by the State of Nevada, the U.S. Department of Energy, and the U.S. Department of Defense.

Franks, S.W., and K.J. Beven. 1997. Bayesian Estimation of Uncertainty in Land Surface-Atmosphere Flux Predictions. In *Geophysical Research* 102, no. D20:23991-23999.

Freer, J. and K. Beven. 1996. Bayesian Estimation of Uncertainty in Runoff Prediction and the Value of Data: an Application of the GLUE Approach. In *Water Resources Research*, 32(7): 2161-2173.

Glasstone, S. and P.J. Dolan. 1977. *The Effects of Nuclear Weapons*, 3rd edition. U.S. Department of Defense and U.S Department of Energy, 653p.

Goishi, W., J.W. Meadows, N. Namboodiri, D.K. Smith, and J.F. Wild. 1995. *Radionuclide Inventory for U.S. Nuclear Tests Conducted Off the NTS and Hydronuclear and Safety Experiments Conducted on the NTS*, UCRL-ID-121901, Secret-Restricted Data. Livermore, CA: Lawrence Livermore National Laboratory.

Hassan, A.E. and M.M. Mohammed. 2003. On Using Particle Tracking Methods to Simulate Transport in Single-Continuum and Dual Continua Porous Media. In *Journal of Hydrology,* 275: 242-260.

Hassan, A.E. 2003. *Long-term Monitoring Plan for the Central Nevada Test Area*, Publication No. 45201, DOE/NV/13609-30, 56p. Prepared for the U.S. Department of Energy, Nevada Operations Office. Las Vegas, NV: Desert Research Institute, Division of Hydrologic Sciences.

Hassan, A.E. 2004a. A Methodology for Validating Numerical Groundwater Models. In *Ground Water*, 42(3): 347-362.

Hassan, A.E. 2004b. Validation of Numerical Ground Water Models Used to Guide Decision Making. In *Ground Water*, 42(2): 277-290.

Knuth, D.E. 1981. *The Art of Computer Programming Vol. 2: Seminumerical Methods* (Second Edition), Addison-Wesley, Reading, Mass.

Liebendorfer, P.J., Nevada Division of Environmental Protection. 2000. Letter to R.C. Wycoff (DOE/NV) entitled, “Evaluation of Groundwater Flow and Transport at the Faultless Underground Nuclear Test Area, Desert Research Institute, September 1999, Publication No. 45165, Corrective Action Unit 443, Central Nevada Test Area, Federal Facility Agreement and Consent Order,” dated 17 March. Carson, City, NV

Liebendorfer, P.J., Nevada Division of Environmental Protection. 2001. Letter to R.C. Wycoff (NNSA/NV) entitled, “Evaluation of the ‘Data Decision Analysis: Central Nevada Test Area,’ Corrective Action Unit 443, submitted by the National Nuclear Security Administration, March 7, 2001,” dated 24 July. Carson City, NV.

Liu, H.H., G.S. Bodvarsson, and L. Pan. 2000. Determination of Particle Transfer in Random Walk Particle Methods for Fractured Porous Media. In *Water Resources Research*, 36(3): 707-713.

Luis, S.J. and D. McLaughlin. 1992. A Stochastic Approach to Model Validation. In *Advances in Water Resources,* 15: 15-32.

Lyles, B.F., G. Pohll, D. Sloop, and C. Papelis. 1998. *Evaluation of Potential Hydrocarbon Transport at the UC-4 Emplacement Hole, Central Nevada Test Area*, DOE/NV/11508-43. Las Vegas, NV: Desert Research Institute, Water Resources Center.

Marsaglia, G.A. 1985. A Current View of Random Number Generators, *in* L. Balliard, ed., *Computational Science and Statistics: the Interface*. Elsevier, Amsterdam.

Massmann, J. and R.A. Freeze. 1987a. Groundwater Contamination from Waste Management Sites: The Interaction Between Risk-Based Engineering Design and Regulatory Policy. 1. Methodology. In *Water Resour. Res.* 23(2): 351-367.

Massmann, J. and R.A. Freeze. 1987b. Groundwater Contamination from Waste Management Sites: The Interaction Between Risk-Based Engineering Design and Regulatory Policy. 2. Results. In *Water Resour. Res.* 23(2): 368-380.

McDonald, M.G. and A.W. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. In *U.S. Geological Survey, Techniques of Water Resources Investigations*, Book 6, Chap. A1, 586p.

Meyer, P.D., and E.D. Brill. 1988. A Method for Locating Wells in Groundwater Monitoring Under Conditions of Uncertainty. In *Water Resources Research*, 24(8), 1277-1282.

Meyer, P., A.J. Valocchi and J.W. Eheart. 1994. Monitoring Network Design to Provide Initial Detection of Groundwater Contamination. In *Water Resources Research,* 30(9): 2647-2659.

Mihevc, T.M., J.B. Chapman, and B.F. Lyles. 1996. "The Application of Borehole Logging to Characterize the Hydrogeology of the Faultless Nuclear Test Site, Nevada, USA." In *Hydrogeology Journal* 4(4), 83-97.

Moltyaner, G.L., M.H. Klukas, C.A. Wills, and W.D. Killey. 1993. Numerical Simulation of Twin Lake Natural-Gradient Tracer Tests: a Comparison of Methods. In *Water Resources Research*, 24(12): 2033-2048.

Morse, B.S., G. Pohll, J. Huntington, and R.R. Castillo. 2003. Stochastic Capture Zone Analysis of an Arsenic-Contaminated Well Using the Generalized Likelihood Uncertainty Estimator (GLUE) methodology. In *Water Resources Research*, 39(6)1151, doi:10.1029/2002WR001470.

Nevada Administrative Code. 1998. NAC 534.4365, "Monitoring Wells: Plugging." Carson City, NV.

Nevada Administrative Code. 2002. NAC 445A.2272, "Contamination of Soil: Establishment of Action Levels." Carson City, NV.

Nork, W.E., E.J. Forslow, and E.H. Essington. 1971. *Radioactivity in Water, Central Nevada Test Area*. Teledyne Isotopes Report, NVO-1229-175, 84p.

Pohll, G. 2002. *Contaminant and Compliance Boundaries for the Faultless Underground Nuclear Test, Central Nevada Test Area*, DRI-SO-05-2002. Prepared for the National Nuclear Security Administration, Nevada Site Office. Secret-Restricted Data. Las Vegas, NV.

Pohll, G. 2003. *Tritium Contaminant Boundary for the Faultless Underground Nuclear Test, Central Nevada Test Area*, DRI-SO-03-2002. Prepared for the National Nuclear Security Administration, Nevada Site Office. Secret-Restricted Data. Las Vegas, NV.

Pohll, G., K. Pohlmann, A. Hassan, J. Chapman, and T. Mihevc. 2002. Assessing Groundwater Model Uncertainty for the Central Nevada Test Area. In *Proceedings of SPECTRUM conference*, August. Reno, NV.

Pohll, G. and T. Mihevc. 2000. *Data Decision Analysis: Central Nevada Test Area*, Publication No. 45179, U.S. Department of Energy, Nevada Operations Office report DOE/NV/13609--07, 25p. Las Vegas, NV: Desert Research Institute, Water Resources Center.

Pohll, G., J. Tracy, and F. Forsgren. 1999. *Data Decision Analysis: Project Shoal*, Publication No. 45166, U.S. Department of Energy, Nevada Operations Office report DOE/NV/11508-42, 27p. Las Vegas, NV: Desert Research Institute, Water Resources Center.

Pohll, G., K. Pohlmann, J. Daniels, A. Hassan, and J. Chapman. 2003. *Contaminant and Compliance Boundaries at the Faultless Underground Nuclear Test*, Publication No. 45196, U.S. Department of Energy, Nevada Operations Office report DOE/NV/13609-24, 50p. Las Vegas, NV: Desert Research Institute, Division of Hydrologic Sciences.

Pohlmann, K.F., J. Chapman, A. Hassan, and C. Papelis. 1999. *Evaluation of Groundwater Flow and Transport at the Faultless Underground Nuclear Test, Central Nevada Test Area*, Publication No. 45165, U.S. Department of Energy, Nevada Operations Office report DOE/NV/11508-41, 129p. Las Vegas, NV: Desert Research Institute, Water Resources Center

Pohlmann, K.F., A. Hassan, and J. Chapman. 2000. Description of Hydrogeologic Heterogeneity and Evaluation of Radionuclide Transport at an Underground Nuclear Test. In *Journal of Contaminant Hydrology* 44, pp.353-386.

Pohlmann, K.F., G. Pohll, J. Chapman, A. Hassan, R. Carroll, and C. Shirley. 2004. *Modeling to Support Groundwater Contaminant Boundaries for the Shoal Underground Nuclear Test*, Publication No. 45184, U.S. Department of Energy, Nevada Operations Office report DOE/NV/13609-13, 152p. Las Vegas, NV: Desert Research Institute, Division of Hydrologic Sciences.

Pruess, K. 1991. *TOUGH2-A: General-Purpose Numerical Simulator for Multiphase Fluid and Heat Flow*, Rep. LBL-29400. Berkeley, CA: Lawrence Berkeley National. Laboratory.

Sargent, R.G. 1990. “Validation of Mathematical Models.” In *GEOVAL-90, Symposium on Validation of Geosphere Performance Assessment Models*, pages 571-579, 14-17 May. Stockholm, Sweden.

Smith, D.K., Lawrence Livermore National Laboratory. 1997. Memorandum to Janet Wille (IT Corporation), copied to Robert Bangerter (DOE/NV), regarding radionuclides recommended by the UGTA Source and Transport Subcommittee of significance for remedial investigations at the Nevada Test Site, 2 April. Livermore, CA.

Smith, D.K. 2001. *Unclassified Radiologic Source Term for Nevada Test Site Areas 19 and 20*, UCRL-ID-141706, 4p. Livermore, CA: Lawrence Livermore National Laboratory.

Smith,D.K., B.K. Esser, and J.L. Thompson. 1995. *Uncertainties Associated with the Definition of a Hydrologic Source Term for the Nevada Test Site*, UCRL-ID-120322, 21 p. Livermore, CA: Lawrence Livermore National Laboratory,

Sudicky, E.A., and E.O. Frind. 1982. Contaminant Transport in Fractured Porous Media: Analytical Solutions for a System of Parallel Fractures. In *Water Resources Research*, 18(6): 1634-1642.

Storck, P., J.W. Eheart and A.J. Valocchi. 1997. A Method for the Optimal Location of Monitoring Wells for Detection of Groundwater Contamination in Three-Dimensional Heterogeneous Aquifers. In *Water Resources Research,* 33(9): 2081-2088.

State of Nevada. 1995. "Mutual Consent Agreement Between DOE and the State of Nevada." Carson City, NV.

Thordarson, W. 1985. Hydrogeologic Monitoring at the Faultless Site, Nye County, Nevada. U.S. Geological Survey, Open-File Report 84-580, p. 34.

