Value of Information Analysis for Corrective Action Unit No. 98: Frenchman Flat

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**VALUE OF INFORMATION ANALYSIS
FOR
CORRECTIVE ACTION UNIT NO. 98:
FRENCHMAN FLAT**

Prepared for
DOE Nevada Operations Office
Las Vegas, Nevada

Prepared by
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4330 South Valley View, Suite 114
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Contract No.: DE-AC08-97NV13052

June 1997

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VALUE OF INFORMATION ANALYSIS
FOR
CORRECTIVE ACTION UNIT NO. 98:
FRENCHMAN FLAT

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List of Acronyms and Abbreviations

cm ³ /g	Cubic centimeter(s) per gram
DPL	Decision Programming Language
ft	Foot (feet)
ft/yr	Feet per year
ft/d	Feet per day
HSU	Hydrostratigraphic Unit
KH	Horizontal hydraulic conductivity coefficient
km	Kilometer(s)
KV	Vertical anisotropy
LD	Depth coefficient
m/yr	Meter(s) per year
m/d	Meter(s) per day
m	Meter(s)
mrem/yr	Millirem(s) per year
pCi/L	PicoCuries per liter

Executive Summary

A value of information analysis has been completed as part of the corrective action process for Frenchman Flat, the first Nevada Test Site underground test area to be scheduled for the corrective action process. A value of information analysis is a cost-benefit analysis applied to the acquisition of new information which is needed to reduce the uncertainty in the prediction of a contaminant boundary surrounding underground nuclear tests in Frenchman Flat. The boundary location will be established to protect human health and the environment from the consequences of using contaminated groundwater on the Nevada Test Site. Uncertainties in the boundary predictions are assumed to be the result of data gaps. The value of information analysis in this document compares the cost of acquiring new information with the benefit of acquiring that information during the corrective action investigation at Frenchman Flat.

Methodologies incorporated into the value of information analysis include previous geological modeling, groundwater flow modeling, contaminant transport modeling, statistics, sensitivity analysis, uncertainty analysis, and decision analysis. Data collection and analysis alternatives have been defined by evaluating the available information for Frenchman Flat contained in the regional data documentation packages, identifying areas where additional data might be needed, proposing individual data gathering and analysis options, considering option combinations (alternatives), and estimating the reduction in uncertainty. The sensitivity and uncertainty analysis has identified the most important uncertainty as a vertical flux for contaminants, migrating from the alluvium of Frenchman Flat to the Lower Carbonate Aquifer. If a vertical flux is present, any contaminant solute reaching the Lower Carbonate Aquifer would be further diluted by the regional groundwater flow system. The regional predictions of contaminant boundaries and the sensitivity analysis of flow and transport parameters have been used as screening tools to simplify the remaining decision analysis. The decision analysis evaluated the estimated improvement in parameter uncertainty and the change in distance from the contaminant source to the contaminant boundary and related them to the cost of each data gathering alternative.

Conclusions from the value of information analysis for Frenchman Flat are:

- Existing data for Frenchman Flat are insufficient to determine if a vertical flux from the alluvium to the Lower Carbonate Aquifer is present.

- A vertical flux may significantly extend the predicted contaminant boundary when basin contamination is introduced into the regional groundwater system of the Lower Carbonate Aquifer.
- If contamination is limited to the alluvium of Frenchman Flat, the major categories of uncertainty in the contaminant boundary are related to horizontal flux, the source term, and other transport parameters such as effective porosity, matrix diffusion, and absorption.
- Reductions in the uncertainty for a contaminant boundary in the basin alluvium are not cost-effective because the improvement in predicted location is small when compared with the large investment costs.

Several work scope alternatives have been proposed for the future corrective action investigation plan for Frenchman Flat. Some alternatives are estimated to reduce the uncertainty of the existence of a vertical flux from the alluvium to the Lower Carbonate Aquifer from approximately 28 percent to 87 percent with an investment ranging from \$3.8 million to about \$14.2 million. One recommended alternative, designated as Alternative Number 5, will assist in determining if contaminant transport is confined to the alluvial aquifer. The alternative includes the following options:

- Evaluate existing data, which should increase confidence in the existence of a vertical flux through more detailed compilation and analysis of Frenchman Flat information.
- Collect new information from existing wells, which should increase confidence in a vertical hydraulic gradient from the measurement of precision water elevations.
- Construct new wells to obtain precision water elevations in Area 11, which should increase confidence in the presence or absence of a vertical hydraulic gradient near the basin boundary.

If modeling using the new information predicts contaminant transport from the alluvium to the Lower Carbonate Aquifer, additional data would be required to resolve the vertical flux issue.

1.0 Overview of Analysis

The value of information analysis was performed in support of the Nevada Test Site Underground Test Area strategy as defined in Appendix VI of the *Federal Facility Agreement and Consent Order* (FFACO, 1996). The strategy bases closure of corrective action units on the ability to predict a site contaminant boundary and to demonstrate compliance with that boundary. The contaminant boundary will be established to protect human health and the environment from the consequences of any long-term exposure to contaminated groundwater on the Nevada Test Site. Prediction of the contaminant boundary contains elements of uncertainty that may be reduced through the acquisition and analysis of additional information. A value of information analysis is a cost-benefit analysis applied to the acquisition of that additional information.

1.1 Purpose and Objectives of the Study

The purpose of this study is to support implementation of the Underground Test Area strategy at Frenchman Flat. The objective of the value of information analysis is to identify potential requirements for further data collection and analysis needed in determining the contaminant boundary. Key actions used in performing the value of information analysis were:

- Establish a preliminary location for the contaminant boundary using available data, the regional models, and current knowledge of the corrective action unit source term from underground testing events.
- Perform a sensitivity analysis of regional groundwater flow and contaminant transport parameters used to estimate the location of the contaminant boundary.
- Identify data gaps that relate to uncertainty in the predicted size and location of the contaminant boundary for the corrective action unit.
- Identify data collection and analysis options to fill these data gaps for Frenchman Flat.
- Combine the deterministic boundary predictions and sensitivity analysis from regional models with the probabilistic decision analysis of proposed options to reduce boundary uncertainty at the corrective action unit scale.
- Evaluate the value of selected data collection and analysis options in reducing uncertainty in the predicted size and location of the contaminant boundary.

- Provide information to support the development of data quality objectives for any potential work scope incorporated into the future corrective action investigation plan for Frenchman Flat.

1.2 Application of the Value of Information Analysis to Frenchman Flat

This value of information analysis compares the cost of acquiring new information during the corrective action investigation at Frenchman Flat with the benefit of acquiring that information. Benefit can be defined as the percent reduction in the distance from a contaminant source to a contaminant boundary. The contaminant boundary is defined as the downgradient location from the contaminant source where a human receptor may ingest groundwater that will not exceed a regulatory water quality standard. A flow diagram for the value of information analysis applied to Frenchman Flat is shown in Figure 1-1.

Methodologies incorporated into the value of information analysis include previous geological modeling, groundwater flow modeling, contaminant transport modeling, statistics, sensitivity analysis, uncertainty analysis, and decision analysis. As shown in Figure 1-1, regional data documentation packages (IT, 1996 Volumes I through VII) provided the available data and interpretations to form the hydrogeological database, to establish regional pathlines, and to perform the sensitivity analysis of groundwater flow and transport in Frenchman Flat. Definition of the contaminant boundary was obtained from consideration of applicable regulatory standards published in Department of Energy Order 5400.5 (DOE, 1993) and the Clean Water Act (ES, 1988). Model prediction of the distance to the contaminant boundary has been based on regional pathlines that initiated from underground test locations in Frenchman Flat. The *Federal Facility Agreement and Consent Order* strategy requires the future development of more detailed corrective action unit models that refine these initial boundary predictions. Seven contaminants were used in the boundary predictions, including six radionuclides and one nonradioactive contaminant. Sensitivity analysis of the regional pathline predictions for Frenchman Flat included consideration of both the groundwater flow and contaminant transport parameters as well as speculative bounding scenarios.

The decision analysis shown in Figure 1-1 used the contaminant boundary predictions from regional modeling, the results of the sensitivity analysis, and the data collection and analysis options to evaluate the cost-effectiveness of potential data gathering activities. The regional predictions of contaminant boundaries and the sensitivity analysis of flow and transport

Figure 1-1
Flow Diagram for the Value of Information Analysis
 (Chapter Discussion Identified in Lower Right Corner)

parameters were used as screening tools to simplify the remaining decision analysis into a consideration of only one contaminant (carbon-14). The data collection and analysis options were obtained by evaluating the current data for Frenchman Flat contained in the regional data documentation packages, identifying potential data gaps, proposing data gathering and analysis options to fill the data gaps, costing the data gathering and analysis options, and estimating the reduction in uncertainty. The decision model used the parameter sensitivities and probabilistic values associated with a data gathering and analysis option to calculate a radioactive dose and a corresponding distance. The decision analysis related the estimated improvement in parameter uncertainty and the change in distance to the contaminant boundary with the cost of the data gathering option.

1.2.1 Description of Frenchman Flat

From 1951 through 1992, there were 908 underground nuclear tests conducted on the Nevada Test Site (DOE, 1994). The test areas were categorized into six corrective action units as shown in Figure 1-2: Frenchman Flat, Western Pahute Mesa, Yucca Flat, Central Pahute Mesa, Rainier Mesa/Shoshone Mountain, and Climax Mine. The Federal Facility Agreement and Consent Order identifies Frenchman Flat as the first corrective action unit of the Underground Test Area to be scheduled for the corrective action process (FFACO, 1996). Frenchman Flat was selected because it contained a small number of corrective action sites (ten) and characterization data from previous studies in existence, making it the simplest of the corrective action units in the Underground Test Area. The locations of the existing wells and the ten underground events in Frenchman Flat are shown in Figure 1-3. The underground events were detonated in Area 11 and Area 5.

Frenchman Flat has a typical Basin and Range-type structure (Figure 1-4). The basin is underlain by up to 3,000 meters (m) (9,840 feet [ft]) of Paleozoic carbonate rocks. The carbonate section is overlain in the northern and western parts of the basin by Tertiary volcanic tuffs. These tuffs, which came from volcanoes to the west and northwest on the Nevada Test Site, are exposed around the northern and western edges of Frenchman Flat and are thickest there. Tuffs are thought to cover much of the Paleozoic rock in the subsurface, but they pinch out toward the southeast. Younger Tertiary sedimentary rocks crop out on the eastern and western margins of the basin and are, therefore, inferred to be present in the basin on top of the volcanic units. There may be locations in the basin where volcanic and Tertiary sedimentary rocks are not present.

Figure 1-2
Underground Test Area Corrective Action Units

Figure 1-3
Selected Wells and Underground Nuclear Tests at Frenchman Flat, Nevada Test Site

Figure 1-4
Conceptual Model Cross Section Through Frenchman Flat

Frenchman Flat basin was formed by down-dropping of the Tertiary and Paleozoic units along a series of interpreted northeast-striking normal faults. The faults are thought to have tilted the strata toward the east in several fault blocks, and the basin has filled with alluvium covering the faults and strata. The alluvium consists mostly of sands and silts and is interpreted, from geophysical data, to be as thick as 1,400 m (4,600 ft) in the center.

The regional water table in Frenchman Flat is shallow enough that the Paleozoic, Tertiary, and alluvium sections are locally saturated. Groundwater elevations range from 716 m (2,349 ft) mean sea level to 734 m (2,408 ft) across the basin, at depths ranging from 157 m (554 ft) to 360 m (1,181 ft).

Regional groundwater flows beneath Frenchman Flat through fractures in the regional carbonate aquifer. The Tertiary tuffs contain local welded tuff aquifer units; however, the tuffs and Tertiary sediments are predominantly confining units which separate the alluvium aquifer from the carbonate aquifer. The direction of regional groundwater flow through Frenchman Flat is generally from northeast to southwest, but water elevations in Frenchman Flat produce hydraulic gradients that are fairly flat, creating a major uncertainty in the local flow directions. Because of the sparsity of water-elevation data for each of the hydrostratigraphic units, local flow directions in Frenchman Flat could be different from the regional flow direction.

1.2.2 Definition of Contaminant Boundary

The basic physical concept of the contaminant boundary surrounding a single nuclear event is shown in Figure 1-5. At least some portion of the cavity created by the subsurface event is assumed to be below the water table. Groundwater flows through the cavity and emerges with dissolved contaminants. The initial contaminant condition that is assumed is an initial finite-width pulse. These contaminants migrate with the groundwater flow. Over time, natural attenuation reduces the plume concentrations of the contaminants through radioactive decay and longitudinal dispersion. However, as a result of different contaminant transport properties (sorption and retardation) and spatial variations in the hydrogeologic properties of the saturated subsurface medium, the actual location of the contaminant boundary is uncertain within specified levels of confidence.

Figure 1-5
Basic Physical Concept

In Figure 1-5, the uncertainty in contaminant boundary location is shown as the distance between the 5 and 95 percent confidence levels. These levels are interpreted to mean that in only 5 percent of the realizations, contamination will migrate no further than this distance downgradient from the event cavity; in 95 percent of the cases, contamination will migrate no further than this distance downgradient from the event cavity. While various levels can be selected to estimate the location of the outer contaminant boundary, the 95 percent level is conservative. It is also consistent with the U.S. Environmental Protection Agency's charter to protect human health and the environment from adverse effects as a result of exposure to harmful contamination.

For purposes of this analysis, the following definition of a contaminant boundary was assumed:

The contaminant boundary is defined as the downgradient transport distance from the individual corrective action site (or group of corrective action sites) to the imaginary, subsurface, three-dimensional boundary within a corrective action unit that is defined by a total contaminant concentration (or activity per volume) not to exceed an annual dose equivalent of 4 millirems per year (mrem/yr) to any human receptor for radionuclides or not to exceed drinking water standards (maximum contaminant levels) for other contaminants.

Additional considerations of boundary uncertainty include:

- The transport distance is obtained using the regional flow and transport models and the 95 percent limit of the transport simulations described in Section 2.0.
- The 95 percent level provides greater confidence (over the 50 percent level) that contamination exceeding 4 mrem/yr will never cross the outer boundary.

Cumulative effects of multiple contaminants can be considered to be additive unless information becomes available to suggest otherwise.

Contaminant boundary predictions for Frenchman Flat are summarized in Section 2.0 and are presented in detail in Appendix A of this report.

1.3 Organization of the Report

An overview of the value of information analysis including a brief description of Frenchman Flat and the definition of the contaminant boundary is contained in Section 1.0. A description of the regional groundwater flow model, contamination sources in Frenchman Flat, regional transport

modeling (including contaminant boundary predictions), and alternate contaminant transport scenarios are contained in Section 2.0. Additional detailed discussion of the analysis used for the prediction of composite and contaminant-specific boundaries in the alluvium of Frenchman Flat is presented in Appendix A. Discussion of the sensitivity analysis, parameter uncertainty, and a summary of the uncertainty analysis is contained in Section 3.0. Detailed treatment of parameter uncertainty and radionuclide transport relevant to boundary predictions in the alluvium of Frenchman Flat is presented in Appendix B. Section 4.0 summarizes the deficiencies in the existing knowledge of Frenchman Flat, the proposed options to gather additional information, and the results of the expert opinion survey for estimates to reduce parameter uncertainties. A more detailed description of the proposed data collection options is presented in Appendix C. Section 5.0 contains a brief description of the decision model, the results of the decision analysis, and the cost-effectiveness of data gathering activities. Appendix D presents the details of the one-dimensional analytical fate and transport solution used in the decision analysis. Conclusions and recommendations are presented in Section 6.0.

2.0 Simulations and Projections of Frenchman Flat Events

Contaminant transport simulations were performed to represent the movement of contaminants from their sources in Frenchman Flat. These simulations incorporated the hydrogeologic system (Figure 1-4) and the physical and chemical processes that attenuate contaminants transported through the alluvial aquifer, volcanics, Tertiary sediments, and carbonate aquifers found in Frenchman Flat. This work was based on the results of the Groundwater Flow Model Documentation Package (Phase I Data Analysis Documentation, Volume VI) and Tritium Transport Model Documentation Package (Phase I Data Analysis Documentation, Volume VII) models for the Underground Test Area (IT, 1996f; IT, 1996g) and focused on:

- Projecting the location of the contaminant boundary using the regional models
- Examining the influence of variance in groundwater flow and transport parameters
- Evaluating the uncertainty in application of the regional groundwater flow model to the local Frenchman Flat scale

The regional groundwater flow model provided the base case for groundwater movement (i.e., pathline, hydrostratigraphic unit, and groundwater flux) from nuclear testing events in Frenchman Flat. Pathlines beginning at selected underground test locations were calculated from the results of the regional groundwater flow model. Contaminant transport simulations were performed along two selected pathlines to determine the concentration of contaminants, as a function of time, at selected downgradient locations. The transport simulations incorporate uncertainty in groundwater flow parameters (i.e., hydraulic conductivity and boundary fluxes [such as recharge and discharge]) as well as transport parameter data (i.e., initial source concentration, porosity, dispersion, chemical adsorption, and matrix diffusion) to determine the potential extent of their contaminant migration. The most important contaminants of concern were identified, and separate simulations were performed to predict the potential extent of migration with time. The result for each radionuclide was converted into dose to identify the boundary location, and the individual doses from all the contaminants were totaled to produce a composite boundary prediction.

2.1 Regional Groundwater Flow Model

The May 1996 version of the Groundwater Flow Model Documentation Package, (Phase I Data Analysis Documentation, Volume VI) (IT, 1996f) provided the base case for the transport simulations. Revisions to the flow model incorporated in the UGTA report (IT, 1997) were not available at the time this work was performed.

2.1.1 Pathlines for Transport Modeling

The transport modeling has been conducted using a one-dimensional model which evaluated advective-dispersive transport along pathlines. Pathlines define the movement of a particle through the flow model and represent the path that contaminants would follow (if released). Pathlines for transport from selected events have been determined from the regional groundwater flow model using the United States Geological Survey particle tracking model, MODPATH (Pollock, 1989). Information about the groundwater flow is summarized by the groundwater flux calculated for each cell in the model. A pathline provides this information to the transport model along a streamtube starting at any selected location in the flow model. The pathline is also processed to provide identification of the hydrostratigraphic unit (HSU) at any point along the pathline. This data defines HSU-specific transport parameters along the pathline. The groundwater flux, the transport parameters, and the flow sensitivity parameters along the pathline are the primary input parameters to the transport models. Pathlines from two shots have been calculated and are displayed on Figure 2-1. The MINUTE STEAK shot has been selected to represent contaminant sources in Area 11, and the DILUTED WATERS shot has been used to represent contaminant sources in Area 5. The pathlines are very similar, and the base case modeling has been conducted primarily along the DILUTED WATERS pathline.

2.1.2 Groundwater Fluxes

The effects of parameter uncertainty in the flow model on the calculated groundwater fluxes were investigated quantitatively as part of the value of information analysis. Changes in groundwater flux with changes in hydraulic parameters (i.e., hydraulic conductivity, anisotropy, and the relationship of conductivity with depth) were provided as input to the transport model as a way of incorporating uncertainty in the flow parameters with the transport results.

An additional uncertainty in the groundwater flow model was the magnitude of the recharge. If recharge were increased proportionally with the hydraulic parameters, the result would be a

Figure 2-1
Location of Underground Nuclear Tests in Frenchman Flat
Pathlines from MINUTE STEAK and DILUTED WATER

similarly calibrated model with respect to hydraulic head, but with increased fluxes. An increase in recharge by a factor of two should be expected to increase the groundwater flux by a factor of approximately two. An additional factor was included in the solute transport model to account for recharge uncertainty. The groundwater flux used in the transport model was multiplied by a recharge factor. The base case value of the factor was one, meaning that the flux was the same as when the calibrated recharge was used. If recharge is assumed to be twice the calibrated amount, the recharge multiplication factor would be two.

2.2 Contamination Sources

Ten underground nuclear tests, each with a yield under 20 kilotons (DOE, 1994), were conducted in Frenchman Flat (Figure 1-3). All tests were assumed to have impacted groundwater because the tests were located beneath the water table or within 100 meters of the water table. As shown in Figure 1-4, three of the tests were in the central portion of the basin (Area 5) and were detonated in alluvium. The other seven tests were conducted in the northern part of the basin (Area 11). These northern tests were detonated at or near the alluvium/Tertiary contact, and their cavities could span both units.

2.2.1 Contaminants of Concern

One nonradioactive contaminant and six radioactive contaminants were selected for examination by the Underground Test Area Subproject Technical Working Group. The contaminants identified were lead, carbon-14, iodine-129, plutonium-239/240, cesium-137, strontium-90, tritium, and uranium-238. These contaminants were selected because they were found in measurable quantities in water sampled from shot cavities or downgradient of cavities, and they have the potential to impact human health and/or are important for modeling considerations. They represent both long-lived and short-lived radionuclides and include radioactive isotopes, or species, that have different migration characteristics. For example, tritium, iodine, and carbon are not retarded (i.e., they travel at the same rate as groundwater). Cesium, lead, and plutonium are strongly sorbed onto the surrounding geologic media; therefore, their movement is retarded (i.e., moves much more slowly than the water). The other constituent, uranium, migrates at rates between the two above-mentioned groups of contaminants.

Migration rate might be impacted if the contaminants are found to be traveling as colloids. Colloids are particles in the groundwater that are smaller than sediment. Contaminants in

colloidal form can behave almost like nonretarded constituents, even for otherwise highly sorbing contaminants. The base case model assumed that colloid transport was not significant.

Lead was also considered since it represented a Resource Conservation and Recovery Act contaminant (RCRA, 1980). Lead was known to have been used in underground nuclear shots in significant quantities, and it was of special interest from both a risk and regulatory perspective. It was assumed that any organic volatile or semivolatile constituents would be consumed during the explosion (RCRA, 1980), but that metals would remain.

2.2.2 Source Term for Transport Modeling

The simulations were performed for the representative set of six radionuclides with different decay rates, adsorptive properties, and degrees of attenuation (based on initial emplacement concentrations). The radionuclides that were considered in the modeling effort were carbon-14, cesium-137, tritium, iodine-129, plutonium-239/240, and uranium-238. Two other contaminants (strontium-90 and lead) were considered but were not included because Strontium-90 has a half-life similar to cesium-137. The distribution coefficient for strontium-90 is about an order of magnitude smaller than that of cesium-137, and it was expected that the strontium-90 results would fall between the results of cesium-137 and tritium. The other contaminant was nonradioactive lead. According to Yu et al. (1993), the distribution coefficient for lead is greater than 100 cubic centimeters per gram (cm^3/g), which is between the values for uranium-238 and plutonium-239/240. The behavior of lead is expected to fall between that of uranium-238 and plutonium-239/240.

The initial concentration values are based on data provided in Daniels (1993) and Smith et al. (1996). For nonsorbing radionuclides, the initial concentrations are conservatively defined to be a factor of approximately two times larger than reported values. In the base case of sorbing radionuclides, the initial concentrations are reflective of dissolved concentrations that would be expected from filtered samples. In all cases, the lower and upper bound concentrations were determined from a lognormal distribution with a standard deviation (in $\log_{10}$) of 0.5. A listing of mean initial concentration levels, lower-bound and upper-bound concentration levels, decay rates, and distribution of absorption coefficients considered in the analysis are presented in Table 2-1 for the base case and in Table 2-2 for the sorbing radionuclides for the case of colloidal transport.

**Table 2-1
Radionuclide Transport Parameters**

Radionuclide	Half-Life (years)	K _d Range (cm ³ /g)	Mean Initial Concentration (pCi/L)	Lower Bound Concentration (pCi/L)	Upper Bound Concentration (pCi/L)
Carbon-14	5,730	0	1.17 x 10 ⁵	1,778	2,041,700
Cesium-137	30.3	100 to 1,000	105	1.54	1,900
Tritium	12.3	0	3.8 x 10 ¹⁰	5.53 x 10 ⁸	6.808 x 10 ¹¹
Iodine-129	1.57 x 10 ⁷	0	21.3	0.328	376
Plutonium- 239/240	2.4 x 10 ⁴	60 to 1,600	1,750	25.65	31,550
Uranium-238	4.5 x 10 ⁹	1 to 5	48.5	0.713	877

pCi/L = PicoCuries per liter

K_d = Distribution coefficient

**Table 2-2
Radionuclide Transport Parameters - Collodial Transport Case**

Radionuclide	Half-Life (years)	K _d Range (cm ³ /g)	Mean Initial Concentration (pCi/L)	Lower Bound Concentration (pCi/L)	Upper Bound Concentration (pCi/L)
Cesium-137	30.3	0 to 10	105	1.54	1,900
Plutonium- 239/240	2.4 x 10 ⁴	0 to 10	1,750	25.65	31,550
Uranium-238	4.5 x 10 ⁹	0 to 2	48.5	0.713	877

The radionuclides are applied as an initial condition over the first 250 m (820 ft) of the transport model grid. This distance represents approximately twice the cavity diameter.

2.3 Transport Modeling

2.3.1 The MC_TRANS Transport Model

The transport analysis was performed using MC_TRANS (IT, 1996i). The MC_TRANS model is a one-dimensional, solute transport model, designed to simulate chains of constituents in

fractured geologic media. Conceptually the model domain is representative of a set of parallel fractures and surrounding porous rock matrix (see details in Appendix B). Groundwater flowing through the fractures contains dissolved radionuclides subject to diffusion into and out of the surrounding rock matrix. The process of advective-dispersive transport of dissolved constituents through the fractures and associated matrix diffusion is based on a dual porosity representation of the geologic matrix system. The model can also be used to simulate transport in nonfractured, dual porosity, or single porosity media which is the case for the alluvial aquifer. The contaminants are subject to advection, dispersion, sorption, and first-order decay in the fracture but subject to only sorption and first-order decay in the matrix domain. The governing equations for advective-dispersive transport in the fractures and diffusion into the matrix are approximate using the Galerkin finite-element approach (Huyakorn and Pinder, 1983). The source input maybe prescribed concentration or mass flux. Analysis of parameter uncertainty is incorporated into the model using a Monte Carlo approach. The Monte Carlo approach is a method of selecting parameter values from a predefined range of values for use in modeling. The sampling sets for the Monte Carlo simulations have been generated using a Latin hypercube sampling code developed for Sandia National Laboratories (Iman et al., 1980; Davenport and Iman, 1982). Parameter uncertainty allows for zonal variations of all input data using several types of statistical distributions. In addition to transport parameter uncertainty, MC_TRANS includes the capacity to consider the sensitivity of flow velocity to hydrologic parameters and to consider recharge as a way to incorporate flow model uncertainty in the transport simulations. Complete documentation of the original MC_TRANS can be found in the GeoTrans report of 1996 (IT, 1996i).

The one-dimensional model evaluates advective-dispersive transport along stream tubes generated by post-processing of the results of fully three-dimensional MODFLOW simulations of groundwater flow at the Nevada Test Site (IT, 1996f). Because flow along a stream tube is based upon a constant volumetric flow rate, the one-dimensional analysis precludes the ability to evaluate the degree of downgradient attenuation associated with mixing perpendicular to the flowline. Since attenuation due to mixing is an important process, a separate sensitivity analysis using the computer code AT123D (Yeh, 1981) was performed to generate the possible range of dilution attenuation factors associated with transverse mixing processes along pathways of various lengths in the Lower Carbonate Aquifer for different values of dispersion coefficient.

2.3.2 *Transport Simulations*

Separate simulations were performed for each contaminant of concern, and a separate contaminant boundary was determined for each one. The dose results for all contaminants of concern were totaled to define the potential extent of migration of all of the contaminants in the alluvium. This latter result is referred to as the base case contaminant boundary. The simulations are summarized in this section with respect to the 4-mrem/yr dose boundary for a short time frame (less than 200 years) and for the long time frame (up to 25,000 years). The simulations for the individual contaminants are presented in Appendix A. The 200-year time frame is consistent with the maximum length of time that tritium is expected to be at a concentration that would be detrimental to human health. The 25,000-year time frame is approximately one quarter of the median groundwater travel time from the center of Frenchman Flat to its southern boundary. It is a time frame consistent with the groundwater flow scenarios that lead to contaminant migration velocities that are more rapid than average.

For each simulation, breakthrough curves for the contaminants were saved for each location and each of the 200 realizations. These data were processed to identify the 4-mrem/yr boundary in space and time. At each location, there were 200 breakthrough curves, each representing one of the 200 Latin hypercube realizations. Therefore, at each point in time along the breakthrough, there were 200 values, one from each realization. These 200 data points were sorted from smallest to largest, and the concentration that was greater than 50, 80, 85, 90, 95, and 100 percent of the values was recorded. For each observation location at each point in time, a dose equivalent was recorded and processed by a contouring program to produce a figure that presented the 4-mrem/yr boundary as a function of space and time.

The fracture transport simulations performed with MC_TRANS are listed in Table 2-3. For each radionuclide, a single simulation was performed where all parameters in the uncertainty study were varied. For the radionuclides subject to absorption, a similar set of simulations was performed, considering the influence of colloidal transport. The third set of simulations were sensitivity analyses where, for each parameter with a defined distribution, a separate run with 200 realizations was performed while all other parameters were assigned their mean values. The fourth set of runs was a similar sensitivity analysis using the colloidal transport analysis absorption coefficient data. These simulations for the six radionuclides represent the first 18

**Table 2-3
Transport Simulations**

Simulation	Contaminant	Description*
1	Carbon-14	All parameters vary simultaneously.
2	Tritium	All parameters vary simultaneously.
3	Iodine-129	All parameters vary simultaneously.
4	Uranium-238	All parameters vary simultaneously.
5	Cesium-137	All parameters vary simultaneously.
6	Plutonium-239/240	All parameters vary simultaneously.
7	Uranium-238	Colloid transport - all parameters vary simultaneously.
8	Cesium-137	Colloid transport - all parameters vary simultaneously.
9	Plutonium-239/240	Colloid transport - all parameters vary simultaneously.
10	Carbon-14	Uncertainty simulations - parameters vary individually.
11	Tritium	Uncertainty simulations - parameters vary individually.
12	Iodine-129	Uncertainty simulations - parameters vary individually.
13	Uranium-238	Uncertainty simulations - parameters vary individually.
14	Cesium-137	Uncertainty simulations - parameters vary individually.
15	Plutonium-239/240	Uncertainty simulations - parameters vary individually.
16	Uranium-238	Colloid transport - parameters vary individually.
17	Cesium-137	Colloid transport - parameters vary individually.
18	Plutonium-239/240	Colloid transport - parameters vary individually.
19	Carbon-14	MINUTE STEAK Pathway - all parameters vary simultaneously.
20	Tritium	MINUTE STEAK Pathway - all parameters vary simultaneously.
21	Carbon-14	Matrix diffusion in alluvium - all parameters vary.
22	Carbon-14	50 percent correlation of parameters - all parameters vary.
23	Carbon-14	90 percent correlation of parameters - all parameters vary.
24	Carbon-14	Two sources in series - all parameters vary simultaneously.
25	Carbon-14	Vertical pathway - DILUTED WATERS - all parameters vary.
26	Carbon-14	Vertical pathway - PIN STRIPE - all parameters vary.
27	Carbon-14	Vertical pathway - NEW POINT - all parameters vary.

*All simulations are pathways originating at the DILUTED WATERS event unless noted otherwise.

simulations. The remainder of the downgradient transport simulations used the carbon-14 parameters, and the simulations were used to examine specific parameters or other scenarios.

Other simulations, as noted in Table 2-3, were performed to study transport from a different site (MINUTE STEAK), the influence of matrix diffusion in the alluvium, the combined plume formation from two sources, and the influence of parameter correlation on simulation results.

2.3.3 Contaminant Boundary Predictions

The base simulations were conducted on the pathline from the DILUTED WATERS nuclear test. This pathline extends approximately 40,000 meters (24.85 miles) downgradient from the shot cavity. The first 5,000 m (16,400 ft) traverses the Alluvial Aquifer; the next 2,500 m (8,200 ft) traverses the Volcanic Tuff Confining Unit; and the rest of the pathline is in the Lower Carbonate Aquifer. Simulations were run for the duration of time needed for concentrations to decrease to dose levels of less than 4 mrem/yr or for a maximum of 25,000 years. A detailed discussion of the contaminant boundary predictions is presented in Appendix A.

The base case analysis examined flow from the center of Frenchman Flat because the center is closer to the southwestern portion of the basin where contaminants would discharge from the basin into the Lower Carbonate Aquifer, based on the regional groundwater flow model. However, there are seven event locations at the northern end of Frenchman Flat that must also be considered. For carbon-14, the distance from the MINUTE STEAK event to the 4-mrem/yr level is again between 5 and 7.5 km (3.1 and 4.7 miles). This is the same result as for the base case from the center of Frenchman Flat. The difference in the present case is that the path does not enter the Lower Carbonate Aquifer until about 12 km (7.5 miles). At that distance, the carbon-14 concentrations are more than one order of magnitude below the 4-mrem/yr level.

The composite dose, constructed by summing the doses from each radionuclide, is given in Figure 2-2. The distance to the 4-mrem/yr composite dose boundary continues to grow to a distance of about 4 km and to encompass a time of about 7,000 years. The boundary then recedes slightly before it stabilizes for a long period of time. At about 13,000 years, the boundary begins to recede and again stabilizes, this time at a distance of about 1,300 meters. For simulation times up to approximately 15,000 years, the cumulative dose is dominated by carbon-14 because of its high mobility and moderately long half-life. For periods of time greater than 20,000 years, the

Figure 2-2
Contours of the 4-mrem/yr Composite Dose at the 95-Percent Level (Base Case)

effects of uranium and plutonium dominate. The short half-lives for cesium-137 and tritium limit the time and distance over which their concentrations will lead to a dose exceeding 4 mrem/yr. Iodine-129 persists longer because of its longer half-life, but the dose rate soon drops below the 4-mrem/yr level because of the relatively low initial concentrations.

The shape and location of the 4-mrem/yr boundary is of more immediate concern for the next 200 years. The simulations indicate that tritium is the dominant radionuclide for the first 80 years. The composite dose is shown in Figure 2-3, and the dose due to tritium is shown in Figure 2-4. Between 80 and 160 years, both tritium and carbon-14 combine to define the cumulative 4-mrem/yr boundary. Carbon-14 will dominate after 160 years, and it is the primary contaminant determining the location of the 4-mrem/yr boundary for thousands of years.

2.4 Alternate Contaminant Transport Scenarios

Variations of the base flow and transport scenario were also examined to evaluate the possible consequences of uncertainty that were not incorporated in the base case flow and transport models. Uncertainties in the flow model include the geologic model, direction of the horizontal gradient, the magnitude of the vertical gradient, and parameter correlation. Because the base case modeling predicted that the contaminant boundary would not leave the Alluvial Aquifer, characteristics of contaminant transport through the other hydrostratigraphic units were not represented. The distance/dose results for the radionuclide contaminants are controlled significantly by time because of radioactive decay and, consequently, the velocity of the groundwater. Because velocities are much higher in fractured hydrostratigraphic units, including volcanics and particularly the Lower Carbonate Aquifer, scenarios involving transport in these units may produce significantly different results from the base case. The transport velocities derived by dividing the Darcy velocity by the effective porosity showed that the difference of magnitudes between transport velocities in the Carbonate Aquifer and the alluvium may reach 1,000:1.

The uncertainties in the transport model include the transport of contaminants in colloidal form (significantly reducing retardation during transport), coalescing contaminant plumes from different sources, and matrix diffusion in the alluvial aquifer.

Figure 2-3
Contour of 4-mrem/yr Composite Dose at the 95-Percent Level (Base Case)

Figure 2-4
Contour of the 4-mrem/yr Dose from Tritium at the 95 Percent Level (Base Case)

Alternate flow and transport scenarios were developed to evaluate the following situations:

- Correlation of flow parameters that are treated as random variables
- Vertical transport of contaminants resulting in a shorter path to the Lower Carbonate Aquifer
- Dilution of contaminants entering the Lower Carbonate Aquifer
- Colloidal transport of sorbing contaminants
- Multiple sources along a pathline
- Matrix diffusion into porous clasts of volcanic rock in the alluvium

The last two scenarios were not derived from the regional groundwater flow model. These required definition of groundwater fluxes based on other available information.

2.4.1 Vertical Flux

Three paths that led directly to the Lower Carbonate Aquifer in the vicinities of the DILUTED WATERS, PIN STRIPE, and NEW POINT underground tests were considered for this scenario. The paths were developed based on the regional geologic model and additional local data. The flow directions are hypothetical and have been created to examine the case of vertical flow which is inconsistent with the regional groundwater flow model. The DILUTED WATERS pathway extends vertically downwards approximately 1,150 m (3,773 ft), traversing 450 m (1,480 ft) through the Alluvial Aquifer, 300 m (984 ft) through the Volcanic Confining Unit, and 400 m (1,310 ft) through the Tertiary Sediments. The PIN STRIPE pathway extends vertically downward approximately 475 m (1,560 ft), traversing 250 m (820 ft) through the Volcanic Confining Unit, and 225 m (740 ft) through the Tertiary Sediments. The third evaluated pathway at the NEW POINT shot extends 650 m (2,130 ft) downward, traversing 400 m (1,310 ft) through the Volcanic Confining Unit and 250 m (820 ft) through the Tertiary Sediments.

Based on a maximum likely vertical gradient of 0.0164 in Frenchman Flat and horizontal hydraulic conductivities of 0.5 to 2.0 meters per day (m/d) (1.6 to 6.6 feet per day [ft/d]) and a horizontal to vertical hydraulic conductivity ratio of 10.0, a conservative, single, steady Darcy velocity of 1.2 meters per year (m/yr) (3.9 feet per year [ft/yr]) was used for this analysis. All other parameters used in the analysis were based on the general parameters for the carbon-14

analysis. The vertical flow pathway did not use the flow model flux velocity field sensitivity nor the 108 hydraulic conductivity parameters because the vertical pathway was defined without using the regional groundwater flow model. The only parameter that the Darcy velocity is dependent on for these simulations is the uncertainty in recharge.

For the vertical flow scenario, only carbon-14 is considered because of the dominant influence of carbon-14 in the horizontal flow cases. Figure 2-5 is the predicted 4-mrem/yr boundary along one of the vertical flow paths in northern Frenchman Flat. This particular example is the shortest vertical pathway, but it represents the general result of all three vertical paths. At the 95 percentile level, the 4-mrem/yr boundary reaches the top of the Lower Carbonate Aquifer (at a distance of about 500 m) very quickly. The concentrations remain above the 4-mrem/yr level for about 1,200 years before finally decreasing. Thus, concentrations above the 4-mrem/yr level could be introduced into the Lower Carbonate Aquifer for a period of time greater than 1,000 years. Once in the Lower Carbonate Aquifer, the carbon-14 would be transported rapidly downgradient. The location of the 4-mrem/yr boundary in the Lower Carbonate Aquifer has not yet been determined.

2.4.2 Dilution Analysis

The conceptual model used in the dilution analysis is based on the "worst case" vertical transport simulations. The system represented in the model assumes vertical transport through the overlying Alluvial Aquifer, volcanics, and Tertiary sediments into the Lower Carbonate Aquifer and assumes horizontal transport through the high transport-velocity Lower Carbonate Aquifer.

It was anticipated that the combination of the high rate of transport velocity in the Carbonate Aquifer versus the relatively slow change of concentration levels in the vertical pathway would produce a relatively steady source of contaminant to the Carbonate Aquifer over a long period of time. A steady source was used to represent the quasi-steady mode of a slowly changing source term in a rapid velocity field.

Figure 2-5
Contour of the 4-mrem/yr Dose from Carbon-14 at the 95-Percent Level

The results show that, for a case using high dispersivities, the dilution attenuation factors ranged from 44 to 369 depending on the length of downgradient travel after the mass entered the Lower Carbonate Aquifer. For a case using conservative dispersivities, the dilution attenuation factors still ranged between 10 and 76 for lengths of travel between 5,000 and 40,000 m (3.1 and 24.85 miles). A third case was also examined to evaluate radioactive decay versus dilution as a source of attenuation. This case showed that for carbon-14, once the mass entered the Lower Carbonate Aquifer, radioactive decay may no longer play an important role in attenuation of the mass, and the transverse mixing processes may be the dominant mode of attenuation.

2.4.3 Colloidal Transport

Simulations were performed to examine other possible scenarios. The first of these examined the possibility of colloidal transport for the three sorbing nuclides (uranium, cesium, and plutonium). Two changes were made to the model input to simulate the case of colloidal transport; the distribution coefficients were decreased substantially (Table 2-2) to represent the combined transport of contaminant and colloid, and initial concentrations were increased to account for dissolved and bound radionuclides.

For both plutonium-239/240 and uranium-238, the distance to the 4-mrem/yr boundary for colloid-facilitated transport is on the order of 1 kilometer (km) (0.62 miles) at the 95 percent cumulative frequency. The distance to the 4-mrem/yr boundary for colloid-facilitated cesium-137 transport is less than 0.3 km (0.19 miles). The differing results for three sorbing contaminants can be attributed to differing half-lives and base case distribution coefficients. The short half-life of cesium-137 causes it to decay rapidly and leads to a small distance to the 4 mrem/yr boundary. Plutonium 234/240 and uranium-238 decay much more slowly and persist in the groundwater system for a much longer period of time. Even with colloids and remaining within the time frame of this analysis (25,000 years), the carbon-14 remains the radionuclide which produces the greatest distance to the 4-mrem/yr boundary.

Figure 2-6 summarizes the case of colloidal transport for plutonium-239/240 and uranium-238. Compare this boundary with the base case shown in Figure 2-2.

Figure 2-6
Contour of the 4-mrem/yr Composite Dose at the 95-Percent Level
(Colloid-Facilitated Transport Case)

2.4.4 Multiple Sources

There is a possibility that two sources could lie along the same flow path. In that case, both sources contribute radionuclides to the flow system, affecting carbon-14 concentrations along the flow path. The modeling results show that the distance to the 4-mrem/yr level is increased enough that it extends into the Lower Carbonate Aquifer. As noted previously, dilution in the Lower Carbonate Aquifer will decrease concentrations significantly.

2.4.5 Matrix Diffusion

The alluvial material of Frenchman Flat has a large proportion of clasts that are derived from volcanic rocks (Hoffman et al., 1977). The volcanic clasts are porous; therefore, it is possible that the flow in the alluvium is predominantly through the interclast region with a matrix diffusion process into the clasts. Using data from Hoffman et al. (1977), the effective porosity has been given a range of 19 to 27 percent, and the matrix porosity has been assigned a range of 5 to 15 percent. The results suggest that the matrix diffusion process in the alluvium does not contribute much uncertainty to the calculation of the contaminant boundary.

3.0 Sensitivity Analysis and Parameter Uncertainty

This section discusses sensitivity analyses of flow and transport parameters and related uncertainty. These sensitivity analyses ultimately screen down the list of constituents and parameters to only those that significantly affect the decision analysis (Section 5.0). The decision analysis in Section 5.0 will use the sensitivities and uncertainties developed in this section.

As presented in the Groundwater Flow Model Document Package (IT, 1996a), a series of sensitivity analyses were performed to:

- Identify the parameters that most impact the calculated groundwater flux
- Define the magnitude of change in the pathline for a change of factor of two in each of many parameters

These parameter changes resulted in only minor changes in groundwater pathline direction, but in more substantial changes in groundwater flow velocity. This parameter uncertainty was carried into the transport modeling for the value of information analysis through flow model sensitivity coefficients.

3.1 Sensitivity Analysis

A series of sensitivity simulations was performed to examine the impact of the individual parameters on the total uncertainty. One parameter at a time was allowed to vary while the remaining parameters were held constant. If 13 parameters were allowed to vary individually, 13 model runs for each of 200 realizations were performed. Figures 3-1 and 3-2 are examples of the presentation of sensitivity for 13 individual parameters that describe flow and transport.

Appendix B gives the actual values of sensitivities used in the decision analysis of Section 5.0. These figures were constructed to display the maximum concentration of carbon-14 as a function of cumulative frequency. The distance from the contaminant source is 3 km (1.86 miles). Because of the large number of curves, separate plots were prepared for each distance (see Appendix B).