Todd, D.K., R.M. Timlin, K.D. Schmidt, and L.G. Everett. 1976. *Monitoring Groundwater Quality: Monitoring Methodology*, EPA-600/4-76-026. Las Vegas, NV: U.S. Environmental Protection Agency.

U.S. Atomic Energy Commission. 1973. *Planning Directive Demobilization, Restoration and Monitoring Central Nevada Test Area,* NVO-90, variable paging.

U.S. Atomic Energy Commission, Nevada Operations Office. 1974. *Summary Report: Central Nevada Test Area Demobilization and Restoration Activities,* NVO-52. Las Vegas, NV.

U.S. Bureau of Land Management. 1997. *Approved Tonopah Resource Management Plan and Record of Decision*. Tonopah, NV: Battle Mountain District, Tonopah Resource Area Office.

U.S. Department of Energy, Nevada Operations Office. 1998a. *Focused Evaluation of Selected Remedial Alternatives for the Underground Test Area,* DOE/NV--465. Las Vegas, NV.

U. S. Department of Energy, Nevada Operations Office. 1998b. *Underground Test Area Quality Assurance Project Plan Nevada Test Site, Nevada*, DOE/NV--341-Rev. 2. Las Vegas, NV.

U.S. Department of Energy, Nevada Operations Office. 1999. *Corrective Action Investigation Plan for the Central Nevada Test Area Subsurface Sites (Corrective Action Unit No. 443)*, Rev. 1, DOE/NV--483-Rev 1. Las Vegas, NV.

U. S. Department of Energy, Nevada Operations Office. 2000a. *NV/YMP Radiological Control Manual*, Rev. 4. Las Vegas, NV.

U. S. Department of Energy, Nevada Operations Office. 2000b. *Underground Test Area Quality Assurance Project Plan Nevada Test Site, Nevada*, DOE/NV--341-Rev. 3. Las Vegas, NV.

U.S. Department of Energy, Nevada Operations Office. 2000c. *United States Nuclear Tests July 1945 through September 1992*, DOE/NV--209-Rev. 15. Las Vegas, NV.

U.S. Department of Energy, Nevada Operations Office. 2001. *Closure Report for Corrective Action Unit 417: Central Nevada Test Site Area, Surface Nevada*, DOE/NV--743-Rev. 1. Las Vegas, NV.

U.S. Department of Energy, Nevada Operations Office. 2002. *Central Nevada Test Area Surface Long-Term Stewardship Plan.* Las Vegas, NV.

U. S. Department of Energy, National Nuclear Security Administration Nevada Site Office. 2003a. *Underground Test Area Quality Assurance Project Plan Nevada Test Site, Nevada*, Rev. 4. DOE/NV--341-Rev.4.

U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office. 2003b. *Nevada Test Site Waste Acceptance Criteria*, Rev 5, DOE/NV--325. Las Vegas, NV.

U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office. 2004. *Central Nevada Test Area Risk-Based End State Vision Document*, DOE/NV--954-Draft. Las Vegas, NV.

U.S. Environmental Protection Agency. 1976. *National Interim Primary Drinking Water Regulations*, EPA-570-9-76-003. Washington, DC: Office of Water Supply.

U.S. Environmental Protection Agency. 1983. *Methods for Chemical Analysis of Water and Waste,* EPA/600/4-79/020. Washington, DC.

U.S. Environmental Protection Agency. 1995. *Contract Laboratory Program Statement of Work for Inorganic Analysis, Multi-Media, Multi-Concentration*, ILM04.0, EPA/540/R-95/121. Washington, DC.

U.S. Environmental Protection Agency. 1996. *EPA Test Methods for Evaluating Solid Waste*, 3rd Edition, Parts 1-4. Washington, DC.

U.S. Environmental Protection Agency. 1997. *Determination of Inorganic Anions in Drinking Water by Ion Chromatography*, EPA/600/R-98/118. Cincinnati, OH.

U.S. Environmental Protection Agency. 1999. *Federal Guidance Report No. 13: Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, EPA 402-R-99-001. Washington DC: Office of Radiation and Indoor Air.

U.S. Environmental Protection Agency. 2000. *Part II. Environmental Protection Agency, 40 CFR Parts 9, 141 and 142: National Primary Drinking Water Regulations; Final Rule*. Fed. Regist. 65(236), 76708-76753 (December 7, 2000).

Appendix A

Proposed Engineering Specifications and Drawings

A.1.0 Proposed Engineering Specifications and Drawings

Three wells will be drilled as part of the corrective action for CAU 443. Logic and rationale for the wells and related testing is presented in Section 5.0 of this document.

The proposed well locations are shown on Figure 5-16. Working coordinates for the wells, in Universal Transmercator (UTM) coordinates (NAD27 Zone 11), in meters are:

MV-1: 0568972 E, 4277002 N
MV-2: 0567564 E, 4275789 N
MV-3: 0568287 E, 4276906 N

Data gathered during the drilling of the first two wells (MV-1 and MV-2) could cause a change in the desired location of MV-3. If this occurs, the new location will be provided to NDEP before drilling MV-3.

The well design involves a single completion well string, with two piezometers installed in the annular space to monitor hydraulic head at other levels in the section. The location of the well screen will be targeted for an elevation of 785 m (approximate depth of 1,075 m). The actual location of the well screen, and the depth of the piezometers, will depend on the lithology encountered during drilling. The upper piezometer will be located at an approximate depth of 200 m. The lower piezometer will be located within the volcanic section of the borehole, as identified based on geophysical logging. It may be targeted for densely welded tuff, if encountered at a suitable depth. The second piezometer may be located between the top of the volcanic section and halfway between the top of the volcanic section and the bottom of the hole, ranging from approximately 700 and 1,000 m depths.

Two possible well completions are shown in Figure A.1-1 and Figure A.1-2. Figure A.1-1 demonstrates a completion for the condition of encountering a densely welded tuff within the range of the deeper piezometer, but not near the target depth of the main well. Figure A.1-2 demonstrates a completion for the condition of encountering densely welded tuff in the target horizon for the well. In this case, the well screen is located higher than 785 m elevation.

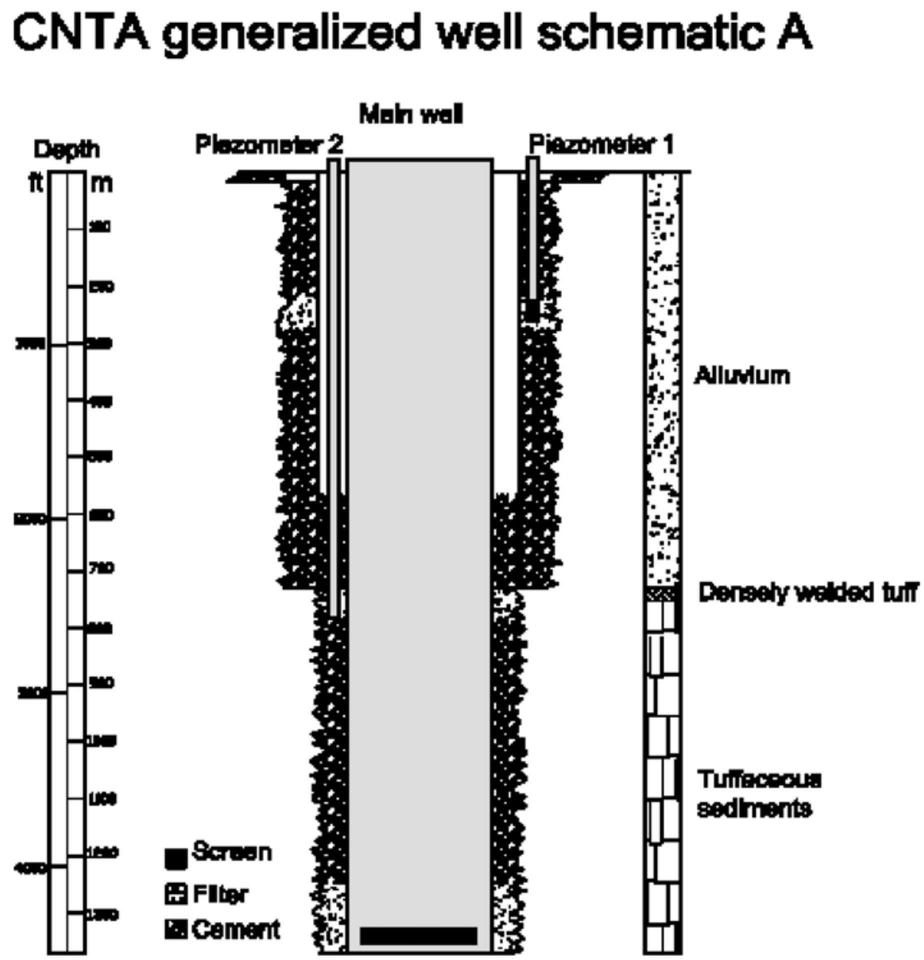


Figure A.1-1
Anticipated well design for the condition of encountering a welded tuff relatively high in the borehole. In this case, the well screen will be placed at the depth identified for transport in the model and a piezometer will be located at the welded tuff.

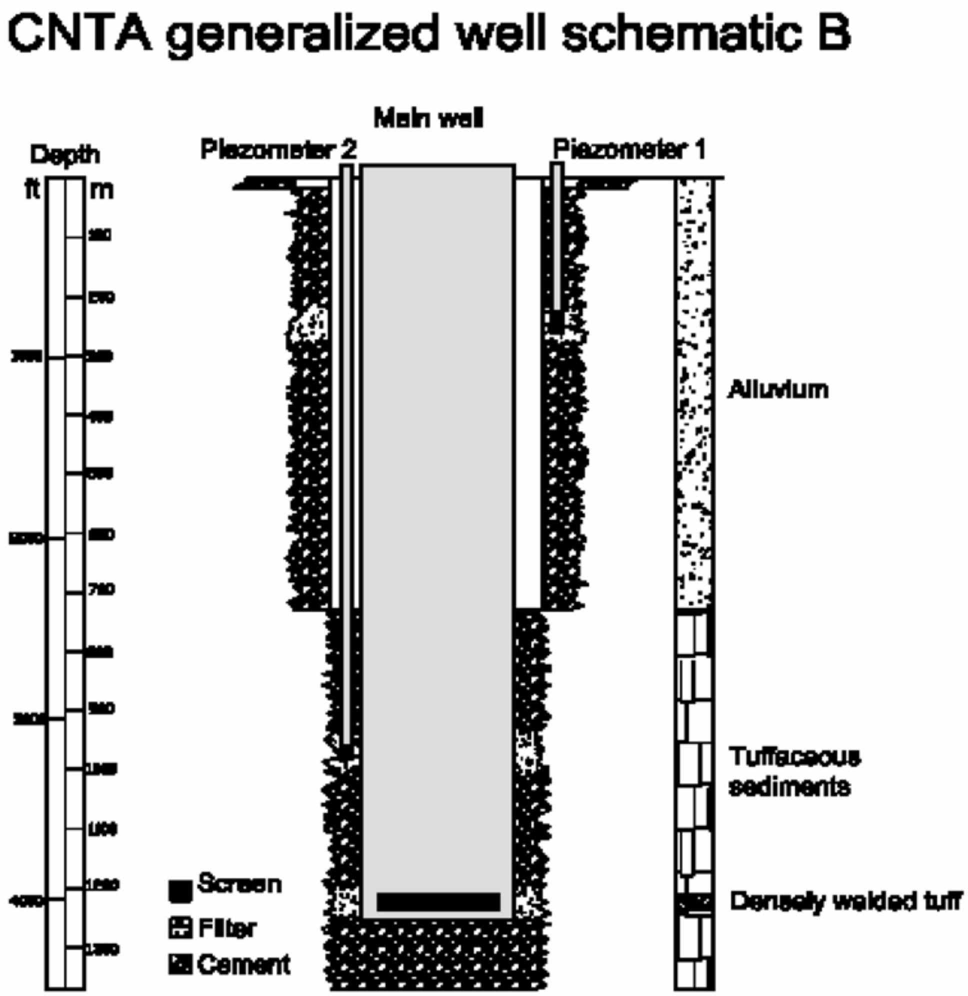


Figure A.1-2
Anticipated well design for the condition of encountering a welded tuff near the nuclear test horizon. In this case, the well screen will be placed across the welded tuff.

A top-down view of the well head is provided in Figure A.1-3. It shows the relationship between the various tubing strings. The drilling will be performed dual-wall reverse circulation to reduce aquifer perturbations with air and water as the drilling fluid; however, drilling conditions may require drilling with mud. An inert chemical tag will be added to any water added as a drilling fluid.

A 30-inch diameter surface conductor will be placed to a depth of 30 m. The intermediate casing string will be 13 3/8-inch diameter carbon steel and will be set at the bottom of the alluvium. The well will be constructed of 7 5/8-inch diameter casing. The well screen will be of the same material, and between 9 and 46 m long. The exact length of well screen will be determined based on downhole conditions. The piezometers will be 2 3/8-inch Hydril flush joint tubing.

A submersible pump will be permanently installed in the well to provide aquifer testing and samples for long-term monitoring. The pump will be set within 100 m of the static water level, depending on the productivity indicated by the screened formation. The pump will be selected based on the aquifer characteristics encountered, and is expected to need a flow rate of 20 to 170 gallons per minute from 275 m.

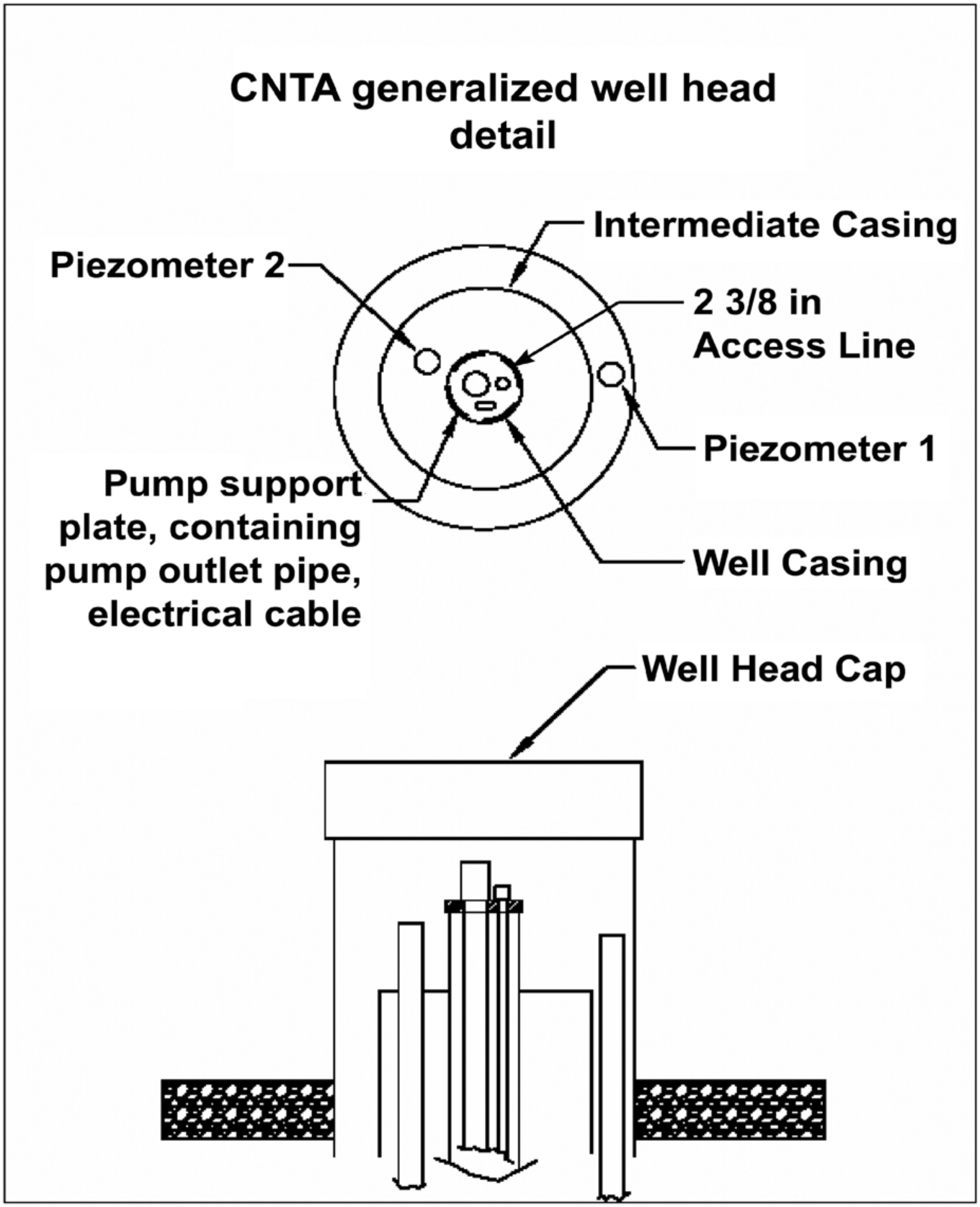


Figure A.1-3
Top Down View of the Final Wellhead Configuration and Side View of the Well Enclosure

This page intentionally left blank

Appendix B

Validation Metrics and Application to the Faultless Model

This page intentionally left blank

B.1.0 Validation Metrics and Application to the Faultless Model

B.1.1 Single Validation Target Illustration

The first criterion is to compute the number of realizations with scores S_j above a reference value. To demonstrate how this reference value is computed, assume we only have one validation target (e.g., the head measurement in one interval in one well). Figure B.1-1 shows the pdf for this head value as produced by the stochastic CNTA model where the triangles represent the 2.5th, 50th, and 97.5th percentiles and the circle indicates a hypothesized field measurement, h_o. The reference value and the score for any individual realization for this simple case are computed as

$$RV = \exp\left[-\frac{(h_o - h_{2.5})^2}{(h_{97.5} - h_{2.5})^2}\right] \quad \text{for } h_o < h_{50}$$

$$RV = \exp\left[-\frac{(h_o - h_{97.5})^2}{(h_{97.5} - h_{2.5})^2}\right] \quad \text{for } h_o > h_{50}$$

(B-1)

$$\text{Realization Score}(S_j) = \exp\left[-\frac{h_o - h_j^{\ 2}}{h_{97.5} - h_{2.5}^{\ 2}}\right] \text{for } j = 1, ..., NMC$$

(B-2)

$$\text{First Criterion } (P_1) = \frac{\text{\# of Realizations where } S_j > RV}{NMC}$$

(B-3)

where j is the realization index and it varies from 1 to NMC (number of Monte Carlo realizations) with NMC being 500 realizations for the CNTA model. This leads to all realizations with absolute errors smaller than ($|h_o - h_{2.5}|$) or ($|h_o - h_{97.5}|$), whichever is smaller, attaining a score higher than the reference value. Figure B.1-2 shows the resulting scores and how they compare to the reference value, *RV* as obtained from the above equations.

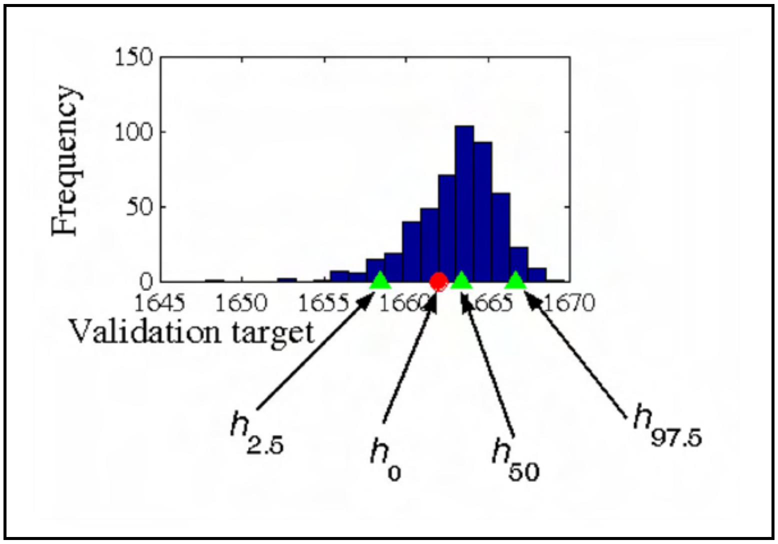


Figure B.1-1
The Head Distribution (or pdf) as Obtained From the CNTA Model With the 2.5th, 50th, and 97.5th Percentiles Shown with the Green Triangles and the Hypothesized Field Data Shown by the Red Circle

It can be seen from Equations B-1 to B-3 that the maximum value that reference value (*RV*) or S_j can attain is 1.0. Thus if the observed value, h_o, is equivalent to the 2.5th or the 97.5th value, P_1 becomes zero because *RV* becomes 1.0 and all S_j values will be less than 1.0. Also, if the observed value is found to be less than $h_{2.5}$ or greater than $h_{97.5}$, P_1 will be automatically set to zero. In such cases, one may conclude that the model output is skewed toward higher or lower values than indicated by field data. However, this does not necessarily indicate conceptual problems and it may be an indication of incorrect input parameter distributions. The other tests and evaluations can help identify the reasons for this output skewness. When the measured value coincides with the mean value (or 50th percentile) of the target output, h_{50}, then P_1 will approximately be 95 percent indicating that 95 percent of the realizations attained scores higher than *RV*.