Figure 3-1 indicates the results for individual transport parameters. Figure 3-2 contains the flow sensitivity parameters from the regional groundwater flow model. In these figures, a flat horizontal line represents a parameter that is not important (insensitive) to the model prediction of

Figure 3-1
Example Plot with Uncertainty of Individual Transport Parameters

Figure 3-2
Example Plot with Uncertainty of Individual Flow Parameters

carbon-14 activity. In Figure 3-2, the flat horizontal line characterizing the model effects of hydraulic conductivity in Zone 6 of the alluvium is not important (insensitive) because it does not contribute to the uncertainty. The hydraulic conductivity zones are regions of the model (IT, 1996f) where a particular model parameter has the same value. Zone 1 of the Alluvial Aquifer includes Frenchman Flat. Zone 6 is the region downgradient from Frenchman Flat between Ash Meadows and Death Valley. The most important (sensitive) parameters in Figure 3-1, the ones that vary the most from a horizontal line, are recharge and the source term.

In the regional transport modeling, recharge is a multiplier to the specific discharge that accounts for the uncertainty in recharge. The multiplier would increase or decrease flow in the regional groundwater model. As shown in Figure 3-2, the most important (sensitive) flow parameters are the horizontal hydraulic conductivity and depth coefficients of Zone 1 of the alluvium of Frenchman Flat.

3.2 *Parameter Uncertainty*

The flow model for Frenchman Flat has been derived directly from the regional groundwater flow model without addition of any local information. Important factors to consider are:

- Conceptual model
- Scale of the predictions
- Need for local accuracy
- Use of the predictions

Modeling for the purpose of defining a contaminant boundary is sensitive to the conceptual model (i.e., whether the boundary prediction will be in one hydrologic regime or another). Major features of the conceptual model and accurate general knowledge of parameter values are important. These must be evaluated within the scale of the predicted boundary.

Uncertainties in the parameters that are used in the transport modeling are incorporated into the conceptual model. Each parameter is given an average value and a range of values that encompass the uncertainty. These ranges are used in the transport modeling to calculate a range of potential contaminant migration distances. The conceptual model is based on the transport model results in which 95 percent of the simulations predicted a lesser extent of contamination. Figures which illustrate the effects of the uncertainty for each individual parameter can be found in Appendix B.

In the case of the Frenchman Flat, the predictions of contaminant boundary are on the scale of the Frenchman Flat basin and primarily within one hydrostratigraphic unit, the alluvium. This is a small subregion of the regional groundwater flow model. Local conditions within this subregion may not be represented very well in detail, and the predictions may not be accurate in detail. However, the predictions may be generally accurate within the context of regional flow and transport regime. Evaluation of the effects of scale was part of the uncertainty analysis.

Another factor is the way in which the predictions will be used. Exact predictions of specific contaminant plumes are not required to define a contaminant boundary within the context of the Underground Test Area strategy. Transport distances from the contaminant source and general distribution of the contaminants are sufficient.

3.2.1 Regional Flow Model

The regional groundwater flow model provided the base conceptual flow model used for the transport simulations. Because the regional model synthesizes the geologic and hydrologic controls on the Nevada Test Site regional groundwater flow system in a mass conservative framework, the inflows and outflows from the whole system are balanced. Additionally, the inflows and outflows from individual cells are also balanced. Flow paths identified from the regional model have the advantage of being consistent not only with the local conditions but, more importantly, with external influences that would be missed if the regional flow were ignored.

Uncertainty in any of the input parameters to the flow model will be reflected in uncertainty in the speed and direction of groundwater flow as embodied in the derived pathlines. Similarly, parameter uncertainty is reflected in the groundwater fluxes calculated from the flow model.

A disadvantage of the regional model approach is the necessary simplification of local geology to the regional scale that must be performed to enable the model to operate efficiently. The simplifications eliminate smaller scale features that are not important at a regional scale, but may be of significance at a local scale. As a result, local scale perturbations in the flow field are not represented in the regional model. The vertical flow paths that were evaluated in Section 2.0 were developed independently of the regional flow model to address local uncertainty. Such local scale flow features cannot be readily addressed with the regional model and will require a more detailed model for CAU-scale investigations. The approach in this value of information analysis

establishes a base conceptual model and also has the flexibility to include other conceptual models which represent local conditions.

3.2.2 Frenchman Flat Geology

Uncertainties in the hydrogeology allow markedly different interpretations of the local groundwater flow regime and resultant contaminant transport. One issue is the extent to which groundwater in the alluvium and Tertiary sections is separated from the regional Carbonate Aquifer. There are various questions about the presence, thickness, and vertical hydraulic conductivity of volcanic units and Tertiary sediments that separate the alluvium from the Lower Carbonate Aquifer. Also, the locations of all of the faulting in the lower units in the basin and the vertical fault displacements are not well known. Displacements could be large enough in some places that the alluvium could be in direct contact locally with the Carbonate Aquifer across a fault. The current regional conceptual model relies heavily on interpretation of geophysical data and inference of structure without drilling data for measurements and confirmation.

3.2.3 Frenchman Flat Water Elevations

Groundwater elevation data are documented in the Potentiometric Data Documentation Package (IT, 1996b). Within Frenchman Flat, water elevations have been measured in 12 piezometers screened in the Alluvial Aquifer, in two wells in the Welded Tuff Aquifer, and in one well in the Lower Carbonate Aquifer. In the Alluvial Aquifer, 11 of the 12 wells are aligned in an approximately north-south line extending from the northern boundary of Frenchman Flat to just south of the playa. The exception to the linear alignment is well WW-1 on the eastern side of the Frenchman Flat Playa. The well is no longer available for measurement, and the only data are from a single measurement in 1950. That single measurement is suspect; therefore, the linear alignment of the remaining wells makes the estimation of the magnitude and direction of the horizontal hydraulic gradient difficult. There are only two data points in the Welded Tuff Aquifer, making it impossible to estimate a gradient. For the Lower Carbonate Aquifer, two other wells, located outside of Frenchman Flat, provide evidence that the horizontal gradient is relatively small with an uncertain direction.

The groundwater elevation data in Frenchman Flat are limited in several ways as noted above. The direction and magnitude of the horizontal hydraulic gradient cannot be adequately determined from the existing data. As a result, the flow direction information provided by the

regional groundwater flow model must be relied upon. In summary, the existing data indicate that heads in the Alluvial Aquifer are higher in the north than in the south. This suggests that, in general, the flow of groundwater is from north to south at the scale of the entire Frenchman Flat. Locally, there is an apparent gradient direction reversal in the area of the Nevada Test Site Area 5 Waste Management Site. Water elevations measured in three pilot wells surrounding the Area 5 site suggest that the direction of groundwater flow may be northward rather than southward as the regional model predicts. The edge of the basin is much nearer in this direction, and contaminants may then enter the Lower Carbonate Aquifer at higher concentrations.

The uncertainty in the direction of the gradient and the resultant flow direction of contaminants may also be significant due to possible differences in the hydrostratigraphic layers separating the alluvium from the Lower Carbonate Aquifer in the eastern and western parts of southern Frenchman Flat. The volcanic hydrostratigraphic unit may not be present in the southeastern part of the basin, placing the alluvium in direct contact with Tertiary sediments.

The vertical hydraulic gradient is equally uncertain. No piezometer nests are present in Frenchman Flat. In the northern portion of Frenchman Flat, the water elevations in the Welded Tuff Aquifer are similar to those in the Alluvial Aquifer, suggesting good hydraulic connection between the two hydrostratigraphic units in that area. The average water elevations in the Alluvial Aquifer and Welded Tuff Aquifers are as much as 10 m above the heads in the carbonate wells. However, the carbonate water elevations must be extrapolated more than 6 km to make the comparison, and it is not clear that extrapolation is valid. Finally, the water elevations in the Lower Carbonate Aquifer are lower than the water elevations in the Alluvial Aquifer except in the southern portion of Frenchman Flat where the water elevations in the Alluvial Aquifer decrease. The actual vertical gradient from the alluvium to the carbonate at the scale of the uncertainty evaluated in the vertical path scenarios in Section 2.0 is unknown.

3.2.4 Frenchman Flat Hydraulic Conductivity

The hydraulic conductivity, or transmissivity, data were taken from published reports of aquifer tests analyses, drill stem tests, slug tests, and laboratory analyses of core. The values are summarized in the Hydrologic Parameter Data Documentation Package (IT Corp, 1996d). In the documentation package, each data value was given a quality ranking of either low, medium, or high depending on the type of test and the reliability of the interpretation.

In Frenchman Flat, four tests in alluvium and one test in the Lower Carbonate Aquifer were given a ranking of medium or high. Each of the values represents the horizontal component of hydraulic conductivity. The data for the alluvium are of good quality, but are concentrated in the center of Frenchman Flat. Only one transmissivity is available for the Lower Carbonate Aquifer in Frenchman Flat, and it is located at the eastern edge of the basin. There are no reliable hydraulic conductivity data for the Volcanic Aquifer units. Data are also not available for the northern portion of Frenchman Flat along the boundary between Areas 5 and 11.

The vertical hydraulic component of hydraulic conductivity is available from an unpublished analysis of the early pumping of the CAMBRIC Experiment (Waddell, 1997). From that analysis, the anisotropy ratio of vertical to horizontal hydraulic conductivity is in the range of 10^{-4} to 10^{-2} . The proximity of the CAMBRIC experiment to the playa suggests that the anisotropy ratio for the CAMBRIC experiment will be smaller than near the basin boundaries where less interbedding of fine grained material is expected. However, an estimate of vertical hydraulic conductivity will likely have at least a two-order-of-magnitude uncertainty associated with it.

In summary, the horizontal hydraulic conductivity of the Alluvial Aquifer is adequately known near the edge of the playa. Limited Carbonate Aquifer and anisotropy data are available. No data are currently available for the northern part of Frenchman Flat.

3.2.5 Regional Groundwater Flux

The flux of groundwater through the groundwater flow system is a function of both the hydraulic conductivity and the hydraulic gradient. The local conductivity and gradient data are not adequate to make accurate flux calculations. The regional groundwater flow model provided the groundwater flux through the system. Uncertainty in the flow model comes from uncertainty in the parameters such as hydraulic conductivity, unit thicknesses, and the amount of recharge. Improvements in the local conductivity and gradient data will improve the flux estimates and provide a better assessment of the accuracy of the flow model generated values.

3.2.6 Frenchman Flat Transport Parameters

The primary transport parameters are effective porosity, matrix diffusion, and adsorption. Effective porosity has been measured in the alluvium at the CAMBRIC Experiment Site. The effective porosity of the volcanic units and the carbonate have been estimated from other sources and are documented in the Transport Parameter Documentation package (IT, 1996e). Matrix

diffusion is likely to occur in the volcanics, if fractured, and in the Carbonate Aquifer. There may also be diffusion into clasts of volcanic rocks within the alluvium. The adsorptive characteristics of different radionuclides are known from literature sources, but no data are available from local experiments in Frenchman Flat.

The transport parameters are generally poorly known in Frenchman Flat with the exception of the effective porosity of the alluvium in the vicinity of the CAMBRIC experiment. Literature data were relied upon for many of the values and, as a result, there are large uncertainties associated with many of the transport parameters.

3.2.7 Frenchman Flat Source Term

Limited sampling of cavity waters in several event cavities, including CAMBRIC is available. Most of the sampling did not follow standard groundwater sampling protocols and may not be representative of all the event cavities. CAMBRIC is also known to have been a nonstandard nuclear test relative to the resultant tritium in the groundwater. Otherwise, the source term is based on apportioning the total inventory for nuclear tests not conducted on Pahute Mesa among all of the tests based on cavity size, as computed from the upper yield value released for each test. This information does not account for any differences in the devices and has the uncertainty inherent in the total inventory estimates and the amount of each radionuclide available in a mobile form. The uncertainty in the source term is currently quite large, particularly with respect to radionuclides other than tritium.

3.3 Uncertainties in Predicting the Contaminant Boundary

The uncertainty analyses presented in Sections 2.0 and 3.0 identified the scenarios or parameters that contributed the greatest uncertainty to the calculation of the 4-mrem/yr boundary. The greatest uncertainty is the possible existence of a downward vertical flux. Along that vertical flux, the single largest contribution to the uncertainty about the contaminant concentration at the top of the Lower Carbonate Aquifer is the uncertainty in the source term. If the existence of the vertical flux can be refuted by later data collection, then the uncertainty along the horizontal flow path will become the next most important parameter in the calculation of the 4-mrem/yr boundary. For the nonsorbing contaminants which dominate the calculation of the boundary for time periods up to 20,000 years, the primary parameters contributing to the uncertainty are

horizontal flux, source term, dispersivity, and effective porosity. For the sorbing contaminants, the most important parameters are the distribution coefficient, source term, and horizontal flux.

To reduce the uncertainty in the calculated 4-mrem/yr boundary, the sources of that uncertainty must be reduced. The uncertainty associated with the vertical flux can be eliminated if it can be demonstrated that such a path does not exist. The existence of a vertical flux cannot be measured directly; it must be inferred from other measurements. If the flux is vertical, for example, measurements will need to demonstrate that the vertical flux is negligible. Vertical flux is not directly measured in groundwater, but it is calculated from measurements of hydraulic conductivity and hydraulic gradient. Hydraulic gradient is obtained from vertical measurements of water elevations. Therefore, a measurement suite designed to demonstrate or refute the existence of a vertical flux would require both hydraulic gradient and hydraulic conductivity data collection. In addition, knowledge of other supporting information about the local geologic structure and stratigraphy will enhance the usefulness of data collection to refute the vertical flux scenario. A variety of linked experiments may be necessary to answer one question.

The reduction in source term uncertainty involves much more than simply collecting several water samples. Implied questions are embodied in the source term uncertainty pertaining to additional contaminants of concern, release mechanisms, and colloids. Again, a variety of measurement options needs to be defined in order to collect the appropriate data to reduce the uncertainty associated with the source term.

Similarly, the horizontal flux is not measured directly. Horizontal hydraulic gradient from measurements of water elevations and conventional aquifer testing will have to be combined to produce a better estimate of horizontal flux. Horizontal flux also requires various types of information in order to answer a single question.

The sources of uncertainty identified in Sections 2.0 and 3.0 may require complicated and elaborate data collections to reduce the uncertainty. A simple concern, such as the source term, contains many questions which may need to be dealt with in order to provide more confidence in the predicted location of a contaminant boundary.

3.4 Major Categories of Uncertainty

A major uncertainty that came from the analyses of potential transport from nuclear events in Frenchman Flat focused on the correct paths to use in transport modeling. There are two general possibilities: horizontal transport to the basin edge and then into carbonate or vertical transport to the underlying carbonate. The vertical path is much shorter, and subsequent transport in the carbonate is much further. The priority of the other uncertainties depends upon the flow path. If vertical transport predominates, the source term becomes the second priority, and transport parameters are the third priority. If horizontal transport predominates, then for nonsorbing contaminants, the horizontal flux is the second priority; the source term is the third priority; and transport parameters are the fourth priority. However, for horizontal transport of sorbing contaminants, transport parameters (specifically the distribution coefficient) are the second priority. Horizontal flux becomes the third priority, and the source term becomes the fourth priority. These categories are discussed at length in the following sections.

3.4.1 Vertical Flux

Focus: Characterize the hydrogeology sufficiently to support flow modeling that will produce representative flow paths which, in turn, are used to model transport of contaminants from shots.

The transport path from a shot is determined by a variety of factors that control groundwater flow including the geologic structure, hydrostratigraphic unit properties, and hydraulic gradient.

Predicting the future transport path requires a model that incorporates these factors throughout the area of transport and also incorporates assumptions about the stability of future conditions.

Presently, there is general information on the hydrogeology of the alluvium in central Frenchman Flat, and a reasonable geologic model of Frenchman Flat has been developed. However, much of the deeper basin structure and hydrostratigraphic unit characteristics are inferred and are subject to considerable speculation. Most drillholes in Frenchman Flat have penetrated the alluvium; only a few have penetrated the underlying volcanics. These drillholes are primarily located in central (Area 5) and north central (Area 11) locations, and they provide a poor spatial basis for determining hydraulic gradient. Several drillholes around the basin have penetrated to the carbonate, but they are not suitable for providing additional information because of their location or physical condition. While the general basin structure has been mapped based on geologic and geophysical interpretation, measurements of deeper hydrostratigraphic unit thicknesses, samples

of the deeper hydrostratigraphic unit materials, tests in those materials, and measurements of vertical hydraulic gradients are not available.

Based on the paths extracted from the regional flow model, transport of contaminants from nuclear events in Frenchman Flat has been modeled primarily as horizontal flow in alluvium. Two special cases of vertical transport to the carbonate with subsequent horizontal transport in the carbonate were also modeled, representing Area 5 and Area 11. Transport in the alluvium is very slow due to low flow velocities (low gradient and high effective porosity) and high retardation for sorbing contaminants. The horizontal transport model predicts transport distances that mostly do not leave the alluvium. However, the vertical transport case presents a much shorter path through the alluvium and the deeper hydrostratigraphic units to the carbonate where transport is much more rapid. This results in much greater transport distance predictions for contaminants once they reach the carbonate. For Frenchman Flat in general (Area 5, Area 11, and downgradient), the actual case is probably a combination of both horizontal and vertical transport. For Area 11 there is also a possible local horizontal gradient near the edge of the basin, which results in a short path to the carbonate.

3.4.2 Source Term

Focus: Characterize the source term so it can be used in transport modeling to provide a sufficiently good prediction of the dose-based boundary in space and time.

Based on the available inventory information for non-mesa shots, an approximate total mass for each contaminant can be assigned to each shot, assuming all shots are proportionately the same based on cavity size. However, the distribution, chemical and physical form, and dissolved concentration of contaminants in the area of the shot cavity are not well known. The available analyses of groundwater samples from shot cavities and wells near shot cavities provide information on the chemical form and concentration of the dissolved contaminants in a few locations, but do not provide any comprehensive definition of the concentration distribution around a shot cavity. Consequently, the assumptions made about the source term concern the shot-specific contaminant inventory, the general concentration distribution of contaminants in the area of the shot cavity, the mass of contaminants that are not already in the groundwater, and the release characteristics of these stored contaminants. In addition, there are some contaminants for which there is little or no concentration information.

The following information about the source term is required for the transport modeling:

- Identification of all important contaminants
- Chemical and physical form and concentration distribution of contaminants in groundwater in the underground event area
- Physical model of the rocks in the underground event area
- Chemical and physical form and mass distribution of those contaminants in storage in the area of the underground event
- Release model for contaminants in storage

3.4.3 Horizontal Flux

Focus: Characterize flow parameters sufficiently to allow accurate modeling of the average groundwater flow rate through Frenchman Flat.

Based on an acceptable geologic model with well-defined hydrostratigraphic unit thicknesses, the horizontal flux is determined by the horizontal gradient and the horizontal hydraulic conductivity. The requirement for knowledge of horizontal gradient includes both direction and magnitude. Currently, the gradient is not well-known due to the poor quality of the hydraulic head measurements used to compute gradient and due to the poor spatial distribution of data points. Gradient information and hydraulic conductivity information for deeper hydrostratigraphic units do not exist and are inferred. In the case of horizontal flow as indicated by the regional flow model, general knowledge of these parameters over the predicted area of transport is acceptable. In the case of Area 11, regarding a possible local gradient near the basin edge, local gradient information is required. Due to difficulties in making measurements to determine head with an accuracy appropriate to the head differences across Frenchman Flat, the uncertainty in gradient may not be reducible to the desired level.

3.4.4 Transport Parameters

Focus: Characterize transport parameters sufficiently to support accurate modeling of the transport velocity of contaminants through Frenchman Flat hydrostratigraphic units and the underlying carbonate aquifer.

Based on the determination of the transport path of contaminants, the general physical parameters controlling the velocity and distance of transport are effective porosity and dispersion. The contaminant-dependent parameters are the distribution coefficient and matrix diffusion. These parameters, with the exception of matrix diffusion, are well known for the alluvium in the location of the CAMBRIC experiment, but poorly known otherwise. Information regarding deeper hydrostratigraphic units is inferred based on the geologic model.

3.4.5 Other Uncertainties

The following list contains four other specific uncertainties that have been identified for Frenchman Flat. These are listed in this report to provide complete information, but they do not fit into the general analysis and are not addressed. They are not judged to present significant uncertainty for the long-term prediction of transport compared to the parameters included in the analysis.

- Recharge to the alluvium and contaminant mobilization, resulting from surface water flow into one event crater in central Frenchman Flat
- Effects of recharge to the Alluvial Aquifer due to disposal of production water from the CAMBRIC experiment to the CAMBRIC ditch
- Contaminant loading to the groundwater from events in the unsaturated zone: the mobilization mechanism and rate
- Contaminant transport from event cavities below the water table, up the chimneys, providing much greater vertical spreading of contaminants from the shot cavity

3.5 Summary of Uncertainty Analysis

The base case conceptual model of the Frenchman Flat groundwater flow system is a description of the general characteristics of the flow system, and it forms the framework for the later simulations. The pathlines from the regional groundwater flow model form the basis of the base line conceptual model which indicates essentially horizontal flow through the Alluvial Aquifer from the nuclear test cavities. Other aspects of the base line conceptual model include the assumption of porous flow in the alluvium and adsorption of selected radionuclides to the aquifer material. Transport simulations based on the base case conceptual model provide an estimate of the potential extent of contaminant migration and serve as the base case contaminant boundaries for the value of information analysis. The best available site knowledge, as well as the

uncertainty in that knowledge, are incorporated into the base case conceptual model. The term "conceptual model" will be used in the text in place of the more cumbersome term "base case conceptual model."

The results of the transport model used to predict a 4-mrem/yr boundary are presented at the 95 percent level, which means that most effects of parameter uncertainty that would tend to increase the distance are included in the prediction. The conceptual model represents the current understanding of reality and is the basis for the approximation of the contaminant boundary location that would be recommended if closure of the corrective action unit were decided today. If the parameter uncertainty in the conceptual model is reduced, the distance from the source to the boundary could be reduced. One goal of the uncertainty analysis is to identify which parameters contribute the most to uncertainty in the conceptual model. This would provide decision-makers with some of the information needed to determine the type and location of additional data that may need to be collected before selection of the remedial alternative.

The major categories of uncertainty are summarized in order of importance.

- First priority: Resolve the uncertainty between the base case conceptual model and the existence of a vertical flux to the Lower Carbonate Aquifer. Resolution of uncertainty requires sufficient characterization of the hydrogeology to support flow modeling that will produce representative flow paths for use in modeling the transport of contaminants from nuclear events. This involves improved knowledge of geology, vertical gradient, and vertical hydraulic conductivity.
- Second priority: Resolve the uncertainty in the conceptual model parameters that control:
 - Horizontal Flux. Resolution of uncertainty requires sufficient characterization of the flow parameters to allow accurate modeling of the average groundwater flow rate through Frenchman Flat. This involves improved knowledge of the geology, horizontal gradient, and horizontal hydraulic conductivity.
 - Source Term. Resolution of uncertainty requires sufficient characterization of the source term to support transport modeling that provides a good prediction of the dose-based boundary in space and time. This involves identification of the key contaminants, their initial concentrations, and the long-term release model for each contaminant as well as determination of their inventories.