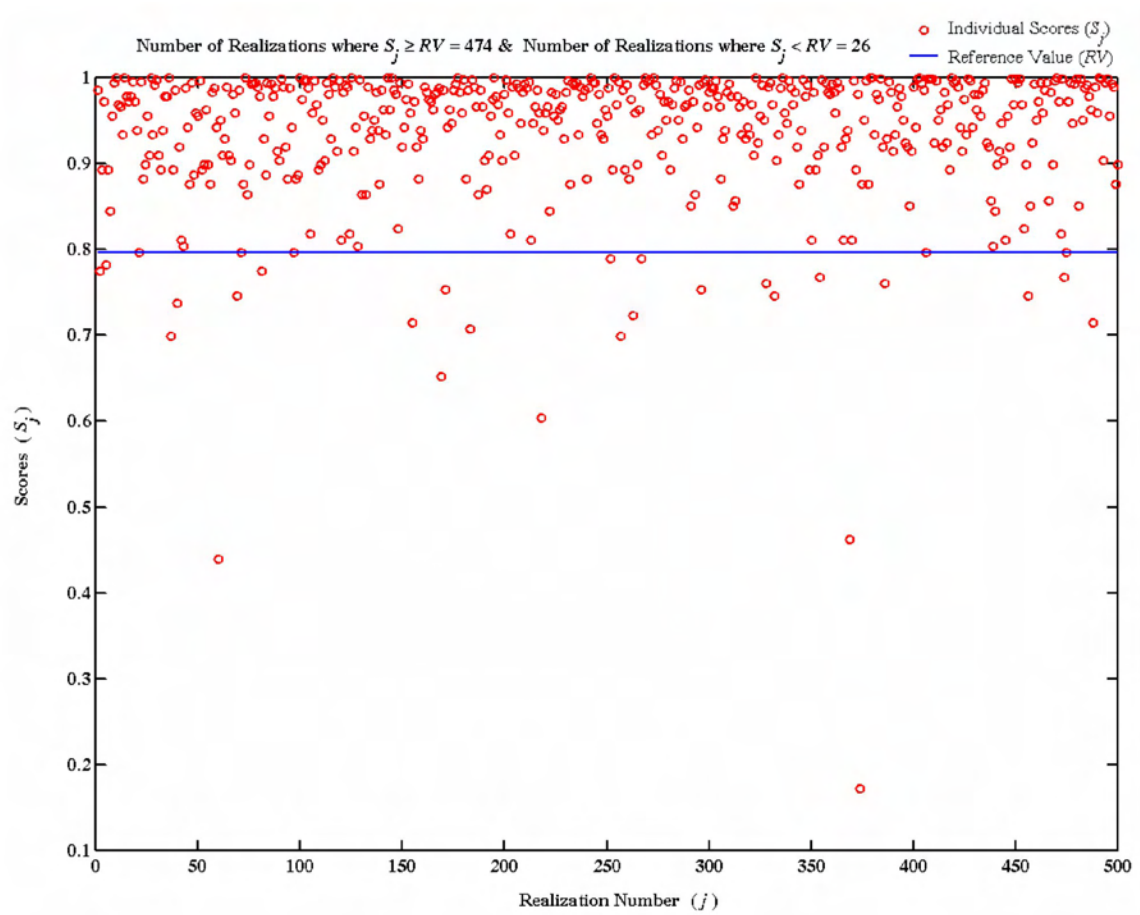


Figure B.1-2
Realizations Scores, S_j, Relative to the Reference Value, RV for the Single Validation Target Case Presented in Figure B.1-1. The P1 Value Here is 94.8 Percent (=474/500)

B.1.2 Testing the Efficacy of P_1 for a Single Validation Target

To investigate the P_1 metric for the case of a single validation target, we assume a distribution form for the model output. For simplicity, it is assumed that the model predictions follow a standard normal distribution with zero mean and unit variance, so h_{50} = 0.0, $h_{2.5}$ = -1.96, and $h_{97.5}$ = 1.96. We test the performance of this metric for a range of measurement values (hypothesized values for the single field data point) between –10.0 and +10.0. For each of these hypothesized values, the *RV* can be obtained according to Equation (B-1) and the results are shown in Figure B.1-3. The *RV* metric decreases rapidly as the observation value approaches the median, h_{50}. When the measured value lies

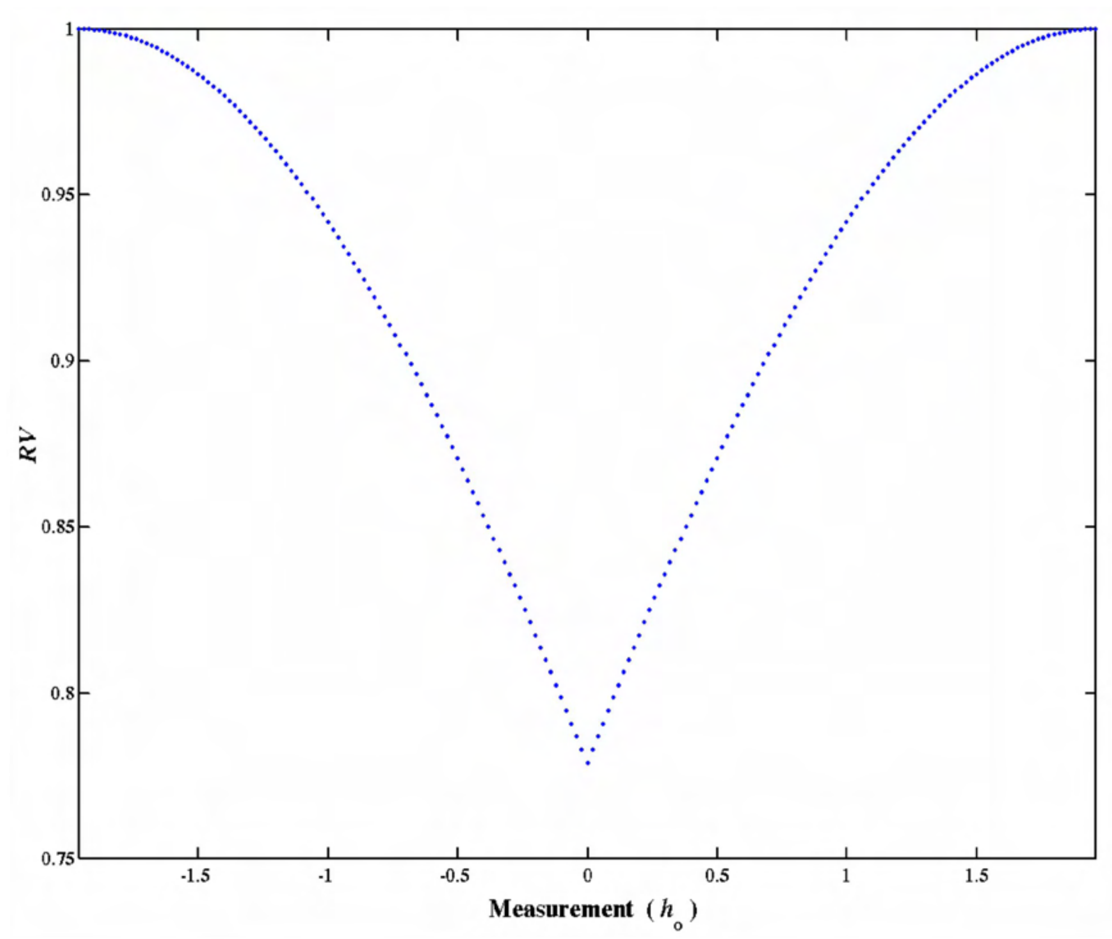


Figure B.1-3
The Reference Value, *RV* for the Single Validation Target Case as a Function of the Measured Field Value

outside the middle 95 percent of the output distribution (i.e., outside the range [-1.96, 1.96]), we do not compute the *RV* since P_1 becomes zero. Also, as shown in Figure B.1-3, when h_o equals –1.96 ($h_{2.5}$) or 1.96 ($h_{97.5}$), *RV* equals 1.0. Due to the exponential form in Equation (B-2), all S_j values will be less than 1.0 resulting in a zero value for P_1 when h_o is at the 2.5th or 97.5th percentile.

The next step is to calculate the S_j score for each Monte Carlo realization, with S_j being a similar measure to the *RV,* but using individual realization predictions. The S_j score is compared to the *RV* score and the relative number of S_j values that exceed the *RV* are tallied to obtain P_1. The S_j values and the corresponding P_1 value were tallied for a range of *single* observation values in the range [-10, 10] as shown in Figure B.1-4.

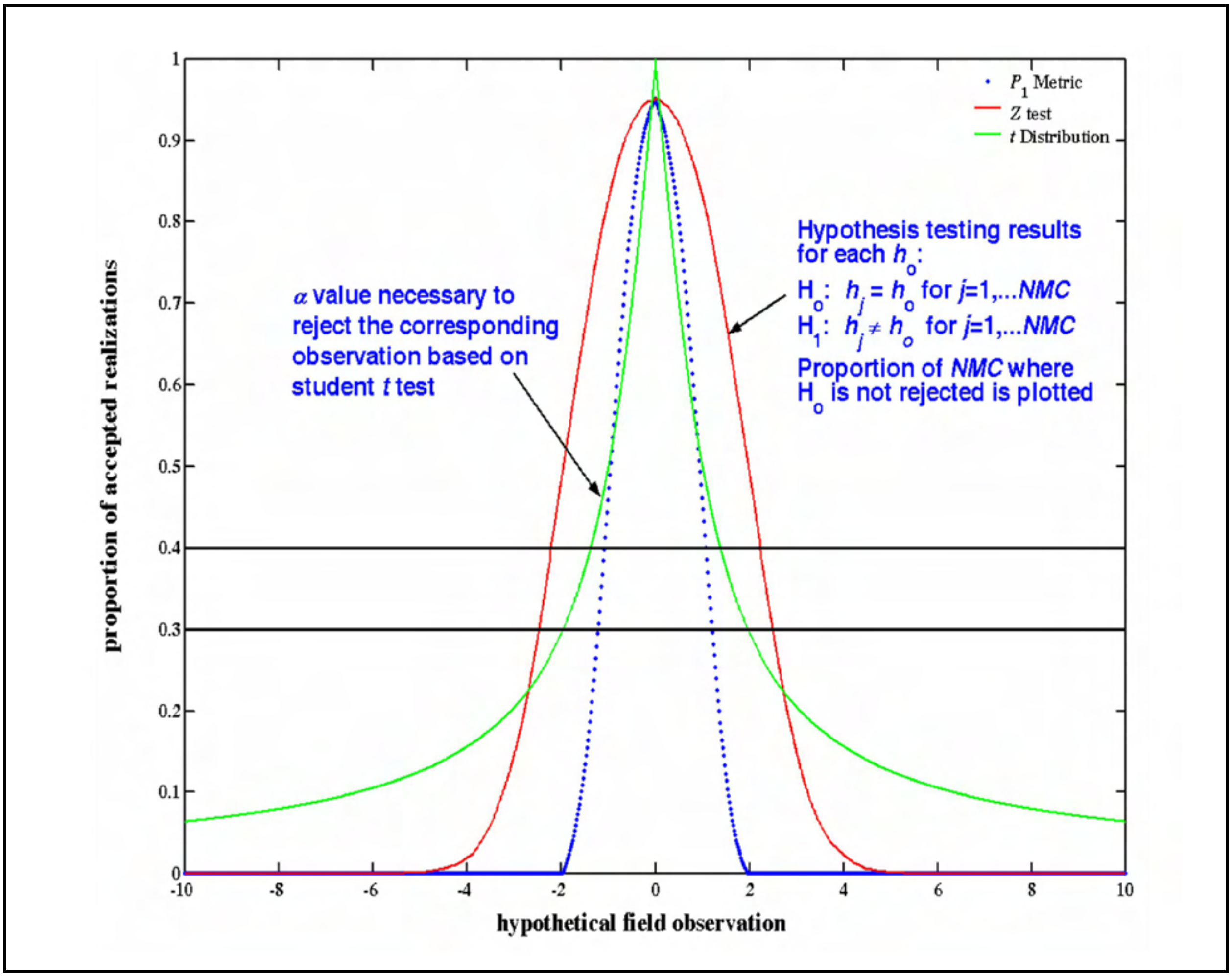


Figure B.1-4
The P_1 Metric, Student *t* Distribution, and the Results of Hypothesis Testing Using the *Z* Test

Figure B.1-4 also compares the P_1 metric to the *t*-distribution with one degree of freedom. The *t*-distribution is commonly used to test the statistical differences among means when the variance of the distribution is not known. The distribution plotted with green in the figure simply shows the value of the significance level, α, at which each observation on the range [–10, 10] would be rejected in a hypothesis testing that evaluates the statistical difference between the mean of the model output (assumed standard normal distribution) and each observed value (assuming that each observed value represents a distribution with only one [n = 1] sample). The one-degree of freedom used in this plot is not exactly correct as the degrees of freedom are actually *n* - 1 = 0. To avoid this limitation, the *Z* test is employed. The Z test is commonly used for the same purpose, but it assumes that the variances of the distributions are known. It is assumed that each observation is a mean of a normal distribution and each output realization represents a mean of a normal distribution. For each observation value, the following hypothesis is tested:

$$\begin{aligned} \mathrm{H}_0 &: h_j = h_o \qquad for\ \ j = 1, \ldots, NMC \\ \mathrm{H}_1 &: h_j \neq h_o \qquad for\ \ j = 1, \ldots, NMC \end{aligned}$$

(B-4)

Then the proportion of Monte Carlo realizations where the null hypothesis, H_0, above is not rejected is plotted against each observation value as shown with the red line in Figure B.1-4.

The plots in Figure B.1-4 provide an indication of how the P_1 test compares against standard statistical tests. According to the figure, one would accept all model realizations for any of the observed values [-10, 10] based on the student *t*-test. In other words, if the *t*-test is used, one would not reject any of the model realizations until approximately the absolute value of the observation is well above 10 (at the 95 percent confidence level). On the other hand, the P_1 measure and the *Z*-test both indicate decreasing proportions of acceptable realizations as one deviates from the median of the model output distribution which is zero in this test case. At the 5 percent significance level and if the observed value coincides with the median of the model output, only 95 percent of the realizations are deemed acceptable using the P_1 measure and the *Z* test. When the observed value deviates from the median, the proportion of acceptable realizations drops faster using the P_1 measure compared to the *Z* test. For example, 40 percent or more of the model realizations would be accepted using the *Z* test for any observation value in the range [-2.22, 2.22], whereas the P_1 measure gives this level of acceptance for a narrower range of observation values [-1.07, 1.07].

At first glance it appears that the two methods (the P_1 measure versus the *Z*-test or the *t*-test) are in large disagreement. But Type I error (rejecting a model realization when in fact it is a good one) versus Type II error (accepting a poor model realization) must be considered. The P_1 metric is essentially reducing the Type II error at the expense of Type I error. As discussed by Sargent (1990), the probability of Type I error is called model builder’s risk, whereas the probability of Type II error is called model user’s risk, and in model validation, model user’s risk is extremely important and must be kept small. As a result, it is believed that the restrictiveness of the P_1 measure helps minimize Type II error and thus reduce the model user's risk (NDEP and the public) at the expense of increasing model builder's risk (DOE).

B.1.3 Multiple Validation Targets Illustration

For the general case of having *N* validation targets, the above equations should be modified to account for these different validation targets. In this case, the *RV* and the individual scores, S_j, will depend on the sum of squared deviations between each observation, h_o, and the corresponding $h_{2.5}$ or $h_{97.5}$. The equations thus become

$$\text{Reference Value } (RV) = \exp\left(-\sum_{i=1}^{N} \min[(h_{o_i} - h_{2.5_i})^2, (h_{o_i} - h_{97.5_i})^2] / \sum_{i=1}^{N} [h_{97.5_i} - h_{2.5_i}]^2\right) \tag{B-5}$$

$$\text{Realization Score } (S_j) = \exp\left(-\sum_{i=1}^{N} [h_{o_i} - h_j]^2 / \sum_{i=1}^{N} [h_{97.5_i} - h_{2.5_i}]^2\right) \quad \text{for } j = 1, \ldots, NMC \tag{B-6}$$

For demonstration purposes and as an example, assume the hypothetical case that data are collected on 28 validation targets. These, for example, could be conductivity data in four wells, three measurements each (i.e., 12 intervals), head data for the same intervals, and the elevation of the top of the densely welded tuff unit. For each one of these targets, the current stochastic CNTA model provides a distribution of values, as each realization of the model has different values for these targets than other realizations. We then assume that the values of the field data are known (we pick at random one realization to provide an example observation for all metrics.) Figure B.1-5 through Figure B.1-7 show the results of this example (Example 1) where P_1 is found to be about 77.4 percent. In this case, we do not check for P_2 and accept the sufficiency of the number of realizations having acceptable scores. Note, however, that if we were to check P_2, it would be 100 percent.

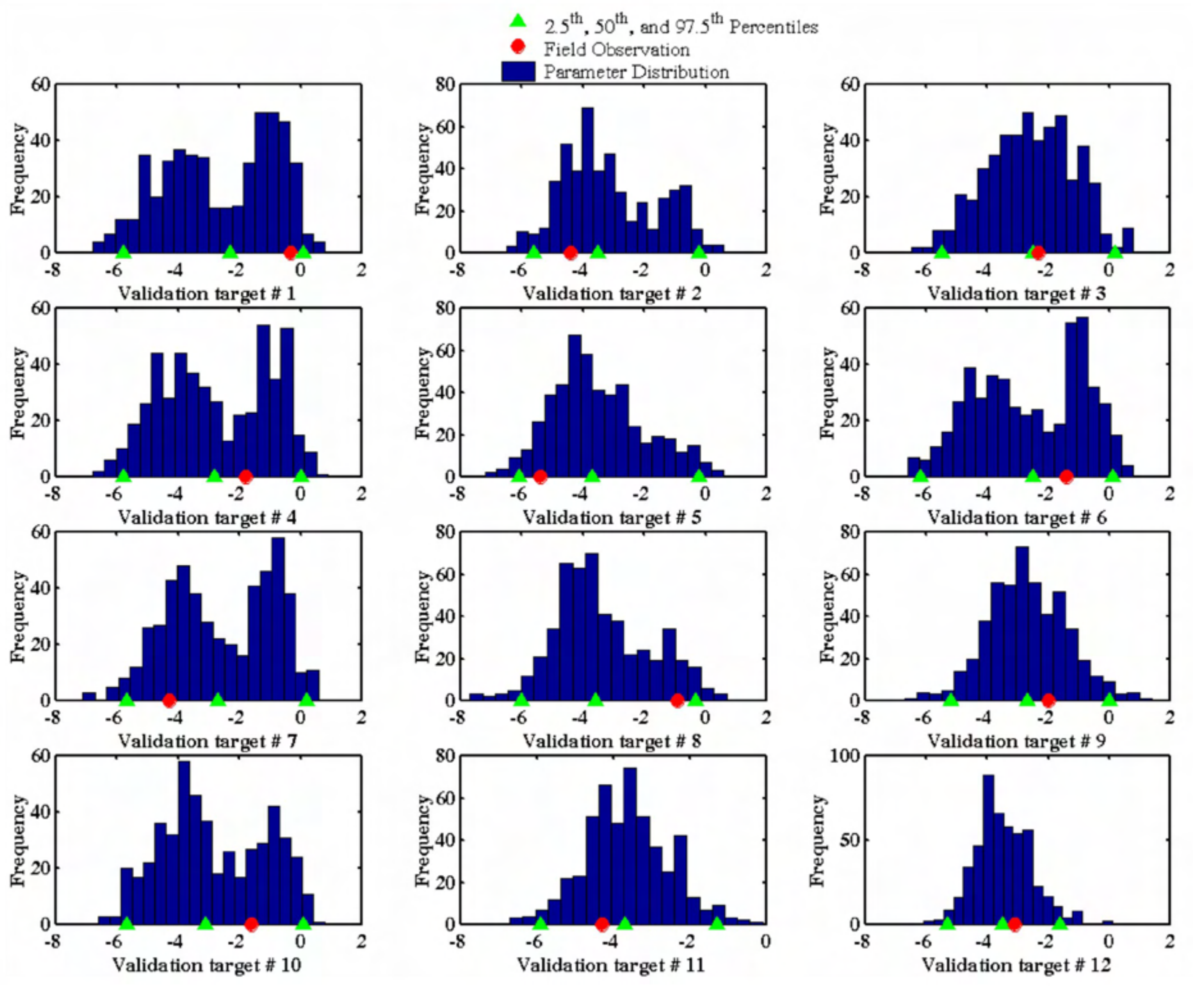


Figure B.1-5
Example 1: The pdf Distributions for Validation Targets 1 through 12 with the 2.5th, 50th, and 97.5th Percentiles Shown with the Green Triangles and the Hypothesized Field Data Shown by the Red Circles

Using another set of random values to hypothesize the field data, we obtain a different result as shown in Figure B.1-8 through Figure B.1-10 for Example 2. In this case both P_1 and P_2 are less than 40 percent (since the number of validation targets where the red circle are between the 2.5th and the 97.5th percentiles is only 7 ~ 25%). In this case the additional hypothesis tests and linear regression evaluations will be performed to assert whether the model needs to be revised or that the parameter distributions need to be modified.