- Transport Parameters. Resolution of uncertainty requires sufficient characterization of the transport parameters to allow accurate modeling of the radionuclide concentrations through Frenchman Flat. This involves improved knowledge of effective porosity, more accurate dispersion coefficients for each hydrostratigraphic unit, and improved knowledge of distribution coefficients for each key contaminant.

4.0 Estimated Reduction in Parameter Uncertainties

Uncertainties in model predictions of contaminant transport and the resulting contaminant boundary have been discussed in Sections 2.0 and 3.0 of this document. These uncertainties include scenarios and parameter values for groundwater flow, the contaminant source term, and contaminant-specific migration in saturated geologic media. Data collection and analysis activities can be proposed to improve the use of existing data or to collect new data that would reduce these uncertainties. This value of information analysis involves estimating the potential reductions in uncertainty for proposed activities and determining their resultant effect on the boundary prediction. These estimates directly support the sixth objective of the value of information analysis, which is to determine the activities that have the most value for reducing uncertainty in the contaminant boundary when compared with their cost.

A variety of data collection and analysis options are presented in this section and will be used as the basis for analyzing the value of reducing uncertainty. Functional groupings of activities, called option combinations, have been developed to address major categories of uncertainty that emerged from the sensitivity analyses. Reduction of uncertainty in the boundary prediction and the cost to achieve that reduction will be developed through use of a decision model, presented in Section 5.0.

4.1 Data Collection and Analysis Options

In order to apply the value of information analysis process to quantify the reduction of uncertainty that might be achieved and the cost to achieve it, specific packages of options called alternatives had to be defined. The options are organized around specific types of parameters used in the flow and transport modeling. Table 4-1 shows the relationship of the option types to the data types and how they were combined to address the major categories of uncertainty in the flow and transport modeling. Note the acronym assigned for each option type. The options are designed to address a specific focus. The specifications for the elements in an option provide a fixed point of reference for the option and allow cost-estimating.

The scenarios and parameter values included in this uncertainty analysis are often related, making it difficult to deal with them independently. For example, when work is done to improve information on one scenario or parameter, information on other scenarios is often improved with

Table 4-1
Categories of Data Collection/Analysis Options
 (Page 1 of 2)

Question - Data Type	Data Collection/Analysis Option Type (acronym)	Frenchman Flat Data Constraints and Ranges	Data Collection and Analysis Category
Hydrogeology	Geology (G)	Interpretation of current field data allows for possibility of downward migration of contaminants. The presence of an aquitard between the alluvium and carbonates is assumed (see Figure 1-4).	Vertical Flux
	Vertical Gradient (VG)	Interpretation of groundwater elevations produces a range in vertical hydraulic gradient of about 0.01 to 0.10 m/m.	
	Vertical Hydraulic Conductivity (VHC)	Assumed to be 10 percent of the horizontal hydraulic conductivity which decreases with depth in the basin alluvium.	
	Horizontal Gradient (HG)	Interpretation of groundwater elevations produces a range horizontal hydraulic gradient of about 0.0001 to 0.001 m/m.	
	Horizontal Hydraulic Conductivity (HHC)	Interpretation of well pumping and recovery tests produces a range in horizontal hydraulic conductivity of about 0.01 to 1.0 m/d in the basin alluvium.	
Source Term	Source Term (ST)	Initial concentrations vary with each contaminant. Radionuclides range in concentration from about 2×10^1 to 4×10^{10} pCi/L, with tritium and carbon-14 contributing most to the source (see Table 2-1).	Source Term

Table 4-1
Categories of Data Collection/Analysis Options
 (Page 2 of 2)

Question - Data Type	Data Collection/Analysis Option Type (acronym)	Frenchman Flat Data Constraints and Ranges	Data Collection and Analysis Category
Transport Parameters	Alluvium Transport Parameters (ATP)	Effective porosity from the CAMBRIC site was used to establish range of 0.25 to 0.35. Matrix diffusion was not considered to be important in the basin alluvium.	Transport Parameters
	Volcanic Transport Parameters (VTP)	No data are currently available for volcanics at Frenchman Flat. If needed, the ranges for effective porosity and matrix diffusion from other portions of the regional flow system can be assumed.	
	Carbonate Transport Parameters (CTP)	No data are currently available for carbonates at Frenchman Flat. The transport velocity in the carbonates was assumed to be about 1,000 times greater than the transport velocity in the alluvium during consideration of the alternate contaminant transport scenarios (see Section 2.4).	
	Distribution Coefficient (DC)	Adsorptive properties for the six radionuclides were obtained from literature, and they range from 0 to 1,600 cm ³ /g (see Table 2-1). The distribution coefficient assumed for lead was 100 cm ³ /g.	

Notes: (1) A more detailed description of the proposed data collection options and costs is presented in Appendix C.
 (2) Values for other modeling parameters are shown in Table B-5.

little or low increase in effort or cost. In order to recognize and incorporate these relationships, the options were combined into functional groups which correspond to major categories of uncertainty. The "option combination category" shown in column three of Table 4-1 introduces the functional groupings that were used for the decision analysis that is discussed in Section 5.0.

Within each option type, the options were subdivided according to three levels of work:

- Level 1 - Use of existing data for evaluation, analysis, or modeling
- Level 2 - Nonintrusive data collection: new analysis of existing samples or text/sample existing wells
- Level 3 - Intrusive data collection: drill new boreholes, construct new wells, test/sample

There are increasing cost and schedule requirements for accomplishing each level of the option. The proposed options are identified in Table 4-2 according to their option type and level. An additional alphabetic designator has been added to the option identifier when there are multiple options at the same level under that option category. The data sheets for each option are in Appendix C, and they include a detailed description, the specific focus, option limitations, and a cost estimate.

The options listed in Table 4-2 do not encompass all possibilities for activities. In some cases, it was determined that all worthwhile work at a specific level had already been done (G1 option type) or that there were no existing data (VTP1 and VHC1 option types), samples, or wells (VHC2 option type) to support an option or that the cost of the option was too great to consider (more elaborate, Level 3 activities). These options are meant to be representative, and they provide reference points within the range of possibilities. These can be refined at a later date, or activities can be redefined.

4.2 Uncertainty Reduction Estimates

Uncertainty reduction can be accomplished by collecting additional information to define the parameter in question at all locations or to define the statistics of the parameter variability for use in stochastic modeling. The latter approach has been adopted here for practical reasons because of the scale of the problem and the cost of collecting information. The intent of the flow and transport modeling is not to provide an exact prediction of the contaminant plumes that may occur

Table 4-2
Matrix of Data Collection and Analysis Options

Data Collection/ Analysis Option Type	Evaluate and/or Model Existing Data	New Analysis of Existing Samples	Test and/or Sample Existing Wells	Construct New Wells, Test and/ or Sample
Geology		G2a, G2b, G2c		G3a, G3b
Vertical Gradient	VG1		VG2	VG3c, VG3d
Vertical Hydraulic Conductivity				VHC3
Source Term	ST1	ST2c	ST2a, ST2b	ST3
Horizontal Gradient	HG1		HG2	HG3
Horizontal Hydraulic Conductivity	HHC1		HHC2	HHC3
Alluvium Transport Properties	ATP1		ATP2	ATP3
Volcanic Transport Properties			VTP2	VTP3
Carbonate Transport Properties	CTP1		CTP2	CTP3
Distribution Coefficients	DC1	DC2		DC3

Notes: A more detailed description of the proposed data collection options is presented in Appendix C.

in the future, but to provide a representative prediction encompassing the uncertainty that cannot be eliminated. The prediction will include the location of the dose-based contaminant boundary in space and time at the 95 percent confidence level. This prediction will ensure that the boundary only encompasses the contaminant plume, rather than defining it. Defining the objective in this manner allows for considerable uncertainty in local detail of flow and transport and reduces the requirement for comprehensive characterization while accomplishing the goal of protecting human health and the environment.

These estimates have been developed by the internal working group members who conducted this value of information analysis. These estimates may be reversed based on additional input. The absolute value of the option scores is not of paramount importance to decision-makers defining the work scope; however, how the options rank with respect to each other is significant in determining what work is necessary.

4.3 Alternatives (Option Combinations)

Four functional categories of alternatives (option combinations) were introduced in Table 4-1: Vertical Flux, Horizontal Flux, Source Term, and Transport Parameters. These combined options pertain to various parameters that were examined in the sensitivity analysis according to their general effects on transport prediction. These four categories directly correspond to the categories of uncertainty that have been discussed, and the alternatives address the objectives for each category. Also for each category, there is a table showing the matrix of the most likely option combinations, giving the estimated potential reduction in uncertainty that was assigned to the alternative. Each alternative has been assigned a unique number for reference. These are described in Appendix C. The individual costs for the options and the total costs for the alternatives are also included. In addition, a figure illustrating the estimated potential reduction in uncertainty versus the cost for each alternative is provided.

4.3.1 Vertical Flux

Focus: Characterize the hydrogeology sufficiently to support flow modeling that will produce representative flow paths which, in turn, are used to model transport of contaminants from nuclear events.

Table 4-3 illustrates various combinations of activity options and the estimated reduction in uncertainty that each combination affords. Figure 4-1 is a graphical representation of this table. Several assumptions were made about alternatives based on a judgement about how the overall activity should be conducted. First, it was assumed that all options would include evaluating existing data (VG1) and second, all options would include collecting improved data from existing wells (VG2).

It is easier to evaluate these combinations in the following groupings:

- Basic option(s) plus the seismic survey
- Basic options plus one or two boreholes
- Basic options plus the seismic survey and one or two boreholes
- All previous option combinations and vertical hydraulic conductivity measurement(s)

Several features of the pattern of estimated reduction in uncertainty should be noted. More importance was given to the specific questions for Area 11 than for Area 5, and less was given to Frenchman Flat in general. The importance was judged relative to the specific potential problems

Table 4-3
Estimated Potential Reduction in Uncertainty for Vertical Flux

Alternative	Option	G2b	VHC3	VG1/HG1	VG2	VG3c	VG3d	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$2,036,934	\$1,999,774	\$50,000	\$224,723	\$3,495,026	\$4,389,456		
1				x				\$50,000	0
2		x		x				\$2,086,934	8
3				x	x			\$274,723	4
4		x		x	x			\$2,311,657	12
5				x	x	x		\$3,769,749	28
6		x		x	x	x		\$5,806,683	41
7				x	x		x	\$4,664,179	22
8		x		x	x		x	\$6,701,113	36
9				x	x	x	x	\$8,159,205	37
10		x		x	x	x	x	\$10,196,139	47
11			x	x	x	x		\$5,769,523	62
12		x	x	x	x	x		\$7,806,457	74
13			x	x	x		x	\$6,663,953	59
14		x	x	x	x		x	\$8,700,887	72
15			xx	x	x	x	x	\$12,158,753	75
16		x	xx	x	x	x	x	\$14,195,687	87

G = Geology
VHC = Vertical Hydraulic Conductivity
VG = Vertical Gradient
HG = Horizontal Gradient

Figure 4-1
Estimated Potential Reduction in Uncertainty for Vertical Flux

noted for these areas which present much more serious consequences regarding transport distance than uncertainty in the general magnitude of transport distance for Frenchman Flat. A synergistic effect with the seismic survey was recognized and considered. The seismic survey was valued more highly when combined with drilling because the drilling provided the required boreholes to tie the seismic to the actual geology of the stratigraphy and the physical properties of the formations.

4.3.2 Source Term

Focus: Characterize the source term for use in transport modeling to provide a good prediction of the dose-based boundary in space and time.

Table 4-4 presents the various combinations of activity options, the cost of the option combination, and the estimated reduction in uncertainty that each combination affords.

Table 4-4
Estimated Potential Reduction in Uncertainty for Source Term

Alternative	Option	ST1	ST2a	ST2b	ST2c	ST3	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$1,247,474	\$326,127	\$199,682	\$138,467	\$1,491,345		
17		x	x				\$1,573,601	15
18		x	x	x			\$1,773,283	30
19		x	x		x		\$1,712,068	35
20		x	x	x	x		\$1,911,750	50
21		x	x			x	\$3,064,946	60
22		x	x	x		x	\$2,264,628	65
23		x	x		x	x	\$3,203,413	65
24		x	x	x	x	x	\$3,403,095	80

ST = Source Term

Figure 4-2 is a graphic representation of this table. Several assumptions about option combinations were made based on judgement about how the overall activity should be conducted. Specifically, Options ST1 and ST2a were considered in every option combination because these options represent funded tasks for FY 97. The other three options are considered independently and in every possible combination. The high degree of uncertainty reduction placed on the ST3

Figure 4-2
Estimated Potential Reduction in Uncertainty for Source Term

option and the combinations containing that option comes from the comprehensive nature of that activity. These factors provided a level of validation for all of the available background data and offered coordinated data that resulted in cavity source. Presently, source term data is an assemblage of different pieces of data from many sources. Recent drilling and sample analyses from Wells ER-20-5 and ER-20-6 suggest that there is considerably more to know about the hydrologic source terms than can be defined or predicted from the existing data. This may be because previous data collection was usually limited to specific purposes rather than general characterization.

4.3.3 Horizontal Flux

Focus: Characterize flow parameters sufficiently to allow accurate modeling of the average groundwater flow rate through Frenchman Flat.

Tables 4-5a and b show various combinations of activity options and the estimated reduction in uncertainty that each combination affords. Figures 4-3 and 4-4 are graphic representations of this table. Activity Option HHC1 was included in all combinations because evaluating existing data provided the basis for incorporating new data from the other options. The most value in reduction in uncertainty was attributed to the HG3 activity and the triple HHC3 option, which provides equivalent data for measuring the general horizontal gradient across Frenchman Flat.

Almost all of the existing wells are located in the central part of the flat and do not provide the necessary two-dimensional base for defining the gradient. The general proximity of the wells to each other also results in the head measurement uncertainty being very large in comparison to the gradient being measured, thus making the gradient measurement very uncertain. Local measurements of horizontal gradient would be beneficial, but may not be achievable due to measurement uncertainties. However, in the case of Area 11, an attempt to determine the local gradient near the edge of the basin would also be very valuable.

This data collection could be considered as an adjunct to the VG3c activity where individual wells would be spread out and additional water table piezometers would be included with the deeper piezometer installations.

The second part of the table (Options 47 through 58) presents a series of option combinations duplicating some of those in the first part of the table (Options 25 through 46), but lists lesser

Table 4-5a
Estimated Potential Reduction in Uncertainty for Horizontal Flux

Alternative	Option	G2b	HHC1	HHC2	HHC3	HG2	HG3	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$2,036,934	\$50,000	\$679,745	\$2,095,105	\$224,723	\$2,172,084		
25			x					\$50,000	0
26		x	x					\$2,086,934	6
27			x			x		\$274,723	10
28		x	x			x		\$2,311,657	17
29			x			x	x	\$2,446,807	43
30		x	x			x	x	\$4,483,741	54
31			x	x		x		\$954,468	14
32		x	x	x		x		\$2,991,402	21
33			x	x		x	x	\$3,126,552	50
34		x	x	x		x	x	\$5,163,486	61
35			x		x	x		\$2,369,828	14
36		x	x		x	x		\$4,406,762	22
37			x		x	x	x	\$4,541,912	50
38		x	x		x	x	x	\$6,578,846	61
39			x		xxx	x		\$6,560,038	62
40		x	x		xxx	x		\$8,596,972	72
41			x	x	x	x		\$3,049,573	19
42		x	x	x	x	x		\$5,086,507	28
43			x	x	xxx	x		\$7,239,783	63
44		x	x	x	xxx	x		\$9,276,717	74
45			x	x	xxx	x	x	\$9,411,867	72
46		x	x	x	xxx	x	x	\$11,448,801	81

G = Geology HHC = Horizontal Hydraulic Conductivity HG = Horizontal Gradient

Table 4-5b
Estimated Potential Reduction in Uncertainty for Horizontal Flux*

Alternative	Option	G2b	HHC1	HHC2	HHC3	HG2	HGc	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$2,036,934	\$50,000	\$679,745	\$1,393,440	\$224,723	\$2,172,084		
47			x		x ^a	x		\$1,668,163	14
48		x	x		x ^a	x		\$3,705,097	22
49			x		x ^a	x	x	\$3,840,247	50
50		x	x		x ^a	x	x	\$5,877,181	61
51			x		xxx ^a	x		\$5,156,708	62
52		x	x		xxx ^a	x		\$7,193,642	72
53			x	x	x ^a	x		\$2,347,908	19
54		x	x	x	x ^a	x		\$4,384,842	28
55			x	x	xxx ^a	x		\$5,836,453	63
56		x	x	x	xxx ^a	x		\$7,873,387	74
57			x	x	xxx ^a	x	x	\$8,008,537	72
58		x	x	x	xxx ^a	x	x	\$10,045,471	81

G = Geology HHC = Horizontal Hydraulic Conductivity HG = Horizontal Gradient

*This table shows options identical to those in the preceding table, but costs are adjusted to eliminate duplicate wells, assuming HHC3 is conducted on the same location(s) as VG3. One monitoring well can serve both activities.

^aCost Adjustment

Figure 4-3
Estimated Potential Reduction in Uncertainty for Horizontal Flux

Figure 4-4
Estimated Potential Reduction in Uncertainty for Horizontal Flux with VG3 Option

costs (see footnote for Table 4-5b, page 13). The cost reductions are based on those option combinations being included with the options in the vertical flux categories, allowing elimination of duplicate or overlapping costs. In particular, the assumption is that the appropriate water level monitoring well in the VG3 activity would be used as the monitoring well for the pumping test in the HHC3 activity.

4.3.4 Transport Parameters

Focus: Characterize transport parameters sufficiently to support accurate modeling of transport velocity of contaminants through Frenchman Flat hydrostratigraphic units and the underlying Carbonate Aquifer.

Tables 4-6, 4-7, 4-8, and 4-9 show various combinations of activity options and the estimated

Table 4-6
Alluvium Transport Properties

Alternative	Option	ATP1	ATP2	ATP3	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$113,430	\$235,850	\$3,278,386		
59		x			\$113,430	5
60		x	x		\$349,280	20
61		x	x	x	\$3,627,666	25
62		x	xx ^a		\$361,280	25
63		x	x	x ^b	\$2,926,001	25

^aAssume 2nd set of core analyses on VG3 core.

^bAssume this test is done in conjunction with a VG3 well set, allowing elimination of one water level monitoring well.

ATP = Alluvium Transport Properties

reduction in uncertainty that each combination affords (Figures 4-5, 4-6, 4-7, and 4-8 are graphic representations of the tables). Several assumptions about activity option combinations were made based on judgement about how the overall activity should be conducted. In all cases, reviewing all relevant existing data will be important for establishing the basis for judging and using new data.

Inclusion of multiple units of some activities was done on occasions when a large value was perceived for multiple tests to improve general characterization of a parameter for a large area or

Table 4-7
Volcanic Transport Properties

Alternative	Option	VTP2	VTP3	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$124,498	\$5,357,244		
64		x		\$124,498	15
65		x	x	\$5,481,742	70
66		xx ^a		\$136,498	40
67		x	x ^b	\$3,847,775	70

^aAssume 2nd set of core analyses on VG3 core.

^bAssume this test is done in conjunction with a VG3 well set, allowing elimination of one water level monitoring well.

VTP = Volcanic Transport Properties

Table 4-8
Carbonate Transport Properties

Alternative	Option	CTP1	CTP2	CTP3	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$98,869	\$121,498	\$6,656,532		
68		x			\$98,869	5
69		x	x		\$220,367	10
70		x	x	x	\$6,876,899	60
71		x	xx ^a		\$232,367	35
72		x	x	x ^b	\$4,646,645	60

^aAssume 2nd set of core analyses on VG3 core.

^bAssume this test is done in conjunction with a VG3 well set, allowing elimination of one water level monitoring well.

CTP = Carbonate Transport Properties

Table 4-9
Distribution Coefficients

Alternative	Option	DC1	DC2	DC3	Cost of Alternative	Estimated % Reduction in Uncertainty
	Option Cost	\$49,365	\$91,678	\$2,960,193		
773		x			\$49,365	10
74		x	x		\$141,043	35
75		x		x	\$3,009,558	60
76		x	x	x	\$3,101,236	70

DC = Distribution coefficients

Figure 4-5
Estimated Potential Reduction in Uncertainty for Alluvium Transport Properties

Figure 4-6
Estimated Potential Reduction in Uncertainty for Volcanic Transport Properties

Figure 4-7
Estimated Potential Reduction in Uncertainty for Carbonate Transport Properties

Figure 4-8
Estimated Potential Reduction in Uncertainty for Distribution Coefficients

when multiples were tied to other activities that increased the value (such as collecting new samples on which to run additional tests). Relative to the total transport predicted for the standard transport path, the uncertainty in transport parameters could make a large difference.

Note that for Table 4-6, the additional estimated reduction in uncertainty, attributed to Option ATP3 (between Option Combinations 60 and 61) is increased by only a small percent. In contrast, on Table 4-7, the additional estimated reduction in uncertainty, attributed to Option VTP3 (between Option Combinations 64 and 65) is much larger.

5.0 Decision Analysis

Decision analysis allows the inclusion of subjective judgments in the report such as those given in Section 4.0. Previously, Section 2.0 introduced the subject of uncertainties in the contaminant boundary and in the predictions of its location. Section 3.0 summarized the sensitivity analyses of regional flow and transport parameters for Frenchman Flat and introduced the concept of the vertical flux. Such sensitivity analyses often purport to generate "optimal" actions on the basis of purely objective inputs. However, the sensitivity analyses in Section 3.0 ignore the subjective judgements of managers and policy makers. Consequently, Section 4.0 introduced the opinions of experts about how much potential field and analysis activities would reduce the uncertainty in the location of the contaminant boundary and the existence of a vertical flux to the carbonate. In fact, decision analysis requires personal judgements; they are important ingredients for making good decisions.