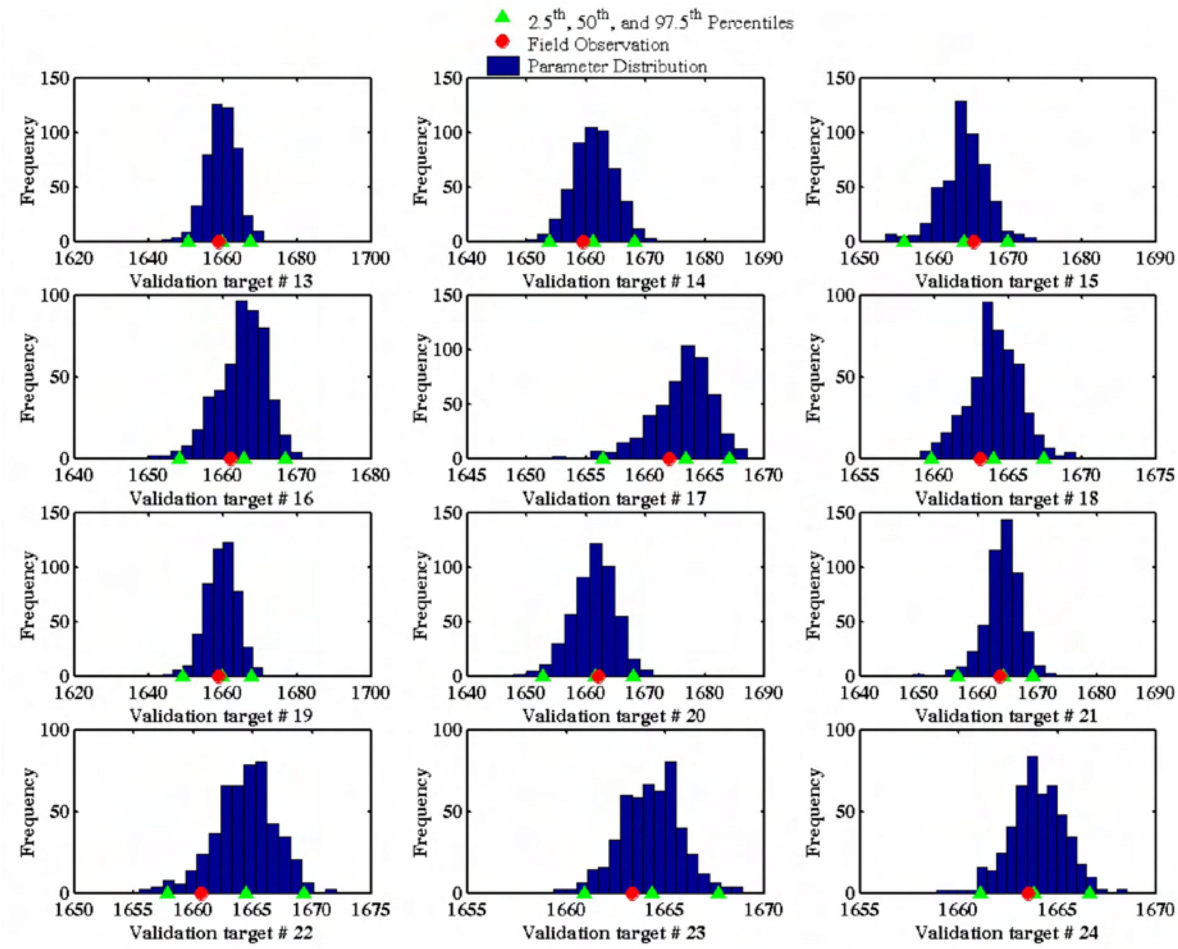


Figure B.1-6
Example 1: The pdf Distributions for Validation Targets 13 through 28 with the 2.5th, 50th, and 97.5th Percentiles Shown with the Green Triangles and the Hypothesized Field Data Shown by the Red Circles

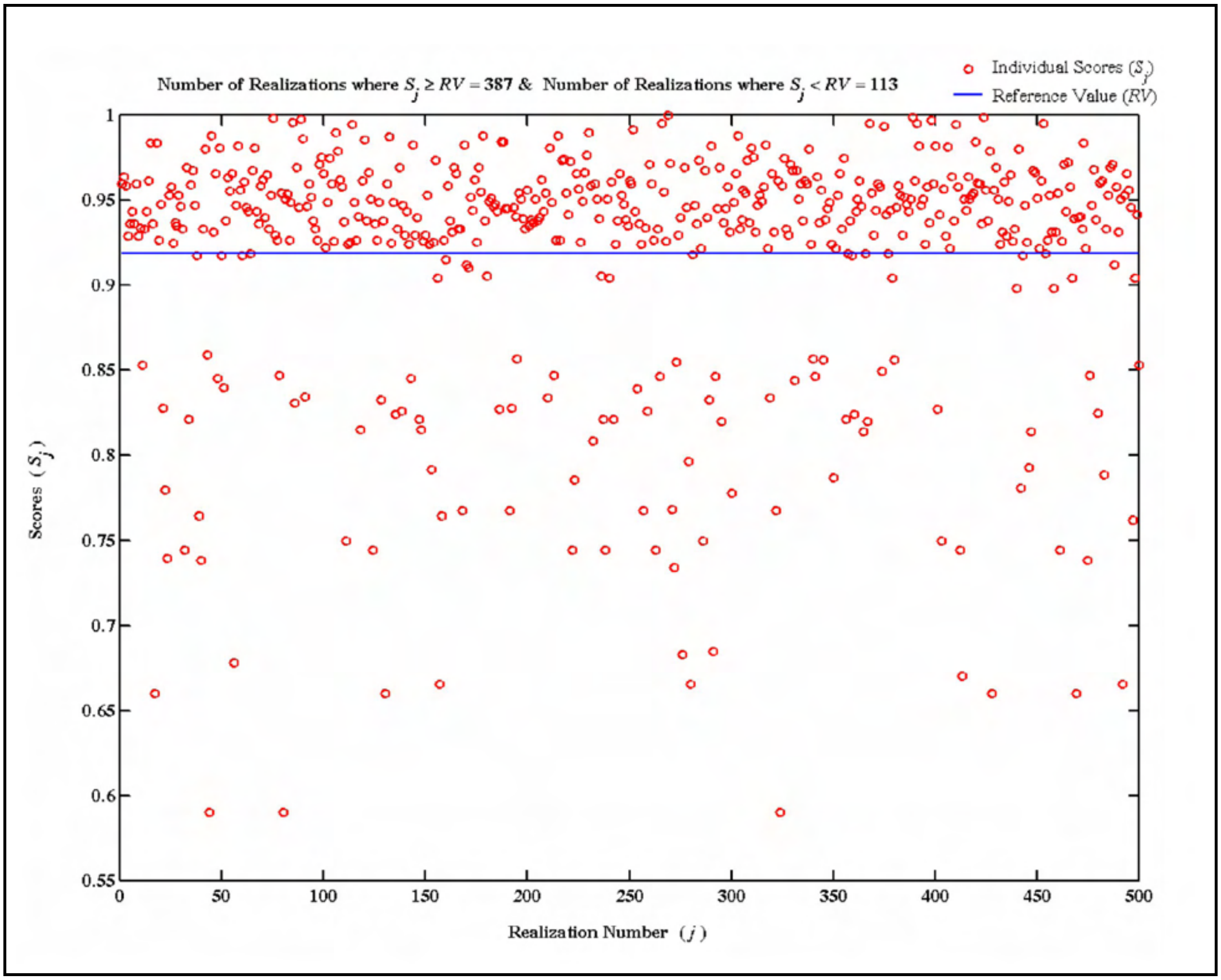


Figure B.1-7
Example 1: Individual Realizations Scores, S_j, Relative to *RV*.
The P_1 Value here is about 77.4 Percent (=387/500).

In Example 1 above, the field data values are hypothesized to be equivalent to one of the model realizations. That is, the values of the 28 validation targets are obtained from one single realization and assumed to represent field data collected for the validation analysis. In spite of assuming field values that exactly match one of the model realizations, the P_1 metric was found to be about 77.4 percent. This value is obviously dependent on which realization is selected. Therefore, we repeated the above example 500 times with each of the model realizations assumed to represent the field data in one of those times. The P_1 metric is obtained for these 500 experiments and its mean value was found to be about 53 percent. Given that the actual field data to be collected for the validation analysis will not exactly match any of the CNTA model realizations, the 30 to 40 percent

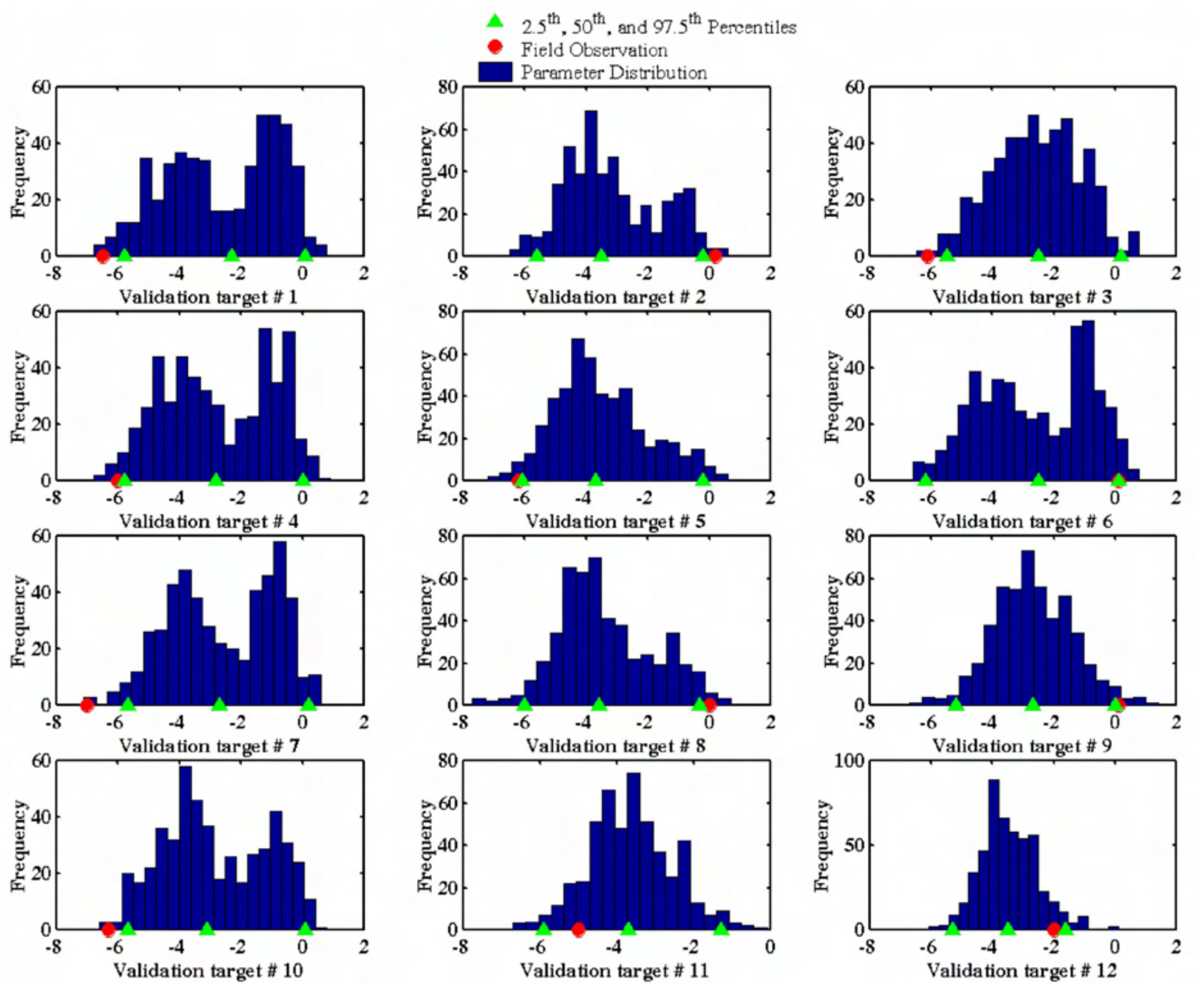


Figure B.1-8

Example 2: The pdf Distributions for Validation Targets 1 through 12 with the 2.5th, 50th, and 97.5th Percentiles Shown with the Green Triangles and the Hypothesized Field Data Shown by the Red Circles

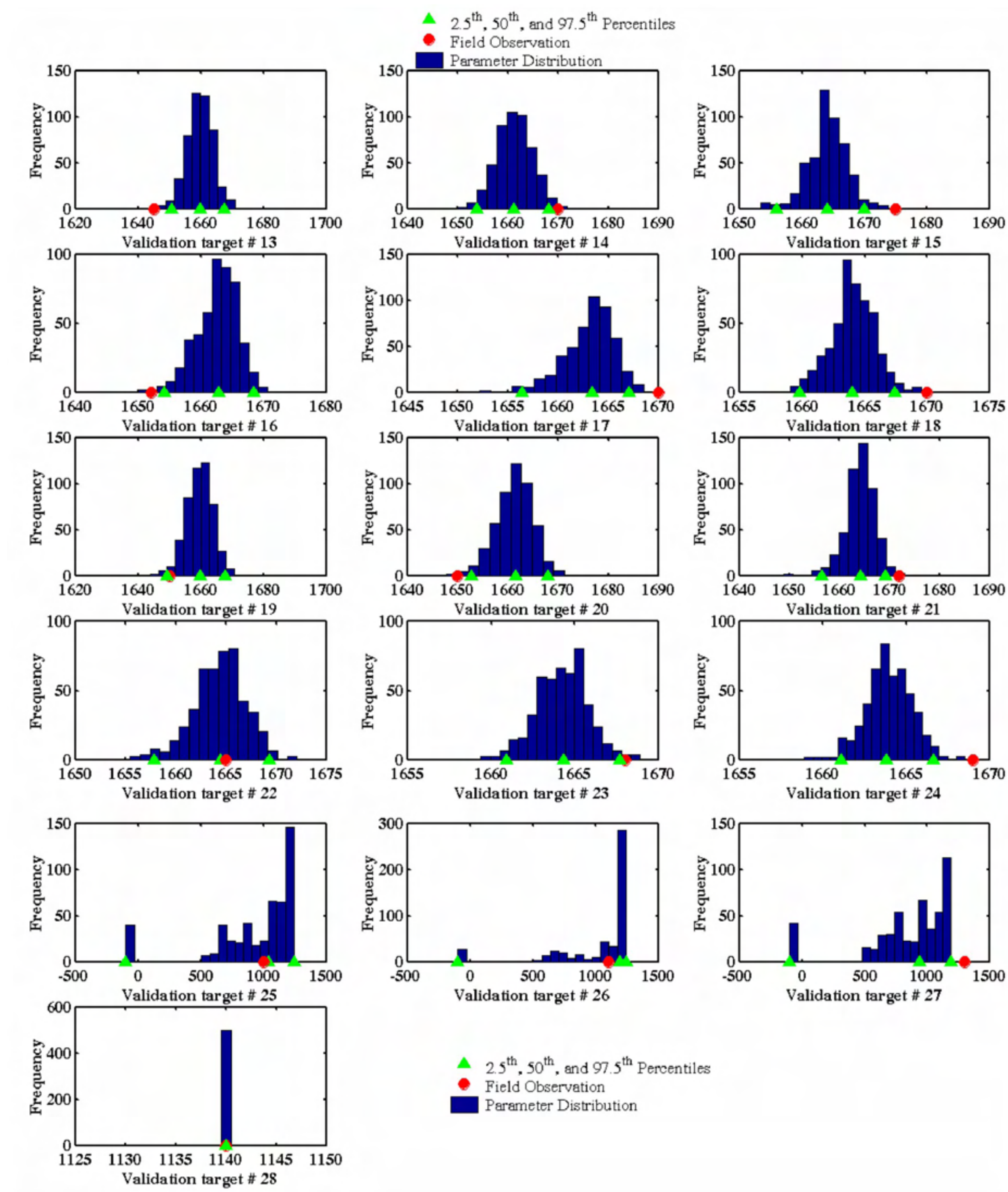


Figure B.1-9

Example 2: The pdf Distributions for Validation Targets 13 through 28 with the 2.5th, 50th, and 97.5th Percentiles Shown with the Green Triangles and the Hypothesized Field Data Shown by the Red Circles

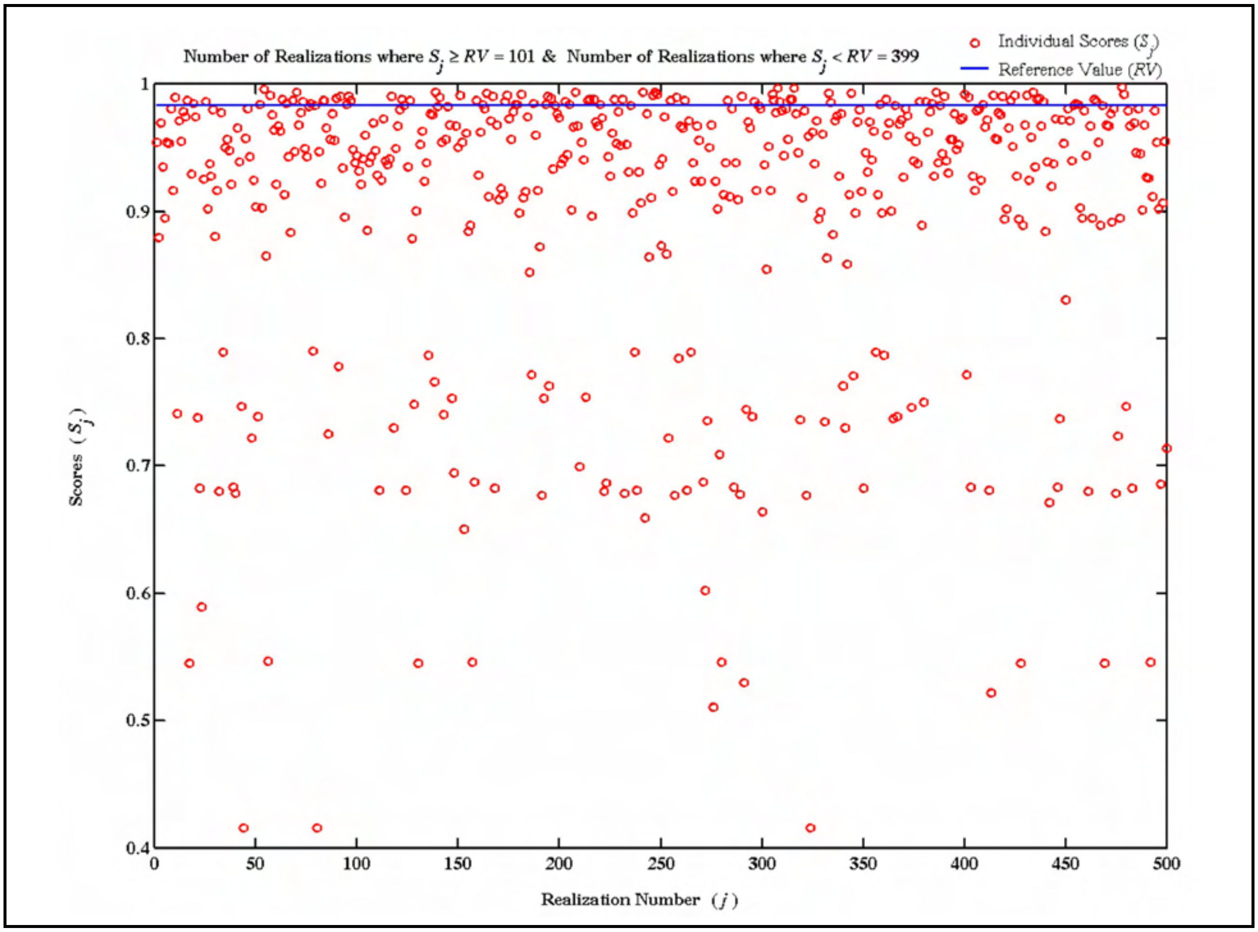


Figure B.1-10
Example 2: Individual Realizations Scores, S_j, Relative to *RV*.
The P_1 Value is about 20.2 Percent (=101/500).

threshold for P_1 is considered realistic. In other words, if one, on average, obtains 53 percent for P_1 when one of the model realizations is assumed to match real field conditions, one can safely assume the model conceptually valid if P_1 is between 30 and 40 percent when using the actual validation data.

B.1.4 Testing the Efficacy of P$_1$ *for Multiple Validation Targets*

A numerical experiment is performed to evaluate the P_1 metric for the case of multiple validation targets. The experiment is run as follows:

- A model is assumed to produce multiple outputs, each following a standard normal distribution with zero mean and unit variance.

- To test the sensitivity of the P_1 metric, 30 observations are randomly selected, with the mean value of each observation being constant. A range of observation means is used to determine at what point the model will be rejected. The mean of each observation set is tested over the range –4.0 to 4.0 (i.e. –4.0, -3.9,...,4.0).
- For each mean value, 30 observations are randomly drawn from a normal distribution with the mean equal to the current mean value (i.e., – 4.0, – 3.9, …, 4.0) and a standard deviation = 1.0.
- The *RV* value for the 30 validation targets is computed using Equation (B-5).
- For each observation mean, the scores S_j for 10,000 realizations of a model (model is assumed to be standard normal) are computed and the metric P_1 is obtained according to Equation (B-3).
- Steps 3 through 5 are then repeated for each observation mean in the range [– 4.0, 4.0].

The purpose of this experiment is to determine the point at which a model will be considered invalid. Each observation set represents data that is either close to the model predictions (i.e. mean values close to zero), or poor fitting data with mean values far away from zero. This experiment allows us to compare the rejection region for using a simple hypothesis test (i.e. z-test) versus the P_1 measure.

Due to the random nature of the distributions generated in the above procedure, we repeated the above experiment 100 times and the average results are shown in Figure B.1-11. The blue dots in the figure represent the results for the P_1 metric, the red line shows the results of the Z test that is similar to the test conducted for the single validation target case, the magenta line represents the mean value (of 100 values) of the P_1 metric at each observation mean, and the black line represents a normal distribution that best fits the P_1 results.