At the same time, human beings imperfectly process information; their insights about uncertainty and preferences can both be limited and misleading, even when they show great confidence. Therefore, decision analysis typically involves an iterative process that:

- Identifies the problem and key parameters (Section 2.0)
- Conducts sensitivity analyses (Section 3.0)
- Assesses uncertainty and preferences (Section 4.0)
- Mathematically represents the decision analysis (this section)

In this iterative process, the decision-maker's perception of the contaminant boundary may change; beliefs about the likelihood of various uncertainties may develop and change; and preferences not previously considered may mature as the decisions are reflected upon. This section systematically integrates the decisions that have been developed in Sections 2.0 and 4.0 with the sensitivities of the various flow and transport parameters and components given in Section 3.0. The next few sections describe the:

- Decision model
- Results of the decision analysis
- Cost-effectiveness of data gathering activities

5.1 Decision Model

To quantify and integrate the individual decisions and identify an optimal information collection and remediation strategy, we used the DPL software developed by Applied Decision Analysis, Inc. (1995). The next few paragraphs briefly describe how this decision analysis measures the "Value of Information," how it uses DPL to tie decisions with the flow and transport calculation of distance to the contaminant boundary, and how the individual judgements of uncertainty affect the calculated distance to the contaminant boundary.

5.1.1 Calculation of the Value of Information

The value of a given piece of information depends on its validity and its worth. An expert's information is said to be "perfect" if it is always correct.

Expected Value of Information = the expected value with information - the expected value without.

Note that perfect information is used as a basis of comparison. We know that perfect knowledge will not be achieved. Therefore, the predicted changes in distance to the boundary represent the potential maximum predicted changes caused by a particular piece of information.

To calculate the value of information, the sensitivity analyses of flow and transport parameters in Section 3.0 have simplified the scope of the decision analyses. They have screened the list of nuclides for consideration down to only carbon-14. These sensitivity analyses showed that the dose from carbon-14 represented the maximum extent of the boundary for a period of up to 15,000 years. The information presented in Section 3.0 can be described as "hard" information. In contrast, Section 4.0 presents the uncertainty reductions assessed by individuals who know the program and the subjects. They ranked the activities and discussed how the information gained would contribute to reduction in uncertainty in the pertinent parameter; then they assigned their estimated, predicted percent reductions. The information presented in Section 4.0 can be described as "soft" information because it is based on the subjective judgements of those individuals who know the program and its subjects. Through the use of the DPL decision software, such "hard" and "soft" information can be combined in a systematic way to evaluate the value of various data collection and analysis options in reducing the uncertainty in the predicted distance to the contaminant boundary. This study calculates the contaminant boundary for a 95 percent confidence level for a 4-mrem/yr dose, both of which represent assumptions that over

predict the distance to the contaminant boundary. These assumptions over-predict the boundary, reduce the risk for human exposure to contaminated groundwater outside the boundary, and maximize the amount of water that is unavailable for future use.

5.1.2 DPL Model

Figure 5-1 gives a schematic of the DPL decision model for Frenchman Flat. The rectangle

Figure 5-1
Schematic of DPL Decision Model for Frenchman Flat

represents the decisions and subjective estimates of uncertainty reduction from Section 4.0. These decisions concern the specific field tests and analyses for the following work scope categories:

- Vertical Flux
- Source Term
- Horizontal Flux

The ovals represent the sensitivities and probabilities for various flow and transport parameters from Sections 2.0 and 3.0. Figure 5-1 shows that information in the form of arrows from the rectangle and ovals goes into a calculation of one-dimensional flow and transport in the first value node (rectangle with rounded corners). Note that the DPL decision model actually performs a flow and transport calculation as part of the decision analysis. This calculation uses the same sensitivities and parameter probabilities used by MC_TRANS in an analytical solution by

van Genuchten and Alves (1982), the details of which are presented in the next section. This flow and transport calculation ultimately predicts the concentration and cumulative dose of carbon-14 at various distances from the source.

Figure 5-1 shows, schematically, how the DPL decision model for Frenchman Flat takes the "soft information" found in the experts' opinions on the subject matter developed in Section 4.0 and couples them in a Monte Carlo manner with the "hard information" developed in the sensitivity analyses of the flow and transport parameters given in Sections 2.0 and 3.0. The next section describes the specifics of the decision category called "Horizontal Flux" in terms of the information links among the decision rectangle, parameter ovals, and value nodes in the diagram.

5.1.3 Horizontal Flux

Section 4 (Table 4-5) gives the estimated potential reduction in uncertainty for the various horizontal flux options or decisions. DPL takes the uncertainty reductions corresponding to each decision and calculates a separate 95-percentile error band for each parameter:

$$\text{Sigma95} = \text{Std. Dev.} * 2 * (1 - \text{Uncertainty Reduction})$$

The above equation is the key link between the "soft" information given in Section 4.0 and the "hard" information given in Sections 2.0 and 3.0. Through this link, DPL can calculate the transport distance to the contaminant boundary for various sizes of the error band according to the uncertainty reduction from each option. DPL calculates Sigma95 for each parameter in which a particular work option changes the uncertainty in its parameter. As the uncertainty reduction increases, the corresponding 95 percent error band for each parameter decreases. In the case of the average Darcian flow velocity, this would correspond to a reduction in the specific discharge components, q_x and q_y (the analysis neglects the effect of uncertainty reduction on because its value is small relative to q_x and q_y). For example, DPL takes q_1^* as defined in Appendix B and simply adds Sigma95 as calculated by the above equation to yield:

$$q_x = q_1^* + \text{Sigma95}$$

If a particular alternative gives no reduction in uncertainty, the decision model calculates the maximum 95-percentile error band for Sigma95. No reduction in uncertainty would yield the

largest possible Darcian flow velocity. So, with the largest possible flow velocity, the decision model would calculate the largest possible distance to the contaminant boundary. In contrast, horizontal flux alternatives that reduce the uncertainty more would then predict smaller distances to the contaminant boundary. These reduced distances would represent the benefit of using information from those alternatives.

DPL calculates the specific discharge component q_y in the same way (while simply using an average value of q_z , as discussed above). From these three components, DPL calculates a resultant Darcian velocity and then a seepage velocity which comes from dividing the resultant Darcian velocity by the porosity and the retardation coefficient.

DPL then sends the seepage velocity to an EXCEL spreadsheet to calculate the concentration and dose of carbon-14 at various distances. The spreadsheet implements the one-dimensional analytical solute transport model (ODAST) originally developed by Ogata and Banks (1961) and modified by van Genuchten and Alves (1982).

The MC_TRANS analyses also assumed a mechanical longitudinal dispersivity of 250 meters. With these data, a benchmark comparison between the ODAST implementation of the pulse boundary condition and the MC_TRANS results was performed.

In Appendix A, Figure A-10 shows that the MC_TRANS finite element code predicts that the 4-mrem/yr composite dose at the 95 percent level occurs at 4,500 meters at about 7,500 years. Figure 2-2 also shows that the contaminant boundary of carbon-14 occurs at a maximum distance of about 4.5 km (2.8 miles) after about 7,500 years. The DPL implementation of the ODAST model calculates a dose of 4.57 mrem/yr at 7,500 years at a distance of 4,500 meters. Given that MC_TRANS is a finite element model that has included much of the geologic and flow field heterogeneity and ODAST had to assume a much simpler system, the two results are rather close.

This is not the last word on modeling for Frenchman Flat. This approach to flow and transport modeling for the value of information analysis simply helps define the additional work which may be needed. We have found that in comparing the MC_TRANS/MODFLOW concentrations with those of the DPL decision model concentrations which use the analytical solution, there was a difference of only about 7 percent for Frenchman Flat. The decision analysis found that this

value of information analysis, at least for Frenchman Flat, is not sensitive to the approach chosen for flow and transport modeling, whether it is three-dimensional or one-dimensional.

5.2 Results of the Decision Model

As described above, the decision model for Frenchman Flat uses the regional groundwater flow and contaminant transport data to predict the location of the contaminant boundary in the alluvium. It also uses the same data to assess what information gathering decisions will best reduce the uncertainty in the existence of a vertical flux. The decision model for Frenchman Flat considers carbon-14 only. The dose from carbon-14 constitutes a significant proportion of the dose at longer time periods. Also, the decision model uses carbon-14 because the screening transport analyses with MC_TRANS found that for the six radionuclides (considering lead), carbon-14 gives the largest distance to the boundary up until about 15,000 years; so the decision analysis only focuses on carbon-14 because it dominates the boundary up until 15,000 years.

The DPL model assesses various categories of work scopes (decision options) to determine what work to collect information had the most value in reducing the uncertainty in either the existence of a vertical flux or the actual distance to the boundary. The first and most important uncertainty to resolve is whether a vertical flux exists because once carbon-14 reaches the carbonate, it will take relatively no time to reach the springs at Ash Meadows. Other major decisions to reduce uncertainty deal with work scopes that better define the horizontal flux, source term, and transport properties.

Within each category of work scope, there are several alternatives that address the issue for that category (for example, Options 25 through 58 were designed to reduce uncertainty in horizontal flux). Each option combination has a different cost and will achieve different reductions in uncertainty. As mentioned earlier, the decision model takes these reductions in uncertainty (i.e., "soft information") and combines them with the "hard information" associated with flow and transport to predict a percent reduction in the distance to the contaminant boundary. The comparison of the distances predicted with and without a given piece of information acquired under a particular option gives the percent reduction in the predicted distance. The next four sections give the value of the uncertainty reductions achieved for various categories of work scope and alternatives within each work scope category for vertical flux, source term, and horizontal flux.

5.2.1 Vertical Flux

To resolve whether or not a vertical flux to the carbonates exists in Area 5 or Area 11, we have not used DPL. Instead, we have simply used expert opinion to estimate reductions in the uncertainty concerning the existence of vertical flux to the carbonates. Figure 5-2 relates the costs of these alternatives against the uncertainty reductions derived from expert opinion. Note that Figure 5-2 shows the same data contained in Figure 4-1. These data tell how much reduction in uncertainty each alternative will achieve in answering whether or not a vertical flux to the carbonates exists.

Figure 5-2 shows that work scopes of different costs may achieve comparable reductions in uncertainty. For example, Alternatives 12, 14, and 15 reduce uncertainty between 70 and 80 percent. However, the cost among them varies from \$8 million to over \$12 million. Based on cost-effectiveness, Alternative 5, 11, or 12 gives the best value for the information acquired to resolve whether vertical flux to the carbonates occurs.

If we assume that a vertical flux exists, we can use DPL to estimate how much the uncertainty reductions from each alternative will affect various issues related to a contaminant boundary. Because current data can be used to estimate the depth to the top of the carbonates, Figure 5-3 compares percent reduction in uncertainty in time to reach the top of the Lower Carbonate Aquifer instead of the reduction in the distance to the contaminant boundary. The analyses assume a depth to the top of carbonate of 1,150 meters. Uncertainty reductions in transport times to the top of the carbonate for various alternatives range from zero percent to nearly 40 percent. Most of the uncertainty reduction results because the alternatives would generate additional information on regional recharge and the porosity of the underlying units. Again, Alternative 5, 11, or 12 gives the best value for the information acquired to reduce the uncertainty in the estimated time to reach the top of the carbonates.

However, these apparently large reductions in the uncertainty of the vertical travel times have little effect on the dose at the top of the carbonates. Figure 5-4 shows that, for all the alternatives, the maximum reduction in the dose uncertainty at the top of the carbonates is less than two percent. The dose at the top of the carbonate remains at about 145 mrem/year. Reasons why the dose at the top of the carbonates seems insensitive to the data gathering alternatives for the vertical flux include:

Figure 5-2
Percent Reduction in Uncertainty in Existence of Vertical Flux to the Lower Carbonate

Figure 5-3
If Vertical Flux Exists, Percent Reduction in Uncertainty in Time to Reach the Top of Lower Carbonate

Figure 5-4

If Vertical Flux Exists, Percent Reduction in Uncertainty in Dose, mrem, at Top to the Lower Carbonate

- The travel time for Carbon-14 to the top of the carbonates is only 10 percent of its half-life, hence radioactive decay has little effect.
- The source term changes little in the time required for Carbon-14 to reach the carbonates.

None of the information derived from Alternative 5, 11, or 12 gives much practical benefit in terms of the change in dose at the top of the carbonates. Furthermore, the AT123 dilution study in Section 3 suggests dilution attenuation factors of between 44 and 10 or 93 and 19 after travel through the 5,000 or 10,000 meters, respectively, of the Lower Carbonate Aquifer. Even though these attenuation factors do not include the additional attenuation caused by matrix diffusion, the dose at 5,000 meters would range between 3 and 14 mrem. At 10,000 meters, the dose would range between 0.8 and 8 mrem. Therefore, with matrix diffusion accounted for, it is likely that the 4-mrem/year requirement would be met somewhere before 10,000 meters.

5.2.2 Source Term

At least three major factors contribute to uncertainty in the source term: the potential for colloidal transport of radionuclides, the selection of the list of contaminants of concern, and the concentration of the contaminants. Figure 2-6 illustrates that colloidal transport of radionuclides starts to push out the distance to 4-mrem/yr organ dose boundary at 17,000 years and that the change in distance with time continues to accelerate as it approaches 25,000 years. At 25,000 years, colloidal transport appears to dominate the boundary as it continues to expand outward.

However, for purposes of this decision analysis, the decision model used carbon-14 because the screening transport analyses with MC_TRANS found that for the six radionuclides (and lead), carbon-14 dominated distance to the boundary until about 15,000 years.

Figure 5-5 shows the reduction in distance to the contaminant boundary for the alternatives that gather additional information to reduce uncertainty in the source term (Table 4-2).

The alternatives proposed for resolving uncertainties in the source term may reduce the uncertainty in the distance to boundary from about 5 to 35 percent, for costs ranging from \$1,500,000 to \$3,400,000.

The strong effect of the source term upon the distance to the contaminant boundary corresponds directly to the high sensitivities in the cumulative frequency plots given in Figures 3-1 and 3-2.

Figure 5-5
Percent Reduction in Distance to Contaminant Boundary from Source Tests for Various Alternatives

Based on cost-effectiveness, Alternatives 22 and 24 give the best value for the information acquired to reduce the uncertainty in the predicted distance to the contaminant boundary.

However, the practical meaning of these large reductions in uncertainty in the distance to the contaminant boundary depends upon the horizontal groundwater velocity. A low groundwater velocity would mean that gathering information on the source term would have little practical benefit in predicting the distance to the contaminant boundary. In contrast, a high groundwater velocity could mean that the gathering of source term information would have great value in predicting the distance to the contaminant boundary.

5.2.3 Horizontal Flux

This category considers alternatives that measure the reduction in uncertainty by the reduction in the distance to the contaminant boundary for flow along a horizontal path. Figures 4-3 and 4-4 show the estimated decrease in uncertainty for horizontal flux for each alternative. Section 5.1.3 describes how the decision model applied these reductions in the uncertainty for horizontal flux to the velocity of contaminant transport in the alluvium. Figure 5-6 shows two clusters of the cost/benefit results for the horizontal flux category: one cluster costs from \$50,000 to \$6 million to reduce the uncertainty in the distance to the boundary by 2 percent or less; the other cluster costs from \$2 million to \$12 million to reduce the uncertainty in the boundary distance between 3 and 6 percent. However, given these small reductions in uncertainty, neither cluster of horizontal flux alternatives seems to have much benefit in reducing uncertainty in the distance to the contaminant boundary.

5.3 Cost-Effectiveness of Data Gathering Activities

Table 5-1 gives the optimum work scope for the key uncertainties when they are considered separately. Table 5-1 shows that for the vertical flux to the carbonates, the work scopes that may resolve the uncertainties in the most cost-effective manner will be either Alternative 5, 11, or 12. These options for vertical flux to the carbonates all involve various combinations of data collection and analysis options and include evaluating existing data, a seismic survey, one or two additional boreholes, and measurements of vertical hydraulic conductivity.

Figure 5-6
Uncertainty Reduction in Horizontal Distance to the Contaminant Boundary with Horizontal Flux Tests

Table 5-1 reflects similar combinations of activities in the optimal work scopes for source term and horizontal flux. Table 5-1 includes no transport parameters because carbon-14, which has a distribution coefficient equal to zero, controls the location of the contaminant boundary.

Table 5-1
Optimum Work Scope for Key Uncertainties

Key Uncertainty	Work Scope Number	Likelihood of Resolving the Existence of a Vertical Flux	Reduction in Uncertainty in Time for Vertical Flux to Reach the Carbonate	Reduction in Uncertainty in Dose at Top of the Carbonate*	Reduction in Distance to 4 mrem/year Contaminant Boundary	Cost (Millions)
Vertical Flux to Lower Carbonate	5	28%	10%	0.34%		\$3.8
	11	62%	25%	0.87%		\$5.8
	12	74%	32%	1.1%		\$7.8
Source Term	22				26%	\$1.9
	24				35%	\$3.4
Horizontal Flux	27				0.7%	\$0.3
	51				4.2%	\$5.2
	55				5.6%	\$5.8

*Lower Carbonate boundary assumed at depth of 1,150 meters.

To resolve whether or not a vertical flux to the carbonates exists in Area 5 or Area 11, Alternative 5, 11, or 12 gives the best value for the information acquired. If we assume that a vertical flux exists, Alternative 5, 11, or 12 also gives the best value for the information acquired to reduce the uncertainty in the estimated time to reach the top of the carbonates.

However, these apparently large reductions in the uncertainty of the vertical travel times have little effect on the dose at the top of the carbonates. None of the information derived from Alternative 5, 11, or 12 gives much practical benefit in terms of the change in dose at the top of the carbonates. In terms of cost-effectiveness, Option 11 for vertical flux gives a 62 percent reduction while Option 55 for horizontal flux gives only a 6 percent reduction for the same cost. So, Option 11 looks more cost-effective than Option 55 if we assume that all considerations are equal.

The strong effect of the source term upon the uncertainty in the distance to the contaminant boundary suggests that data gathering activities along this line may have considerable value. Based on cost-effectiveness, Alternatives 22 and 24 give the best value for the source term information to reduce the uncertainty in the predicted distance to the contaminant boundary.

However, the practical meaning of these large reductions in uncertainty in the distance to the contaminant boundary depends upon the horizontal groundwater velocity. A low groundwater velocity, such as that believed to exist at Frenchman Flat, means that gathering information on the source term will have little practical benefit in predicting the distance to the contaminant boundary.

In conclusion, while some of the vertical flux and source term alternatives may greatly reduce the uncertainty in the time to reach the Lower Carbonate Aquifer and the distance to the contaminant boundary, respectively, they both may have little practical benefit. In the case of the vertical flux alternatives, the large reductions in the uncertainty of the vertical travel times have little effect on the dose at the top of the carbonates. Estimates of the dilution potential of the Lower Carbonate Aquifer may confirm this hypothesis. In the case of the source term alternatives, the large reductions in uncertainty may also have no practical effect because of the low groundwater velocities.

6.0 Summary, Conclusions, and Recommendations

A value of information analysis has been completed as part of the Corrective Action process for Frenchman Flat. A value of information analysis is a cost-benefit analysis applied to the acquisition of new information which may reduce the uncertainty in the prediction of a contaminant boundary surrounding underground nuclear tests at the Nevada Test Site. The benefit can be defined as the potential reduction in distance from the underground event locations to the contaminant boundary that may be obtained from the gathering and analysis of additional field data. The cost is the investment made to obtain the new information in Frenchman Flat.

Methodologies incorporated into the value of information analysis include geological modeling, groundwater flow modeling, contaminant transport modeling, statistics, sensitivity analysis, uncertainty analysis, and decision analysis. The *Federal Facility Agreement and Consent Order* requires the future development of more detailed corrective action unit models than those used to make the initial boundary predictions used in this document. Sensitivity analysis of the regional pathline predictions included consideration of regional groundwater flow, contaminant transport parameters for seven contaminants, and speculative bounding scenarios. Carbon-14 emerged from the screening process as the primary contaminant of potential concern over the long term (15,000 yrs). The uncertainty analysis further identified the importance of establishing the existence or nonexistence of a downward vertical flux in the alluvium of Frenchman Flat.

The decision analysis used the contaminant boundary predictions from the regional modeling, the results of the sensitivity analysis, and the data collection and analysis alternatives to evaluate the cost benefit of data gathering activities. Alternatives for data collection and analysis were obtained by evaluating the current data for Frenchman Flat contained in the regional data documentation packages, identifying the data gaps, proposing data gathering and analysis alternatives, estimating the costs of the alternatives, and using expert opinion to estimate the reduction in uncertainty obtained by implementing each alternative. The decision model for Frenchman Flat used parameter sensitivities and probabilistic values associated with each data gathering alternative to calculate a radioactive dose and a corresponding downgradient distance. The decision analysis related the estimated reduction in parameter uncertainty to the change in distance at the contaminant boundary with the cost of each data gathering alternative. In this manner, the value of information analysis compared the cost of acquiring new information in a

future corrective action investigation at Frenchman Flat with the benefit of acquiring that information.

The conclusions of the value of information analysis for Frenchman Flat were:

- Existing data for Frenchman Flat are insufficient to determine if a vertical flux from the alluvium to the Lower Carbonate Aquifer is present.
- A vertical flux may significantly extend the predicted contaminant boundary when basin contamination is introduced into the regional groundwater system of the Lower Carbonate Aquifer.
- If contamination is limited to the alluvium of Frenchman Flat, the major categories of uncertainty in the contaminant boundary are related to horizontal flux, source term, and other transport parameters such as effective porosity, matrix diffusion, and adsorption.
- Reductions in the uncertainty for a contaminant boundary in the basin alluvium are not cost-effective because the improvement in predicted location is insignificant when compared to the large investment costs.

Several work scope alternatives recommended for consideration are shown in Figure 5-2 as numbers 5, 11, and 12. These numbers identify specific work scope that are described in more detail (as data gathering options) in Table 4-5. Alternatives 5, 11, and 12 are estimated to reduce the uncertainty in the existence of a vertical flux from about 28 percent to 74 percent with an investment ranging from approximately \$3.8 million to about \$7.8 million. Each data gathering option (such as G2b, VHC3) is described in further detail in Appendix C.

Field data gathering options that the three alternatives have in common are VG1/HG1, VG2, and VG3c (Table A-3). These three field options (constituting, in combination, Alternative 5) are estimated to reduce the uncertainty in the existence of a vertical flux to the carbonates by 28 percent at a cost of about \$3.8 million. They include:

- Evaluate existing data (VG1/HG1), which should increase confidence in the existence or absence of a vertical flux through more detailed compilation and analysis of Frenchman Flat information.
- Collect new information from existing wells (VG2), which should increase confidence in vertical hydraulic gradient from the measurement of precision water elevations.

- Construct new wells to obtain vertical precision water elevations levels in Area 11 (VG3c), which should increase confidence in the existence or absence of a vertical hydraulic gradient near the basin boundary.

The potential reduction in uncertainty through implementation of Alternative 5 is obtained by progressively gaining accuracy in the measurement of vertical water elevations and, consequently, determining if a vertical hydraulic gradient in Area 11 exists. Because Area 11 is near the basin periphery of Frenchman Flat, the thickness of the alluvium is less than that of the basin center (Area 5), and a higher probability of a vertical flux near a contaminant source is present at Area 11. However, the implementation of Alternative 5 only helps with the vertical hydraulic gradient issue. This issue could be mitigated by the presence of a confining layer between the alluvium and the Lower Carbonate Aquifer. If modeling using the new information predicts contaminant transport from the alluvium to the Lower Carbonate Aquifer, additional data would be required to resolve the vertical flux issue.

Alternative 11 includes the three field options of Alternative 5 with the addition of VHC3 (Table 4-3), estimated to reduce the uncertainty in the presence or absence of a vertical flux to the carbonates by 62 percent at a cost of \$5.8 million. The reduction of uncertainty for a vertical flux in the vicinity of Area 11 is obtained by determining if a confining layer between the alluvium and the Lower Carbonate Aquifer exists. The additional field option of Alternative 11 is to construct new wells to obtain vertical hydraulic conductivity information in Area 11 (VHC3), which should increase confidence in the determination of the vertical flux.

Alternative 12 includes the four field options of Alternative 11 with the addition of G2b (Table 4-3), estimated to reduce the uncertainty in the presence or absence of a vertical flux from the alluvium to the carbonates by 74 percent at a cost of \$7.8 million. The reduction in uncertainty for a vertical flux in the vicinity of Area 11 is obtained by using a two-dimensional, seismic survey to help determine geologic structure, which should increase confidence in placing the new wells at the best locations.

Alternative 16, a very expensive alternative, includes the four field options of Alternative 11, with the additional construction of a vertical gradient well in Area 5 (VG3d), new wells to obtain vertical hydraulic conductivity information in Area 5 (VHC3), and a two-dimensional seismic survey in Areas 5 and 11 to determine geologic structure and to aid in the location of exploratory

boreholes (G2b). Alternative 16 is estimated to reduce the uncertainty in the existence of a vertical flux to the carbonates by 87 percent at a cost of about \$14.2 million. The additional field options for Alternative 16 are:

- Construct new wells to obtain precision water elevations in Area 5 (VG3d), which should increase confidence in the existence or absence of a vertical hydraulic gradient near the basin center.
- Construct new wells to obtain vertical hydraulic conductivity information in Area 5 (VHC3), which should increase confidence in the determination of the vertical flux.
- Perform a two-dimensional seismic survey in Areas 5 and 11 to help determine geologic structure (G2b), which should increase confidence in placing the new wells in the best locations.

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Appendix A

Contaminant Boundary Analysis

A.1.0 Contaminant Boundary Analysis

The complete set of transport simulations of the contaminant boundary is presented in this appendix, which includes the 4-mrem/yr dose boundary for a short term (less than 200 years), for the long term (up to 25,000 years), for individual contaminants, and for composite dose from all six contaminants. The 200-year time frame is consistent with the maximum length of time tritium is expected to be at a concentration that would be detrimental to human health. The 25,000-year time frame is approximately one quarter of the median groundwater travel time from the center of Frenchman Flat to its southern boundary. It is a time frame consistent with the groundwater flow scenarios that lead to contaminant migration velocities that are more rapid than average. The figures that illustrate the boundary lines for the various contaminants are at the end of this section.

A.1.1 Method for Defining the Contaminant Boundary

For each simulation, breakthrough curves for the contaminants were saved for each location and each of the 200 realizations. These data were processed to identify the 4-mrem/yr boundary in space and time. At each location, there were 200 breakthrough curves, each representing one of the 200 Latin hypercube realizations. Therefore, at each point in time along the breakthrough, there were 200 values, one from each realization. These 200 data points were sorted from smallest to largest, and the concentration that was greater than 50, 80, 85, 90, 95, and 100 percent of the values was recorded. These percentages are commonly considered in the analysis of data (with the exception of the 100 percent value). The 100 percent case is included to provide a maximum concentration. Each concentration was converted into a dose equivalent using the multiplication factors given in Table A-1 (Adams, 1996). The multiplication factors were

Table A-1
Dose Conversion Factors

Radionuclide	Dose Conversion Factor (mrem per pCi/L)
Iodine-129	0.19320
Plutonium-239/240	2.47590
Cesium-137	0.035
Carbon-14	0.001463
Tritium	0.0000448
Uranium-238	0.1785

determined using a drinking water ingestion dose model. For each observation location at each point in time, a dose equivalent was recorded and processed by a contouring program to produce a figure that presented the 4-mrem/yr boundary as a function of space and time. The discussions in the following text will be limited to the 95 percent case. The 95 percent case is considered the maximum reasonable case because lower percentages will lead to closer boundaries. The 100 percent case is the maximum of the 200 realizations and, as such, represents an extreme case that should not be considered likely to ever occur. Other cases (such as 50 percent or 80 percent levels) will show a boundary that is closer to the sources than the 95 percent level boundary.

A.1.2 Horizontal Flow Case (Long-Term Results)

The 4-mrem/yr boundary lines for cesium-137, tritium, iodine-129, carbon-14, uranium-238, and plutonium-239/240 are given in Figures A-1 to A-6, respectively. The short half-lives for cesium-137 (Figure A-1) and tritium (Figure A-2) limit the time and distance over which their concentrations will lead to a dose exceeding 4 mrem/yr. Iodine-129 (Figure A-3) persists longer because of its longer half-life, but the dose rate drops below the 4-mrem/yr level because of the relatively low initial concentrations. Carbon-14 (Figure A-4) is an interesting case because of its high mobility and moderately long half-life. The distance to the 4-mrem/yr boundary continues to grow to a distance of about 4 km and a time of about 7,000 years. The boundary then recedes slightly before it stabilizes for a long period of time. At about 13,000 years, the boundary begins to recede and again stabilizes, this time at a distance of about 1,300 meters. At the source (distance zero), the carbon-14 concentrations exceed the 4-mrem/yr dose for a period of 15,000 years.

The final two plots, uranium (Figure A-5) and plutonium (Figure A-6), have similar behavior because of their very long half-lives and lower mobility due to sorption. Although the transport travel distances are short, these two radionuclides persist at concentrations above the 4-mrem/yr level for many years. The composite dose, constructed by summing the doses from each radionuclide, is given in Figure A-7. For simulation time up to approximately 15,000 years, the composite dose is dominated by carbon-14. For periods of time greater than 20,000 years, the effects of uranium and plutonium dominate. For the composite dose, the 4-mrem/yr boundary expands for the first 7,000 years, stabilizes until 15,000 years, decreases until 20,000 years, and finally appears to stabilize again after 20,000 years.

A.1.3 Horizontal Flow, Case (Short-Term Results)

The plots in Section 3.1 show that for the longer time period, the 4-mrem/yr boundary is dominated by carbon-14. A more immediate concern is the shape and location of the 4-mrem/yr boundary over the shorter time frame of the next 200 years. Parallel with that concern is the identification of the radionuclides that most influence the 4-mrem/yr boundary over the next 200 years. Figures A-8, A-9, and A-10 depict the 4-mrem/yr boundary for tritium, and carbon-14 and the composite dose for a period of 200 years. An examination of these figures reveals that tritium is the dominant radionuclide for the first 80 years. Between 80 and 160 years, both tritium and carbon-14 combine to define the composite 4-mrem/yr boundary. Carbon-14 will dominate after 160 years and is the primary contaminant determining the location of the 4-mrem/yr boundary for thousands of years.

A.1.4 Horizontal Flow With Colloidal Transport

Sorbing contaminants are allowed to move more freely because of colloidal transport, Figures A-11 and A-12 depict the 4-mrem/yr boundary for uranium-238 and plutonium-239/240. The uranium plot is minimally different from the base case because the change in the distribution coefficient in the colloidal transport case is small. Table 2-2 states that the distribution coefficient for uranium-238 ranged from 1 to 5 cm³/g for the base case, and it was decreased to the range of 0 to 2 cm³/g for the colloid facilitated travel case. This change is much smaller than for cesium-237 or plutonium-239/240. For plutonium, the difference between the base case and Figure A-13 is dramatic. The composite dose plot, Figure A-10, reflects the influence of the colloidal transport of plutonium. In this case, the 4-mrem/yr line stabilizes until about 17,000 years and then begins to expand again.

A.1.5 Vertical Path Scenarios

Only the effect of carbon-14 is considered for this example because of the dominant influence of carbon-14 in the horizontal flow cases. Figure A-14 is the predicted 4-mrem/yr boundary along one of the vertical flow paths in northern Frenchman Flat. This particular example is the shortest vertical pathway, but it represents the general result of all three vertical paths. At the 95 percentile level, the 4-mrem/yr boundary reaches the top of the Lower Carbonate Aquifer (at a distance of about 500 m) very quickly. The concentrations remain above the 4-mrem/yr level for about 1,200 years before finally decreasing. Thus, concentrations above the 4-mrem/yr level could be introduced into the Lower Carbonate Aquifer for a period of time greater than

1,000 years. Once in the Lower Carbonate Aquifer, the carbon-14 would be transported rapidly downgradient. The exact location of the 4-mrem/yr boundary in the Lower Carbonate Aquifer has not been determined. However, as noted in Section 2.2.2, there will be from one to two orders of magnitude dilution in the Lower Carbonate Aquifer because of the three-dimensional dispersion effects not accounted for in the one-dimensional analysis as part of the regional flow and transport modeling.

A.1.6 *Boundary Conclusions*

The figures provided in this section provide insight into the distance to the 4-mrem/yr boundary as a function of time. For time periods up to 80 years, tritium is the contaminant that defines the location of the boundary in the horizontal flow case and would likely do the same in the vertical path case. At intermediate time periods (120 to 20,000 years), carbon-14 dominates the location of the 4-mrem/yr boundary in the horizontal flow case. Between 80 and 120 years, both the tritium and carbon-14 combine to define the 4-mrem/yr boundary. If colloidal transport is occurring, then long-lived radionuclides such as plutonium-239/240 may become important at longer time periods (greater than 20,000 years). In all the horizontal flow cases, the 4-mrem/yr boundary did not enter the Lower Carbonate Aquifer and did not extend beyond the geographic boundary of Frenchman Flat.

If such a vertical path or another similar short path to the Lower Carbonate Aquifer is present, water with radionuclide concentrations above the 4-mrem/yr limit could be introduced into the Lower Carbonate Aquifer. These higher concentrations will be rapidly transported downgradient. The distance to the 4-mrem boundary in the Lower Carbonate Aquifer is uncertain at this time and would require more detailed three-dimensional transport simulations.

Figure A-1
Contour of the 4-mrem/yr Dose from Cesium-137 at the 95 Percent Level (Base Case)

Figure A-2
Contour of the 4-mrem/yr Dose from Tritium at the 95 Percent Level (Base Case)

Figure A-3
Contour of the 4-mrem/yr Dose from Iodine-129 at the 95 Percent Level (Base Case)

Figure A-4
Contour of the 4-mrem/yr Dose from Carbon-14 at the 95 Percent Level (Base Case)

Figure A-5
Contour of the 4-mrem/yr Dose from Uranium-238 at the 95 Percent Level (Base Case)

Figure A-6
Contour of the 4-mrem/yr Dose from Plutonium-239/240 at the 95 Percent Level (Base Case)

Figure A-7
Contour of the 4-mrem/yr Composite Dose at the 95 Percent Level (Base Case)

Figure A-8
Contour of the 4-mrem/yr Dose from Tritium at the 95 Percent Level (Base Case)

Figure A-9
Contour of the 4-mrem/yr Dose from Carbon-14 at the 95 Percent Level (Base Case)

Figure A-10
Contour of 4-mrem/yr Composite Dose at the 95 Percent Level (Base Case)

Figure A-11
Contour of the 4-mrem/yr Dose from Uranium-238 at the 95 Percent Level (Colloid-Facilitated Transport Case)

Figure A-12
Contour of the 4-mrem/yr Dose from Plutonium-239/240 at the 95 Percent Level
(Colloid-Facilitated Transport Case)

Figure A-13
Contour of the 4-mrem/yr Composite Dose at the 95 Percent Level (Colloid-Facilitated Transport Case)

Figure A-14
Contour of the 4-mrem/yr Dose from Carbon-14 at the 95 Percent Level
(Vertical Flow Case - Northern Frenchman Flat)

Appendix B

Radionuclide Transport Analysis

B.1.0 Radionuclide Transport Analysis

B.1.1 Computer Models

The transport analysis for Frenchman Flat value of analysis was performed using MC_TRANS, a one-dimensional, advective-dispersive solute transport model (IT, 1996a). MC_TRANS is an extended version of MC_TRANS (GeoTrans, 1996) that has been updated to allow for input of a set of realizations prepared by an independent sampler. For the analysis performed in conjunction with the value of information analysis, the sampling sets were generated using the Latin hypercube sampling code developed for Sandia National Laboratories (Iman et al., 1980; Davenport and Iman, 1982). Additional changes to the original MC_TRANS model found in MC_TRLHS include the capacity to consider the sensitivity of flow velocity to hydrologic parameters and to recharge as a way to incorporate flow model uncertainty in the transport simulations.

B.1.1.1 MC_TRANS

The MC_TRANS model is a one-dimensional, solute transport model designed to simulate chains of constituents in fractured geologic media. Conceptually, the model domain is representative of a set of parallel fractures and surrounding porous rock matrix (Figure B-1).

Groundwater flowing through the fractures contains dissolved radionuclides subject to diffusion into and out of the surrounding rock matrix. The process of advective-dispersive transport of dissolved constituents through the fractures and associated matrix diffusion is based on a dual porosity representation of the geologic matrix system. The model assumes complete mixing across the fractures, and a mass transfer coefficient controls interaction between fracture and matrix systems. The model can also be used to simulate transport in nonfractured, dual porosity, or single porosity media. The contaminants are subject to advection, dispersion, sorption, and first-order decay in the fracture, but subject to only sorption and first-order decay in the matrix domain. The governing equations for advective-dispersive transport in the fractures and diffusion into the matrix are approximated using the Galerkin finite-element approach (Huyakorn and Pinder, 1983). The source input may be prescribed concentration or mass flux. Analysis of parameter uncertainty is incorporated into the model using a Monte Carlo approach. The Monte Carlo approach is a method of selecting parameter values from a predefined range of values for

Figure B-1
Conceptual Diagram of Parallel Fractures and Porous Matrix

use in modeling. Parameter uncertainty allows for zonal variations of all input data using several types of statistical distributions. Complete documentation of the original MC_TRANS can be found in the IT report (IT, 1996i).

B.1.1.2 Latin Hypercube Sampling

The Latin hypercube sampling method is an effective sampling technique developed to generate a reliable set of realizations that will reflect the statistical distributions of the sampled parameters without needing as large a sample set as the Monte Carlo method. The method is based upon the division of the range of each variable into n intervals of equal probability. By forcing each sampling interval to have a probability of $1/n$, the endpoints of each interval can be defined by the probability distribution of the variable (Figure B-2).

In Figure B-2 for both uniform and nonuniform distributions, the total range in parameter value is given by A to B or G to H. The range of each interval is A to C, C to D, et cetera. In theory, the

Source: Iman et al., 1980

Figure B-2
Latin Hypercube Sampling Segments for Normal and Uniform Distributions

total range of normal and lognormal distributions is infinite or undefined. In practice, an effective total range of these distributions can be defined. For normal and lognormal distributions, an acceptable total range for the samples, A to B, is chosen based on an acceptable truncation of the infinite range of the distribution. For the sampling methodology used here, the lower (A) and upper (B) ranges of the sample population are based on the assumption that A represents the 0.001 quantile and B represents the 0.999 quantile, or ± 3.09 standard deviations from the mean. In terms of mean and standard deviation, the mean (or mean of the log) is defined by $\mu = (A + B)/2$ and the standard deviation is defined by $\sigma = (B - \mu)/3.09 = (B - A)/6.18$. The variable samples are then derived by random selection within each interval with the density of the variable prorated within the interval.

The choice of the Latin hypercube sampling model was also based upon the wish to evaluate whether the assumption of independence among variables is appropriate. Correlations are likely to exist among some of the variables used in the model. The 1982 release of the Latin hypercube sampling model (Davenport and Iman, 1982) allows the user to import an approximate correlation

matrix. This model is especially practical in its capability of allowing the modeler to make a sophisticated guess about a set of correlation coefficients. Although such a set of pair-wise correlation coefficients may not assemble into a positive-definite correlation matrix, the code contains an algorithm that can take a set of pair-wise correlations and iteratively adjust the correlation matrix until it is positive-definite. This allows the user to assume different degrees of correlation among variables and to evaluate the need for studying the correlations between variables.

B.1.1.3 Flow Sensitivity Parameters

The fracture flow domains evaluated in the value of information analysis modeling study were based upon groundwater travel along stream tubes, with velocity components derived from fully three-dimensional MODFLOW analyses. Stream tubes were evaluated from the center of specific shots along downgradient pathways for distances of up to 40,000 meters (m). To help circumvent the need for computationally intensive simulations, shorter pathways were analyzed for radionuclides with half-lives which would not allow measurable mass to reach 40,000 m. The spatially variant, one-dimensional velocity fields along the stream tubes were derived from velocity components of base case MODFLOW simulations. Uncertainty in the velocities along specified pathways was considered by using the results of MODFLOW sensitivity analyses as well as the influence of changes in specific flow parameters within the MODFLOW model on the velocity components in the stream tube. The parameters considered in the sensitivity studies were horizontal hydraulic conductivity (K_h), vertical hydraulic conductivity (K_v), and a functional parameter describing the variation of hydraulic conductivity with depth (L_d). The hydrostratigraphic units represented in the groundwater flow model are listed in Table B-1.

The parameters of several hydrostratigraphic units were subdivided into smaller geographic regions, called zones, which facilitated the calibration of the flow model (IT, 1996f). The three parameters were varied for each hydrostratigraphic unit and associated subzones (36 zones) in the three-dimensional sensitivity analysis, generating 108 sensitivity parameters. The sensitivity parameters, $S_{ij} = \Delta q_j(x,y,z) / \Delta P_i$, describe the change of specific discharge, $q_j(x,y,z)$, components versus change in each parameter, P_i .

Table B-1
Underground Test Area Hydrostratigraphic Units

Unit Number	Description
20	Alluvial Aquifer
19	Timber Mountain Aquifer
18	Tuff Cone
17	Bullfrog Confining Unit
16	Belted Range Aquifer
15	Basal Confining Unit
14	Basal Aquifer
13	Volcanic Tuff Aquifer
12	Volcanic Tuff Confining Unit
11	Volcanic Undifferentiated
10	Tertiary Sediments, Death Valley Section
9	Lower Carbonate Aquifer (Yucca Flat Upper Plate), Upper Carbonate Aquifer in Nevada Test Site Area
8	Upper Clastic Confining Unit
7	Lower Carbonate Aquifer
6	Lower Clastic Confining Unit
5	Lower Carbonate Aquifer (Upper Plate)
4	Lower Clastic Confining Unit (Upper Plate)
3	Lower Carbonate Aquifer (Lower Plate)
2	Lower Clastic Confining Unit (Lower Plate)
1	Intrusives

Assuming a lognormal distribution for each of the $N = 108$ parameters and, for this analysis, taking a Latin hypercube sample set for each parameter P_i , the specific discharge for each finite element (q) can be defined as:

$$\hat{q}(x) = \sqrt{q_1^{*2} + q_2^{*2} + q_3^{*2}} \quad (2-1)$$

where

$$q_1^* = q_1 + \sum_{i=1}^N S_{i1} \frac{P_i - \bar{P}_i}{\bar{P}_i} \quad (2-2)$$

$$q_2^* = q_2 + \sum_{i=1}^N S_{i2} \frac{P_i - \bar{P}_i}{\bar{P}_i} \quad (2-3)$$

$$q_3^* = q_3 + \sum_{i=1}^N S_{i3} \frac{P_i - \bar{P}_i}{\bar{P}_i} \quad (2-4)$$

and P_i is the sampled parameter.

B.1.1.4 AT123D

The dilution analysis to account for multidimensional effects of transport in the Lower Carbonate Aquifer was performed using the computer code AT123D. AT123D is a program of analytical solutions for one-, two-, or three-dimensional transport of heat, dissolved chemicals, or dissolved radionuclides in a homogeneous aquifer subject to a uniform, stationary regional flow field (Yeh, 1981). The code, based on Green's functions (Huyakorn and Pinder, 1983), combines the product of solutions of point and/or integrated line sources in each of the three principle directions to allow for solution of advective-dispersive transport from a point, planar, or rectangular source. The modeled aquifer is infinite in the direction of flow, but can be considered to be finite or infinite in the vertical and transverse horizontal directions. The source considered may be instantaneous, steady (finite or infinite in length), or variable over time.

For simple geometries and a separable coordinate system, the Green's function, G , can be written in the following form (Yeh and Tsai, 1976):

$$G(x,y,z,t;\xi,\eta,\zeta,\tau) = G_1(x,t;\xi,\tau)G_2(y,t;\eta,\tau)G_3(z,t;\zeta,\tau) \quad (2-5)$$

As presented in Yeh (1981), the general solution solved in AT123D is in the form

$$C(x,y,z,t) = \int_0^t \frac{\dot{M}}{n_e R_d} F_{ijk}(x,y,z,t;\tau) d\tau \quad (2-6)$$

for a continuous or finite steady source (of intensity) with $t < T$, or

$$C(x,y,z,t) = \int_0^T \frac{\dot{M}}{n_e R_d} F_{ijk}(x,y,z,t;\tau) d\tau \quad (2-7)$$

for a finite steady source and $t > T$, or

$$C(x,y,z,t) = \frac{M}{n_e R_d} F_{ijk}(x,y,z,t;\tau) \quad (2-8)$$

for an instantaneous source release of mass, M , while n_e is the effective porosity, and R_d is the retardation coefficient. F_{ijk} is the spatial integral of the Green's function, G , and in terms of the three-directional components, it can be written in the form

$$F_{ijk} = X_i Y_j Z_k \quad (2-9)$$

where

$i = 1$ or 2 and defines whether the source is a point or line source in the x - direction;

$j = 1, 2, 3$ or 4 ; and

$k = 1, 2, 3$ or 4 and defines whether the source is a point source or line source and whether the aquifer is finite or infinite in the y - and z - directions, respectively (Table B-2). The 10 functions, X_i , Y_j and Z_k , are presented in Yeh (1981). For the dilution analysis, the rectangular, steady-source, and finite-depth aquifer options were used.