For the Z test, we assume that each output realization represents a mean of a normal distribution. For each observation mean value, we then test the following hypothesis:

$$\begin{aligned} \mathrm{H}_0 : h_j = h_o \qquad & for\ \ j = 1, \ldots, NMC \\ \mathrm{H}_1 : h_j \neq h_o \qquad & for\ \ j = 1, \ldots, NMC \end{aligned}$$

(B-7)

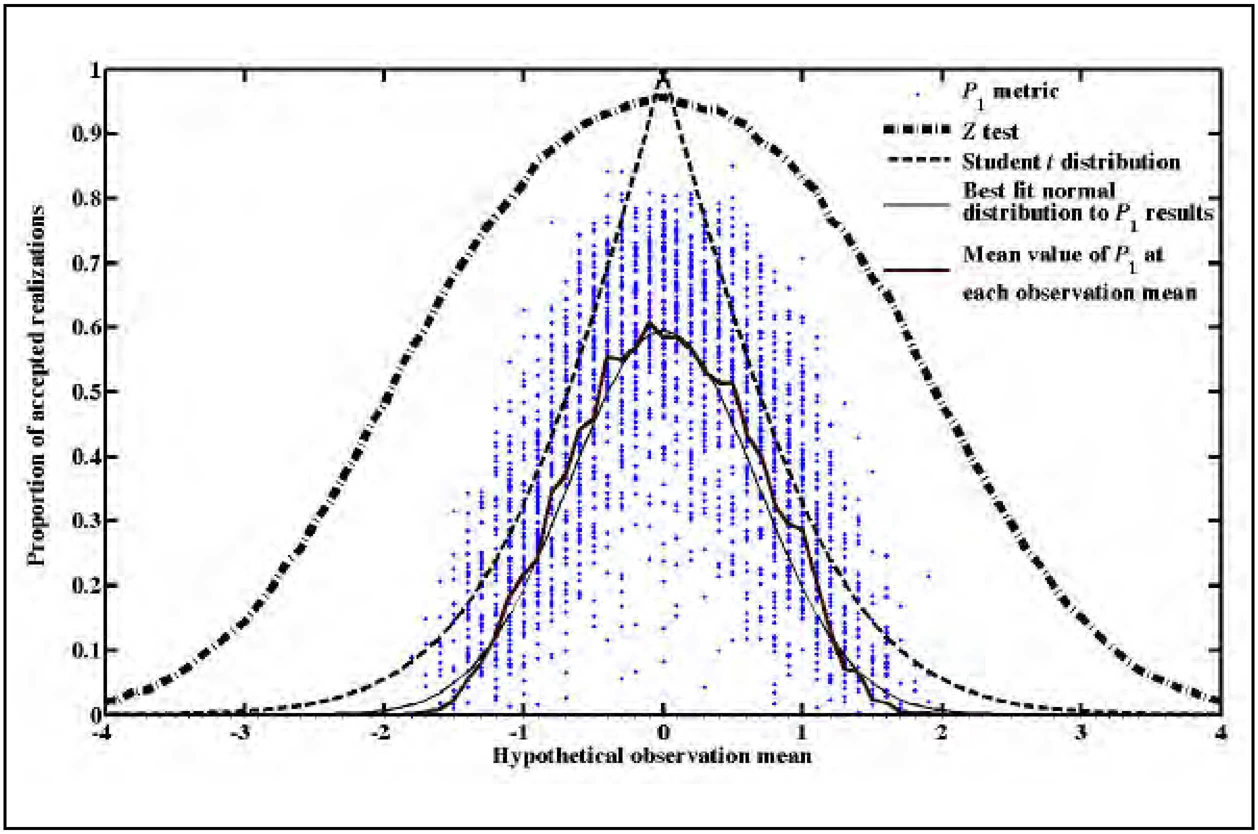


Figure B.1-11
The P_1 Metric, its Mean, its Best Fit Normal Distribution, Student *t* Distribution, and the Results of Hypothesis Testing Using the *Z* Test for the Multiple Validation Targets Case

Then the proportion of Monte Carlo realizations (assumed 10,000 in this experiment) where the null hypothesis, H_0, above is not rejected is plotted against each observation mean as shown with the red line in Figure B.1-11. According to the figure, the *t* test would suggest that we accept all model realizations if the mean value of the observations was inside the range [–2.2, 2.2] at 95 percent. The P_1 criterion has a narrower acceptance region ([–1.6, 1.6] according to the black or magenta line) again suggesting that the P_1 metric is overemphasizing (i.e., trying to reduce) Type II error. Therefore, the P_1 criterion is more stringent than typical hypothesis tests and provides a useful method to test multiple validation targets, which is a more difficult task with standard hypothesis test procedures.

It is important to note that according to P_1 and the *Z* test, decreasing proportions of acceptable realizations are obtained as one deviates from the median of the model output distribution (zero in this test case). At a 5 percent significance level and if the observed mean value coincides with the median of the model output, 95 percent of the realizations are deemed acceptable using the *Z* test, whereas only 60 percent of the model realizations are deemed acceptable using the P_1 measure. Therefore a rejection region of less than 30 percent for the P_1 criteria is very stringent and should not be confused with the 95 percent confidence interval used for presenting the output uncertainty.

B.1.5 Testing the Efficacy of P_2 for Multiple Validation Targets

A numerical experiment is constructed to test the efficacy of the P_2 metric as follows:

- A model is assumed to produce output according to a standard normal distribution.
- Observations are assumed to follow a normal distribution with mean μ and unit variance. The numerical experiment chooses mean values μ from an observation distribution range –4.0 to 4.0 (i.e., –4.0, -3.9, …, 4.0).
- For each mean value, a random sample of 30 observations is drawn from a normal distribution with the mean equal to the current mean value (i.e., – 4.0, – 3.9, …, 4.0) and a standard deviation equal to 1.0.
- Each of the 30 observations is then compared to the model's distribution N (0,1) to determine what percentage fall outside of the 95 percent confidence interval (i.e., –1.96 to 1.96).
- The process is repeated for all observation means [–4.0, 4.0].

Due to the random nature of the distributions generated in the above procedure, we repeated the above experiment about 100 times and the results are shown in Figure B.1-12. The figure shows that if 50 percent is chosen as the rejection threshold for the P_2 metric, the model would be accepted for $\mu = [-1.96, 1.96]$. This is a very interesting result as one might initially think that 95 percent should be the acceptance threshold, but 50 percent yields the same acceptance region as a standard *t* test at a 95 percent confidence level.

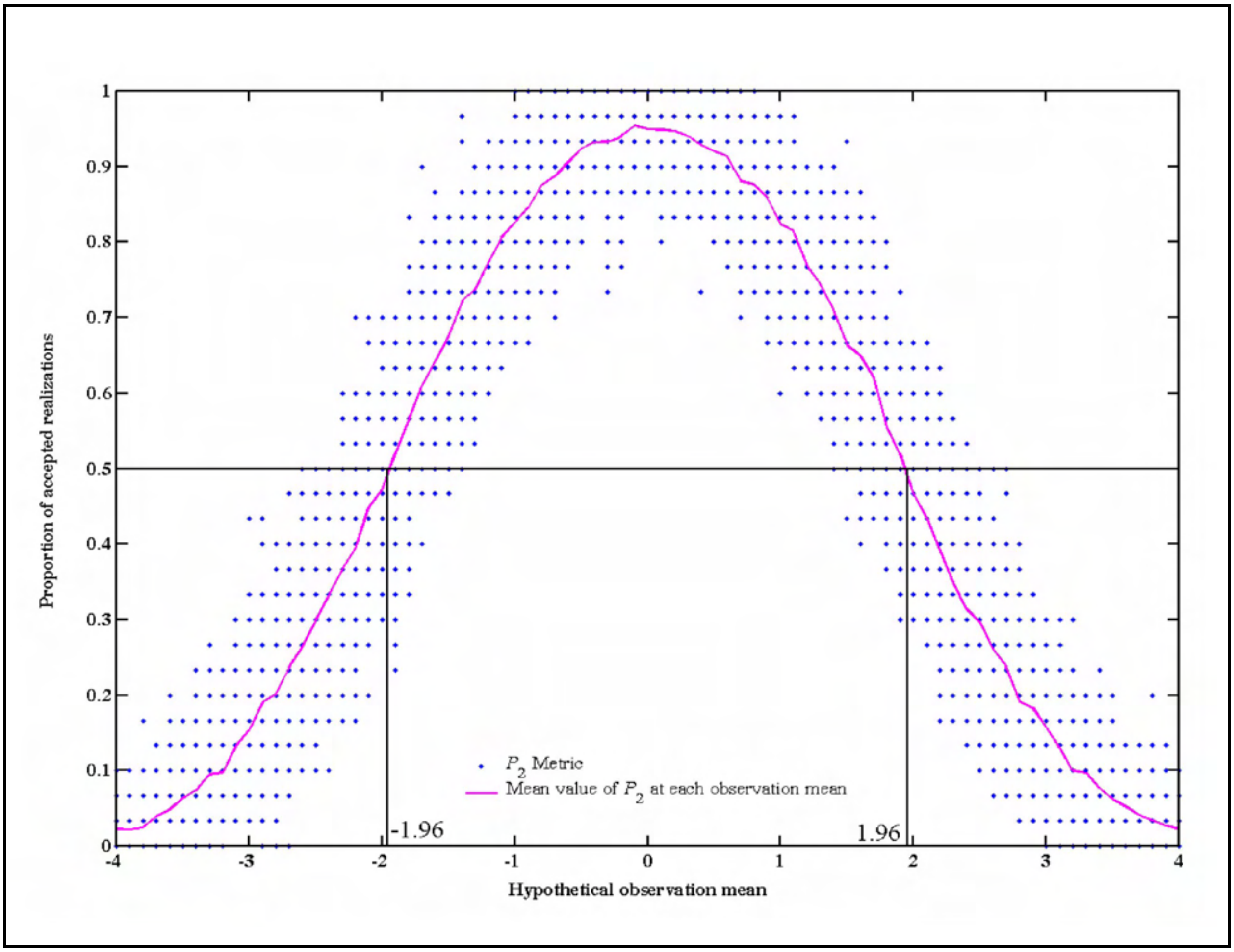


Figure B.1-12
The P_2 Metric (blue) and its Mean (magenta) for the Multiple Validation Targets Case. The Black Lines Show that at the 50 Percent Threshold, the Acceptance Region is [-1.96, 1.96] which is the Same Acceptance Region for a Standard *t* Test at the 95 Percent Confidence Level

This page intentionally left blank

Library Distribution List

	Copies
U.S. Department of Energy National Nuclear Security Administration Nevada Site Office Technical Library P.O. Box 98518, M/S 505 Las Vegas, NV 89193-8518	1 (Uncontrolled)
U.S. Department of Energy Office of Scientific and Technical Information P.O. Box 62 Oak Ridge, TN 37831-0062	1 (Uncontrolled, electronic copy)
Southern Nevada Public Reading Facility c/o Nuclear Testing Archive P.O. Box 98521, M/S 400 Las Vegas, NV 89193-8521	2 (Uncontrolled, electronic copy)
Manager, Northern Nevada FFACO Public Reading Facility c/o Nevada State Library & Archives Carson City, NV 89701-4285	2 (Uncontrolled, electronic copy)