Table B-2
Solution Functions Used in AT123D

Function	Source	Boundaries
X ₁	point	-∞, ∞
X ₂	line	-∞, ∞
Y ₁	point	Finite width
Y ₂	line	Finite width
Y ₃	point	-∞, ∞
Y ₄	line	-∞, ∞
Z ₁	point	Finite depth
Z ₂	line	Finite depth
Z ₃	point	0, ∞
Z ₄	line	0, ∞

B.1.2 Simulations

The simulations are grouped into three categories: one-dimensional transport along flow paths derived from the regional flow model, one-dimensional transport along vertical flow paths, and three-dimensional analysis of dilution in the Lower Carbonate Aquifer.

B.1.2.1 Radionuclide Transport Simulations

The radionuclide pathway analyses were performed for six representative radionuclides: carbon-14, cesium-137, tritium, iodine-129, plutonium-239/240, and uranium-238. The ten underground nuclear test locations in Frenchman Flat and the paths from two of those tests used in this analysis are presented in Figure B-3. These two paths were chosen on the basis of travel times to represent flow from the nuclear events in central and northern Frenchman Flat. The main objective was to look at the major parameters controlling the transport of these radionuclides at the Nevada Test Site in order to help determine the relative importance of these parameters. The relative importance of each parameter would then be used in a decision-making process to help evaluate what new information could most effectively reduce the uncertainty in the prediction of distance to the contaminant boundary.

Uncertainty associated with parameters (such as hydraulic conductivity, recharge, effective porosity, matrix porosity, longitudinal dispersivity, initial mass-in-place, matrix-block width,

Figure B-3
Conceptual Model Cross Section Through Frenchman Flat

matrix diffusion coefficient, and species absorption coefficient) were considered in the modeling effort. A listing of radionuclides, mean initial concentration levels, lower-bound and upper-bound concentration levels, decay rates, and distribution of absorption coefficients considered in the analysis are presented in Table B-3 for the base case and in Table B-4 for the sorbing

Table B-3
Radio Transport Parameters

Radionuclide	Half-Life (years)	K _d Range (cm ³ /g)	Mean Initial Concentration (pCi/L)	Lower Bound Concentration (pCi/L)	Upper Bound Concentration (pCi/L)
Carbon-14	5,730	0	1.17 x 10 ⁵	1,778	2,041,700
Cesium-137	30.3	100 to 1,000	105	1.54	1,900
Tritium	12.3	0	3.8 x 10 ¹⁰	5.53 x 10 ⁸	6.808 x 10 ¹¹
Iodine-129	1.7 x 10 ⁷	0	21.3	0.328	376
Plutonium-239/240	2.4 x 10 ⁴	60 to 1,600	1,750	25.65	31,550
Uranium-238	4.5 x 10 ⁹	1 to 5	48.5	0.713	877

Table B-4
Radionuclide Transport Parameters - Colloidal Transport Case

Radionuclide	Half-Life (years)	K _d Range (cm ³ /g)	Mean Initial Concentration (pCi/L)	Lower Bound Concentration (pCi/L)	Upper Bound Concentration (pCi/L)
Cesium-137	30.3	0 to 10	105	1.54	1,900
Plutonium-239/240	2.4 x 10 ⁴	0 to 10	1,750	25.65	31,550
Uranium-238	4.5 x 10 ⁹	0 to 2	48.5	0.713	877

radionuclides for the case of colloidal transport. The influence of uncertainty was modeled through the use of Latin hypercube sampling, and sets of 200 sampled realizations were analyzed for scenarios considered.

In addition to the set of general simulations performed for each of the selected radionuclides, the radionuclide carbon-14 was chosen as the base component for a set of different scenarios. The choice was based on its initial concentration and radioactive decay rate (Table B-3), which fall in a range that results in potential exposure doses of over 4 mrem/yr near the edge of the alluvium in

Frenchman Flat. For conservative species with little adsorption and long half-lives, it is expected that transport into the Lower Carbonate Aquifer will occur eventually, and for radionuclides with short half-lives, it is unlikely they will ever leave the alluvial aquifer. Simulation results for carbon-14 analyses were expected to show the most variability due to uncertainty in the transport parameters.

B.1.2.1.1. Downgradient Pathways

The general simulations are based on the expected flowpath from the DILUTED WATERS underground event. The pathway that was followed extends approximately 40,000 meters (24.85 miles [mi]) downgradient from the shot cavity. The first 5,000 m (16,400 ft) of the pathway extend through the Alluvial Aquifer; the next 2,500 m (8,200 ft) extend through the Volcanic Tuff Confining Unit; and the rest of the pathway passes through the Lower Carbonate Aquifer. Distributions for all nonradionuclide-specific transport parameters for each hydrostratigraphic unit can be found in Table B-5. Distribution types found in Table 2-5 include constant (0), lognormal (2), and uniform (3). Simulations were run for the duration of time needed for the concentration levels of the radionuclides to decrease to a dose rate level of less than 4 mrem/yr or for a maximum of 25,000 years.

The radionuclides are applied as an initial condition over the first 250 m (820 ft) of the transport model grid. This distance represents approximately twice the cavity diameter. The initial concentration levels for each radionuclide are based upon the mean concentration given in Table B-5 and a lognormal distribution and associated $\log_{10}$ standard deviation of 0.5 (unless otherwise noted). Darcy velocities along the 40,000-m (24.85-mi) pathway range from 0.0136 to 0.0231 meters per year (m/yr) (0.045 to 0.0758 ft/yr) in the alluvial aquifer, from 0.0237 to 0.54 m/yr (0.078 to 1.77 ft/yr) in the volcanics, and from 0.23 to 6.8 m/yr (0.75 to 22.3 ft/yr) in the Lower Carbonate Aquifer. The transport velocities derived by dividing the Darcy velocity by the effective porosity (Table B-5) show that the difference of magnitudes between transport velocities in the carbonate aquifer and the alluvium may reach 10,000:1. Four sets of general simulations were performed in the analysis.

The transport simulations performed with MC_TRANS are listed in Table B-6. For each radionuclide, a single simulation where all parameters in the uncertainty study were varied was performed. For the radionuclides subject to absorption (Table B-4), a similar set of simulations

Table B-5
Parameter Distribution for Latin Hypercube Simulations
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Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Upgradient Source Concentration	NA ^c	constant	0	NA
Radioactive Decay Coefficient for the Upgradient Source (1/yr)	NA	constant	0	NA
Log Initial Concentration in the Flow Region (pCi/L)	NA	lognormal	see footnote b	0.50
Log Initial Concentration in the Matrix (pCi/L) (if applicable)	NA	lognormal	see footnote b	0.50
Longitudinal Dispersivity (m)	Lower Carbonate Aquifer	uniform	100	1000
Longitudinal Dispersivity (m)	Volcanic Tuff Confining Unit	uniform	100	500
Longitudinal Dispersivity (m)	Alluvial Aquifer	uniform	50	500
Diffusion Coefficient in Water (m ² /yr)	all units	constant	4.73x10 ⁻²	NA
Tortuosity (dimensionless)	all units	constant	0.1	NA
Log Effective Porosity	Lower Carbonate Aquifer	lognormal	-2.44	0.6
Log Effective Porosity	Volcanic Tuff Confining Unit	lognormal	-1.66	0.35
Effective Porosity	Alluvial Aquifer	uniform	0.25	0.35
Matrix Porosity	Lower Carbonate Aquifer	uniform	0.01	0.07
Matrix Porosity	Volcanic Tuff Confining Unit	uniform	0.08	0.36
Matrix Porosity	Alluvial Aquifer	constant	0	NA
Block Width for Diffusion (m)	all units	uniform	0.1	1.5
Bulk Density of the Matrix (g/cm ³)	all units	constant	1.8	NA
Distribution Coefficient in the Flow Region (cm ³ /g)	all units	constant	see footnote b	NA
Distribution Coefficient in the Matrix (cm ³ /g)	all units	constant	see footnote b	NA
Log Matrix Diffusion Coefficient (m ² /yr)	Lower Carbonate Aquifer	lognormal	-2.842	0.35
Log Matrix Diffusion Coefficient (m ² /yr)	Volcanic Tuff Confining Unit	lognormal	-2.842	0.35
Matrix Diffusion Coefficient (m ² /yr)	Alluvial Aquifer	constant	0	NA

Table B-5
Parameter Distribution for Latin Hypercube Simulations
(Page 2 of 7)

Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Radioactive Decay Coefficient (1/yr)	all units	constant	see footnote b	NA
Log Hydraulic Conductivity (m/day) for Intrusives	NA	lognormal	-3.07	0.35
Log Hydraulic Conductivity (m/day) for Lower Clastic Confining Unit Zone 1	NA	lognormal	-2.17	0.35
Log Hydraulic Conductivity (m/day) for Lower Clastic Confining Unit Zone 2	NA	lognormal	-1.07	0.35
Log Hydraulic Conductivity (m/day) for Lower Carbonate Aquifer Zone 1	NA	lognormal	1.53	0.35
Log Hydraulic Conductivity (m/day) for Lower Carbonate Aquifer Zone 2	NA	lognormal	2.37	0.35
Log Hydraulic Conductivity (m/day) for Lower Carbonate Aquifer Zone 3	NA	lognormal	-1.77	0.35
Log Hydraulic Conductivity (m/day) for Lower Carbonate Aquifer Zone 4	NA	lognormal	1.71	0.35
Log Hydraulic Conductivity (m/day) for Lower Carbonate Aquifer Zone 5	NA	lognormal	0.12	0.35
Log Hydraulic Conductivity (m/day) for Lower Carbonate Aquifer Zone 6	NA	lognormal	-0.37	0.35
Log Hydraulic Conductivity (m/day) for Upper Clastic Confining Unit	NA	lognormal	-2.77	0.35
Log Hydraulic Conductivity (m/day) for Upper Carbonate Aquifer	NA	lognormal	-1.77	0.35
Log Hydraulic Conductivity (m/day) for Tertiary Sediments	NA	lognormal	-1.77	0.35
Log Hydraulic Conductivity (m/day) for Volcanics Undifferentiated	NA	lognormal	-0.37	0.35
Log Hydraulic Conductivity (m/day) for Volcanic Tuff Confining Unit	NA	lognormal	-1.77	0.35
Log Hydraulic Conductivity (m/day) for Volcanic Tuff Aquifer Zone 1	NA	lognormal	-0.17	0.35
Log Hydraulic Conductivity (m/day) for Volcanic Tuff Aquifer Zone 2	NA	lognormal	-0.9	0.35
Log Hydraulic Conductivity (m/day) for Basal Aquifer	NA	lognormal	-0.29	0.35
Log Hydraulic Conductivity (m/day) for Basal Confining Unit	NA	lognormal	-2.07	0.35
Log Hydraulic Conductivity (m/day) for Belted Range Aquifer	NA	lognormal	0.53	0.35

Table B-5
Parameter Distribution for Latin Hypercube Simulations
(Page 3 of 7)

Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Log Hydraulic Conductivity (m/day) for Bullfrog Confining Unit	NA	lognormal	-1.59	0.35
Log Hydraulic Conductivity (m/day) for Tuff Cones Zone 1	NA	lognormal	0.53	0.35
Log Hydraulic Conductivity (m/day) for Tuff Cones Zone 2	NA	lognormal	0.53	0.35
Log Hydraulic Conductivity (m/day) for Tuff Cones Zone 3	NA	lognormal	0.53	0.35
Log Hydraulic Conductivity (m/day) for Tuff Cones Zone 4	NA	lognormal	0.53	0.35
Log Hydraulic Conductivity (m/day) for Tuff Cones Zone 5	NA	lognormal	-0.47	0.35
Log Hydraulic Conductivity (m/day) for Timber Mountain Aquifer Zone 1	NA	lognormal	0.53	0.35
Log Hydraulic Conductivity (m/day) for Timber Mountain Aquifer Zone 2	NA	lognormal	0.074	0.35
Log Hydraulic Conductivity (m/day) for Timber Mountain Aquifer Zone 3	NA	lognormal	0.13	0.35
Log Hydraulic Conductivity (m/day) for Timber Mountain Aquifer Zone 4	NA	lognormal	0.18	0.35
Log Hydraulic Conductivity (m/day) for Timber Mountain Aquifer Zone 5	NA	lognormal	0.0073	0.35
Log Hydraulic Conductivity (m/day) for Alluvial Aquifer Zone 1	NA	lognormal	-0.29	0.6
Log Hydraulic Conductivity (m/day) for Alluvial Aquifer Zone 2	NA	lognormal	-2.07	0.35
Log Hydraulic Conductivity (m/day) for Alluvial Aquifer Zone 3	NA	lognormal	-0.29	0.35
Log Hydraulic Conductivity (m/day) for Alluvial Aquifer Zone 4	NA	lognormal	-1.77	0.35
Log Hydraulic Conductivity (m/day) for Alluvial Aquifer Zone 5	NA	lognormal	0.63	0.35
Log Hydraulic Conductivity (m/day) for Alluvial Aquifer Zone 6	NA	lognormal	0.33	0.35
Log Anisotropy Ratio for Intrusives	NA	lognormal	-1.07	0.25
Log Anisotropy Ratio for Lower Clastic Confining Unit Zone 1	NA	lognormal	-0.9	0.25
Log Anisotropy Ratio for Lower Clastic Confining Unit Zone 2	NA	lognormal	-0.9	0.25

Table B-5
Parameter Distribution for Latin Hypercube Simulations
(Page 4 of 7)

Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Log Anisotropy Ratio for Lower Carbonate Aquifer Zone 1	NA	lognormal	-1.9	0.25
Log Anisotropy Ratio for Lower Carbonate Aquifer Zone 2	NA	lognormal	-1.9	0.25
Log Anisotropy Ratio for Lower Carbonate Aquifer Zone 3	NA	lognormal	-1.9	0.25
Log Anisotropy Ratio for Lower Carbonate Aquifer Zone 4	NA	lognormal	-1.9	0.25
Log Anisotropy Ratio for Lower Carbonate Aquifer Zone 5	NA	lognormal	-1.9	0.25
Log Anisotropy Ratio for Lower Carbonate Aquifer Zone 6	NA	lognormal	-1.9	0.25
Log Anisotropy Ratio for Upper Clastic Confining Unit	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Upper Carbonate Aquifer	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Tertiary Sediments	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Volcanics Undifferentiated	NA	lognormal	-2.77	0.25
Log Anisotropy Ratio for Volcanic Tuff Confining Unit	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Volcanic Tuff Aquifer Zone 1	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Volcanic Tuff Aquifer Zone 2	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Basal Aquifer	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Basal Confining Unit	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Belted Range Aquifer	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Bullfrog Confining Unit	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Tuff Cones Zone 1	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Tuff Cones Zone 2	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Tuff Cones Zone 3	NA	lognormal	-1.77	0.25

Table B-5
Parameter Distribution for Latin Hypercube Simulations
(Page 5 of 7)

Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Log Anisotropy Ratio for Tuff Cones Zone 4	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Tuff Cones Zone 5	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Timber Mountain Aquifer Zone 1	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Timber Mountain Aquifer Zone 2	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Timber Mountain Aquifer Zone 3	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Timber Mountain Aquifer Zone 4	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Timber Mountain Aquifer Zone 5	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Alluvial Aquifer Zone 1	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Alluvial Aquifer Zone 2	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Alluvial Aquifer Zone 3	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Alluvial Aquifer Zone 4	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Alluvial Aquifer Zone 5	NA	lognormal	-1.77	0.25
Log Anisotropy Ratio for Alluvial Aquifer Zone 6	NA	lognormal	-1.77	0.25
Log Depth Coefficient (1/m) for Intrusives	NA	lognormal	-2.9	0.25
Log Depth Coefficient (1/m) for Lower Clastic Confining Unit Zone 1	NA	lognormal	-2.9	0.25
Log Depth Coefficient (1/m) for Lower Clastic Confining Unit Zone 2	NA	lognormal	-2.99	0.25
Log Depth Coefficient (1/m) for Lower Carbonate Aquifer Zone 1	NA	lognormal	-3.12	0.25
Log Depth Coefficient (1/m) for Lower Carbonate Aquifer Zone 2	NA	lognormal	-3.12	0.25
Log Depth Coefficient (1/m) for Lower Carbonate Aquifer Zone 3	NA	lognormal	-3.12	0.25

Table B-5
Parameter Distribution for Latin Hypercube Simulations
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Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Log Depth Coefficient (1/m) for Lower Carbonate Aquifer Zone 4	NA	lognormal	-3.12	0.25
Log Depth Coefficient (1/m) for Lower Carbonate Aquifer Zone 5	NA	lognormal	-3.12	0.25
Log Depth Coefficient (1/m) for Lower Carbonate Aquifer Zone 6	NA	lognormal	-3.12	0.25
Log Depth Coefficient (1/m) for Upper Clastic Confining Unit	NA	lognormal	-2.9	0.25
Log Depth Coefficient (1/m) for Upper Carbonate Aquifer	NA	lognormal	-3.12	0.25
Log Depth Coefficient (1/m) for Tertiary Sediments	NA	lognormal	-2.47	0.25
Log Depth Coefficient (1/m) for Volcanics Undifferentiated	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Volcanic Tuff Confining Unit	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Volcanic Tuff Aquifer Zone 1	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Volcanic Tuff Aquifer Zone 2	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Basal Aquifer	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Basal Confining Unit	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Belted Range Aquifer	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Bullfrog Confining Unit	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Tuff Cones Zone 1	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Tuff Cones Zone 2	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Tuff Cones Zone 3	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Tuff Cones Zone 4	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Tuff Cones Zone 5	NA	lognormal	-2.77	0.25

Table B-5
Parameter Distribution for Latin Hypercube Simulations
(Page 7 of 7)

Parameter Name	Hydrostratigraphic Unit	Distribution Type	Mean/ Minimum ^a	Standard Deviation/ Maximum ^b
Log Depth Coefficient (1/m) for Timber Mountain Aquifer Zone 1	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Timber Mountain Aquifer Zone 2	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Timber Mountain Aquifer Zone 3	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Timber Mountain Aquifer Zone 4	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Timber Mountain Aquifer Zone 5	NA	lognormal	-2.77	0.25
Log Depth Coefficient (1/m) for Alluvial Aquifer Zone 1	NA	lognormal	-2.47	0.6
Log Depth Coefficient (1/m) for Alluvial Aquifer Zone 2	NA	lognormal	-2.47	0.25
Log Depth Coefficient (1/m) for Alluvial Aquifer Zone 3	NA	lognormal	-2.47	0.25
Log Depth Coefficient (1/m) for Alluvial Aquifer Zone 4	NA	lognormal	-2.47	0.25
Log Depth Coefficient (1/m) for Alluvial Aquifer Zone 5	NA	lognormal	-2.47	0.25
Log Depth Coefficient (1/m) for Alluvial Aquifer Zone 6	NA	lognormal	-2.47	0.25
Recharge Multiplier (dimensionless)	NA	lognormal	0	0.25

^aThis column is the minimum and maximum value for a uniform distribution or the mean and standard deviation of any other distribution. For a lognormal distribution, the log₁₀ mean and log₁₀ standard deviation are presented. For a constant, the value is given by the mean, and the standard deviation is not used.

^bInitial concentrations and distribution coefficients are contaminant-specific and are presented in Tables B-3 and B-4.

^cNot applicable

Table B-6
Transport Simulations

Simulation	Contaminant	Description*
1	Carbon-14	All parameters vary simultaneously.
2	Tritium	All parameters vary simultaneously.
3	Iodine-129	All parameters vary simultaneously.
4	Uranium-238	All parameters vary simultaneously.
5	Cesium-137	All parameters vary simultaneously.
6	Plutonium-239/240	All parameters vary simultaneously.
7	Uranium-238	Colloid transport - all parameters vary simultaneously.
8	Cesium-137	Colloid transport - all parameters vary simultaneously.
9	Plutonium-239/240	Colloid transport - all parameters vary simultaneously.
10	Carbon-14	Uncertainty simulations - parameters vary individually.
11	Tritium	Uncertainty simulations - parameters vary individually.
12	Iodine-129	Uncertainty simulations - parameters vary individually.
13	Uranium-238	Uncertainty simulations - parameters vary individually.
14	Cesium-137	Uncertainty simulations - parameters vary individually.
15	Plutonium-239/240	Uncertainty simulations - parameters vary individually.
16	Uranium-238	Colloid transport - parameters vary individually.
17	Cesium-137	Colloid transport - parameters vary individually.
18	Plutonium-239/240	Colloid transport - parameters vary individually.
19	Carbon-14	MINUTE STEAK Pathway - all parameters vary simultaneously.
20	Tritium	MINUTE STEAK Pathway - all parameters vary simultaneously.
21	Carbon-14	Matrix diffusion in alluvium - all parameters vary.
22	Carbon-14	50 percent correlation of parameters - all parameters vary.
23	Carbon-14	90 percent correlation of parameters - all parameters vary.
24	Carbon-14	Two sources in series - all parameters vary simultaneously.
25	Carbon-14	Vertical pathway - DILUTED WATERS - all parameters vary.
26	Carbon-14	Vertical pathway - PIN STRIPE - all parameters vary.
27	Carbon-14	Vertical pathway - NEW POINT - all parameters vary.

*All simulations are pathways originating at the DILUTED WATERS event unless otherwise noted.

that considered the influence of colloidal transport (which was approximated using reduced absorption coefficients and increased initial concentrations) was performed. The third set of simulations were sensitivity analyses. This consisted of performing a separate run with 200 realizations for each parameter with a defined distribution, while all other parameters were assigned their mean values.

The fourth set of runs was a similar sensitivity analysis that used the colloidal transport analysis absorption coefficient data. These simulations for the six radionuclides represent the first 18 simulations. The remainder of the downgradient transport simulations used the carbon-14 parameters, and the simulations were used to examine specific parameters or other scenarios. Other simulations, as noted in Table B-6, were performed to study transport from a different site (MINUTE STEAK), to determine the influence of matrix diffusion in the alluvium, to examine the combined plume formation from two sources, and to determine the influence of parameter correlation on simulation results.

B.1.2.1.2. Vertical Flow Paths

Three potential vertical flow paths were also considered in the analysis. The vertical flow pathways or potential short circuits to the Lower Carbonate Aquifer examined in this study were based on potential vertical paths in the vicinity of the DILUTED WATERS, PIN STRIPE, and NEW POINT underground shots. The DILUTED WATERS pathway extends vertically downward approximately 1,150 m (3,773 ft), traversing 450 m (1,480 ft) through the Alluvial Aquifer, 300 m (984 ft) through the volcanic confining unit, and 400 m (1,310 ft) through the Tertiary Sediments. The PIN STRIPE pathway extends vertically downward approximately 475 m (1,560 ft), traversing 250 m (820 ft) through the volcanic confining unit, and 225 m (740 ft) through the Tertiary Sediments. The third evaluated pathway at the NEW POINT shot extends 650 m (2,130 ft) downward vertically, traversing 400 m (1,310 ft) through the volcanic confining unit and 250 m (820 ft) through the Tertiary Sediments.

Based on a maximum likely vertical gradient of 0.0164 in Frenchman Flat, horizontal hydraulic conductivities of 0.5 to 2.0 meters per day (m/d) (1.6 to 6.6 ft/d), and a horizontal to vertical hydraulic conductivity ratio of 10.0, a conservative, single, steady Darcy velocity of 1.2 m/yr (3.9 ft/yr) was used for this analysis. All other parameters used in the analysis are based on the general parameters for the carbon-14 analysis and are listed in Tables B-3 and 2-5. The vertical

flow pathway did not use the flow model velocity field sensitivity nor the 108 hydraulic conductivity parameters because the vertical pathway is defined without using the regional groundwater flow model. The only parameter that the Darcy velocity is dependent on for these simulations is the uncertainty in recharge.

B.1.2.2 Dilution Analysis

The basic conceptual model used in the dilution analysis is based on the "worst case" vertical pathway simulations. The general system represented in the model assumes vertical transport over a 250- by 250-m (820- by 820-ft) area, travels through the overlying alluvial aquifer, volcanics, and tertiary sediments into the Lower Carbonate Aquifer, and assumes horizontal transport through the high transport-velocity Lower Carbonate Aquifer. It was anticipated that the combination of the high rate of transport velocity in the carbonate aquifer versus the relatively slow change of concentration levels in the vertical pathway would produce a relatively steady source of contaminant to the carbonate aquifer over a long period of time. A steady source was used to represent the quasi-steady mode of a slowly changing source term in a rapid velocity field.

In the model, the thickness of the Lower Carbonate Aquifer was assumed to be 1,000 m (3,280 ft), and the Darcy velocity in the aquifer was set to 5.0 m/yr (16.4 ft/yr). The conservative value for effective porosity of 0.0033 was used so that the influence of decay was not overestimated. The radionuclide was assumed to be carbon-14 (with the decay rate of 1.21×10^{-4} [1/yr]), and no adsorption was considered. Two sets of dispersivities were considered. The first represented higher likely values commonly associated with transport in fractured carbonates, and the second set represented conservative estimates. The two sets, as presented in Table B-7, are $\alpha_L = 500$ m (1,640 ft), $\alpha_T = 100$ m (330 ft), and $\alpha_z = 5$ m (16.4 ft) for Case 1; $\alpha_L = 100$ m (330 ft), $\alpha_T = 20$ m (66 ft), and $\alpha_z = 1$ m (3.3 ft) for Case 2; and $\alpha_L = 500$ m (1,640 ft), $\alpha_T = 100$ m (330 ft), and $\alpha_z = 5$ m (16.4 ft), but $\lambda = 0.0$ for Case (3).

The mass loading from the vertical leg of transport into the Lower Carbonate Aquifer is approximated by a rectangular source of 250 m (820 ft) in length and width and 60 m (197 ft) in thickness. The 60-m (197-ft) thickness of the source is based on the equation used by the U.S. Environmental Protection Agency (EPA) to calculate mixing depth when coupling vertical

Table B-7
Results of the AT123D Dilution Study

Distance Advected	Dilution Attenuation Factors (DAFs)		
	Case 1	Case 2	Case 3
5,000 m	46	10	-
10,000	93	19	-
15,000	140	29	-
20,000	187	38	-
40,000	369	76	368

Case 1

$\alpha_L = 500$ m
 $\alpha_T = 100$ m
 $\alpha_Z = 5$ m
 $\lambda = 1.21 \times 10^{-4} \text{ g}^{-1}$

Case 2

$\alpha_L = 100$ m
 $\alpha_T = 20$ m
 $\alpha_Z = 1$ m
 $\lambda = 1.21 \times 10^{-4} \text{ yr}^{-1}$

Case 3

$\alpha_L = 500$ m
 $\alpha_T = 100$ m
 $\alpha_Z = 5$ m
 $\lambda = 0.0$

Other Parameters

$V_{\text{DARCY}} = 5.0$ m/yr
 $Q = 0.0033$
 Source Volume = 250 m x 250 m x 60 m
 Vertical Darcy Velocity = 1.2 m/yr

transport models with horizontal transport models (EPA, 1988). The mixing depth formula is normally presented in the form:

$$P_d = \sqrt{2\alpha_z x_o} + H \left[1 - \exp\left(-\frac{x_o I}{H V_s \theta}\right) \right]$$

(2-10)

where

P_d = penetration depth (m);
 α_z = vertical dispersivity coefficient (m);
 x_o = length of source in groundwater flow direction (m);
 H = thickness of aquifer (m);
 V_s = horizontal seepage velocity (m);
 I = infiltration rate (m/y); and
 θ = porosity (-).

The first term in Equation 2-10 represents the increased vertical thickness of the plume due to dispersion, and the second term represents the influence of the vertical component of flow due to infiltration on the plume as it is advected downgradient in the source area. Note that for this analysis, the first term, which is presented here for completeness, is disregarded since, unlike the analytical solution used in the EPA report (1988), AT123D includes the effects of vertical

dispersion under the source in the solution. For the parameters used in this analysis (as presented in Table B-6), the penetration or mixing depth, P_d , is approximately 60 m (197 ft). The source term in AT123D is a mass flux term. To allow for direct interpretation of results in terms of the dilution attenuation factor, the source term was given a mass flux rate equivalent to that which would be produced by water with a radionuclide concentration of 1 pCi/L leaving the vertical leg of the system. Thus, the inverse of the resultant concentrations represents the dilution attenuation factors.

Results of the analysis for maximum concentrations are presented in Table B-7. These results show that for Case 1, with the higher dispersivities, the dilution attenuation factors range from 44 to 369 depending on the length of downgradient travel after the mass enters the Lower Carbonate Aquifer (for this analysis, lengths of 5,000 m [3.1 mi], 10,000 m [6.2 mi], 15,000 m [9.3 mi], 20,000 m [12.43 mi], and 40,000 m [24.85 mi] were considered). For the conservative dispersivities, the dilution attenuation factors still range between 10 and 76 for lengths of travel between 5,000 and 40,000 m (3.1 and 24.85 mi). A third case that neglected radioactive decay as a source of attenuation was also examined (Table B-7). This case showed that, for carbon-14, when the radioactive mass enters the Lower Carbonate Aquifer, decay may no longer play an important role in attenuation of the mass. The transverse mixing processes may be the dominant mode of attenuation.

B.1.3 Results of Uncertainty Analyses

A total of twenty-seven simulations were identified in Table B-6. These represent a variety of cases in which the uncertainty in the predicted radionuclide concentrations was evaluated as a function in the uncertainty of a parameter or conceptual model. The maximum concentration at each downgradient location was recorded for each of the 200 simulations performed. The uncertainty in each parameter is presented in Table B-5. The uncertainty in any parameter is coupled with the transport model's sensitivity to that specific parameter in order to define the predicted radionuclide uncertainty. Thus, a parameter with a low sensitivity, but having a large uncertainty, may be more important than a more sensitive parameter that has a much smaller uncertainty.

B.1.3.1 Presentation Format

The results of the uncertainty analyses are presented in two ways. First, a series of simulations involving the simultaneous variation of all parameters is shown to help define the most important parameters and scenarios. An example of this type of presentation is given in Figure B-4 for the case of carbon-14. The reader should note that Figure B-4 and all remaining figures are at the end of this section. The vertical axis is the carbon-14 concentration (in pCi/L), and the horizontal axis is the cumulative frequency of the 200 realizations. Each curve represents the results at a different downgradient location. To create the figure, the maximum concentration at each downgradient location was recorded for each realization. In essence, this records the peak of the breakthrough curve and examines the largest concentration that would occur at any location.

At each location, the maximum concentration for each of the 200 realizations is sorted from smallest to largest and assigned a cumulative frequency value using the equation (Benjamin and Cornell, 1970).

$$F_i = \frac{i}{(n + 1)} \quad (2-11)$$

where

- F_i = the cumulative frequency of the i th smallest value;
- i = the counter for the sorted activity values ($i = 1$ is the smallest value, and $i = n$ is the largest value); and
- n = number of realizations.

For any particular frequency, the carbon-14 concentration of 70 percent of all realizations was less than the plotted value. Consider, for example, the 3-km (1.86-mi) distance in Figure B-4. The 70 percent value is 1.1×10^3 pCi/L, and the 95 percent value is 7.1×10^3 pCi/L. This means that 70 percent of the realizations produced a peak carbon-14 value of less than 1.1×10^3 pCi/L at a distance of 3 km (1.86 mi). Additionally, 95 percent of the realizations produced a maximum carbon-14 concentration of less than 7.1×10^3 pCi/L. The wide range of predicted maximum carbon-14 concentrations at each location is due to the uncertainty in the input parameter values.

To examine the impact of the individual parameters on the total uncertainty, a series of uncertainty simulations was performed that involved allowing one parameter at a time to vary

while the remaining parameters constant. If 13 parameters were allowed to vary individually, then 13 model runs of 200 realizations each were performed. Figures B-5 and 2-6 are examples of the presentation of the uncertainty results for 13 individual parameters. Because of the large number of curves, separate plots were created for each distance.

In Figures B-5 and B-6, the distance is 3 km (1.86 mi). The figures were constructed in the same way as Figure B-4 and display maximum carbon-14 concentration as a function of cumulative frequency. Figure B-5 contains the results for individual transport parameters, while Figure B-6 contains the flow sensitivity parameters out of the regional groundwater flow model as described in Section 2.1.3. In these figures, a horizontal line represents a parameter that is not important to the predicted carbon-14 activity. In Figure 2-6, the horizontal hydraulic conductivity Zone 6 of the alluvium is not important because it does not contribute to uncertainty. The hydraulic conductivity zones defined in the IT report (1996f) are regions of the model where a particular model parameter has the same value. Zone 1 of the alluvial aquifer includes Frenchman Flat. Zone 6 is the region between Ash Meadows and Death Valley and is downgradient of Frenchman Flat. The most important parameters in Figure B-5, the ones that vary the most from a horizontal line, are recharge and source term.

In the transport modeling, recharge is a multiplier to the specific discharge that accounts for the uncertainty in recharge, which would increase or decrease flow in the groundwater system. From Figure B-6, the most important flow sensitivity parameters are KH-20-1 and LD-20-1, which are the horizontal hydraulic conductivity and depth coefficient of Zone 1 of the alluvium in Frenchman Flat. The nomenclature for the sensitivity parameters is in the form AB_#1_#2. The letters "AB" refer to KH, the horizontal hydraulic conductivity at the land surface; LD, which is the depth coefficient defining the decrease in hydraulic conductivity with depth; or KV, which is the vertical anisotropy ratio. The first set of numbers (#1) defines the hydrostratigraphic layer number as in Table B-3. The last number (#2) is the parameter zone identifier as defined in the Groundwater Flow Model Documentation Package (IT, 1996f). As shown in Equations (2-1) to (2-4), the flow sensitivity parameters modify the specific discharge.

B.1.3.2 Results of Simultaneous Variation of all Parameters

In this section, the results of simultaneous variations of parameters are presented. This provides an estimate of total uncertainty and a way to compare different scenarios.

B.1.3.2.1. Horizontal Flow from Central Frenchman Flat - Base Case

Figures B-7 through B-12 provide the maximum activity versus cumulative frequency plots for the case of all parameters, varying simultaneously for the following radionuclides: carbon-14, tritium, iodine-129, uranium-238, cesium-137, and plutonium-239/240. Before describing these figures in detail, it is important to put the concentrations of the radionuclides in perspective with respect to the risk to human health. An IT Corporation scientist (Adams, 1996) calculated the concentration of each radionuclide in water (pCi/L) that would produce a 4-mrem/yr dose to a human receptor; these concentrations are given in Table B-8.

Table B-8
Concentration of a Radionuclide in Water Which Produces a
4mrem/yr Drinking Water Ingestion Dose

Radionuclide	Concentration (pCi/L) Resulting in a 4 mrem/yr Dose Rate
Plutonium-239/240	1.55
Iodine-129	19.9
Uranium-238	21.5
Cesium-137	110
Carbon-14	2,620
Tritium	85,600

The concentrations in Table B-8 serve as a guide when viewing Figures B-7 through B-12. When calculated radionuclide activity falls well below the values in Table B-8, that particular radionuclide is no longer of concern.

The concentration of carbon-14 exceeds the 4-mrem/yr level at the 95 percent frequency for distances of 5 km (3.1 mi) and less. At distances greater than 7.5 km (4.7 mi), the carbon-14 does not exceed the 4-mrem/yr level at the 95 percent frequency. The 7.5-km (4.7-mi) distance is significant because it marks the approximate location where the flow path enters the Lower Carbonate Aquifer at the southern end of Frenchman Flat. The carbon-14 concentration apparently does not change once the flow path enters the Lower Carbonate Aquifer. This result is due, in part, to the one-dimensional modeling approach, which does not account for mixing of fluids as they enter the Lower Carbonate Aquifer and does not account for dispersion of radionuclides in the transverse and vertical directions in the Lower Carbonate Aquifer.

Preliminary calculations described in Section 2.2.2 suggest that additional dilution in the Lower Carbonate Aquifer will reduce radionuclide activities by at least one order of magnitude. In fact, the dilution will be even greater because the infiltration rate of 1.2 m/yr (3.9 ft/yr) used in Section 2.2.2 is about one order of magnitude larger than the value of about 0.1 m/yr (0.33 ft/yr) that is appropriate in this case. The main conclusion to be drawn from Figure B-7 is that carbon-14 activity may exceed the 4-mrem/yr limit at nearly all points of a 7.5-km (4.7-mi) flow path from the center of Frenchman Flat to a point on the southwestern boundary, but will drop below the 4-mrem/yr level once the path enters the Lower Carbonate Aquifer.

In Figure B-8, the tritium concentration at the 95 percent cumulative frequency drops below the 4-mrem/yr level at a distance of 0.5 km (0.31 mi). The transport of tritium is strongly influenced by the short half-life, which causes the tritium concentration to decrease rapidly. The 4-mrem/yr boundary was used instead of the 20,000 pCi/L boundary to facilitate comparison of different radionuclides.

The iodine-129 concentration (Figure B-9) at the 95 percent cumulative frequency drops below the 4-mrem/yr level at distance of less than 1 km (0.62 mi). Beyond 1 km (0.62 mi), the peak concentration of iodine decreases by about one order of magnitude before it gets to the Lower Carbonate Aquifer at 7.5 km (4.7 mi). The very long half-life of iodine-129 causes it to persist for long periods of time, and the only mechanism that decreases its concentration is dispersion in the alluvium with matrix diffusion also occurring in the Lower Carbonate Aquifer.

Uranium-238 is modeled as weakly sorbing radionuclide when compared with cesium-137 and plutonium-239/240 (Yu et al., 1993). Even so, it does not move readily in the groundwater system, as evidenced by the fact that the uranium-238 concentration does not exceed the 4-mrem/yr level beyond 1 km (0.62 mi) at the 95 percent level (Figure B-10).

For the strongly sorbing radionuclide cesium-137 (Figure B-11), the distance to the 4-mrem/yr level is very small, less than 0.3 km (0.19 mi) at the 95 percent cumulative frequency level.

The final radionuclide, plutonium-239/240 (Figure B-12), exhibits similar behavior to cesium-137 because of the strong influence of adsorption, which causes plutonium-239/240 to migrate very slowly.

For these first series of plots, the pathline is essentially horizontal from the DILUTED WATERS event, located near the center of Frenchman Flat. The strongly sorbing radionuclides, such as cesium-137 and plutonium-239/240, do not migrate far from the source. Uranium-238, which was modeled as a weakly sorbing radionuclide, moved 1 km downgradient before the concentration decreased below the 4-mrem/yr limit. Tritium does not move far downgradient because it decays rapidly. The remaining two radionuclides, iodine-129 and carbon-14, are treated as mobile in the groundwater system. Low initial activity levels for iodine-129 lead to a relatively small distance to the 4-mrem/yr line. If initial activities are larger than previously assumed, then iodine-129 could migrate further downgradient and compete with carbon-14 as the most significant radionuclide. The radionuclide with the largest distance to the 4-mrem/yr line is carbon-14 because of the relatively large initial concentration compared with iodine-129.

B.1.3.2.2. Horizontal Flow from Central Frenchman Flat - Colloidal Transport Case

Additional simulations were performed to examine other possible scenarios. The first of these examines the possibility of colloidal transport for the three sorbing nuclides (uranium, cesium, and plutonium). Two changes were made to the model input to simulate the case of colloidal transport; the distribution coefficients were decreased substantially (Table B-4) to represent the combined transport of contaminant and colloid, and initial concentrations were increased to account for dissolved and bound radionuclides.

Figure B-13 is a plot of colloid-facilitated cesium-137 transport. The distance to the 4-mrem/yr boundary is less than 0.3 km (0.19 mi). This is not a significant change from the base case. For both plutonium-239/240 (Figure B-14) and uranium-238 (Figure B-15), the distance to the 4-mrem/yr boundary is on the order of 1 km (0.62 mi) at the 95 percent cumulative frequency. The differing results for three sorbing contaminants can be attributed to differing half-lives and base case distribution coefficients. The short half-life of cesium-137 causes it to decay rapidly and leads to a small distance to the 4-mrem/yr boundary. Plutonium-234/240 and uranium-238 decay much more slowly and persist in the groundwater system for a much longer period of time. Even with colloids and within the time frame of this analysis (25,000 years), the carbon-14 remains the radionuclide which produces the greatest distance to the 4-mrem/yr boundary.

B.1.3.2.3. Horizontal Flow from Central Frenchman Flat - Matrix Diffusion in the Alluvium

The alluvial material of Frenchman Flat has a large proportion of clasts that are derived from volcanic rocks (Hoffman et al., 1977). The volcanic clasts are porous; therefore, it is possible that the flow in the alluvium is predominantly through the interclast region with a matrix diffusion process into the clasts. Using data from Hoffman et al. (1977), the effective porosity was given a range of 19 to 27 percent, and the matrix porosity was assigned a range of 5 to 15 percent. The results, presented in Figure B-16, are not much different than the base case (Figure B-7). This suggests that matrix diffusion processes in the alluvium do not contribute much uncertainty to the calculation of the contaminant boundary location.

B.1.3.2.4. Horizontal Flow from Central Frenchman Flat - Correlation of Parameters

The Latin hypercube sampling program generates a series of random values for each parameter that follows a prescribed distribution as in Table B-5. The sampling program generates independent random variables for each parameter; the value of one parameter for any particular realization is generated independently of the other values. However, there are parameters that may be correlated, for example, fracture effective porosity and hydraulic conductivity. The greater the number of fractures and the greater the apertures, the larger will be the porosity and the larger will be the hydraulic conductivity. Therefore, those two parameters should be positively correlated so that when one value is large, the other should also be large.

Table B-9 contains the parameter pairs that were assumed to be correlated and the type of correlation (positive or negative). These correlations are considered plausible, but have not been demonstrated to occur in Frenchman Flat. They are presented here to assess the potential impact

Table B-9
Parameters Treated as Correlated

Parameter 1	Parameter 2	Correlation
Dispersivity	Effective porosity	Negative
Matrix porosity	Diffusion coefficient	Positive
Effective porosity	Hydraulic conductivity	Positive
Effective porosity	Conductivity-depth coefficient	Positive
Hydraulic conductivity	Conductivity-depth coefficient	Positive

of parameter correlation on the calculated 4-mrem/yr boundary. The degree of correlation is unknown; therefore, the following two example cases were considered: 50 and 90 percent correlation of parameters. The results for carbon-14 for the 50 and 90 percent correlation runs are provided in Figures B-17 and B-18. The results are very similar to the base case (Figure B-7) indicating that, for this value of information analysis, correlation of parameters is not a significant issue.

B.1.3.2.5. Horizontal Flow from Central Frenchman Flat - Double Source Case

There is a possibility that two sources could lie along the same flow path. In that case, both sources contribute radionuclides to the flow system that affect carbon-14 concentrations along the flow path. Figure B-19 is a plot of the Case 2 source case using carbon-14. It shows that the distance to the 4-mrem/yr level is increased enough that it extends into the Lower Carbonate Aquifer. As noted in Section 2.2.2, additional dilution in the Lower Carbonate Aquifer will decrease concentrations further.

B.1.3.2.6. Horizontal Flow Path from Northern Frenchman Flat

The base case analysis examined flow from the center of Frenchman Flat because the center is closer to the southwestern portion of the basin (which is the discharge point), based on the regional groundwater flow model. However, there are seven event locations at the northern end of Frenchman Flat that were also considered. The results of a pathway from the MINUTE STEAK event in the northern portion of Frenchman Flat are presented in Figure B-20. For carbon-14, the distance to the 4-mrem/yr level is again between 5 and 7.5 km (3.1 and 4.7 mi). This is the same result as for the base case (Figure B-7). The difference in the present case is that the path does not enter the Lower Carbonate Aquifer until about 12 km (7.5 mi). At that distance, the carbon-14 concentrations are more than one order of magnitude below the 4-mrem/yr level. The conclusion from these simulations is that if flow is horizontal throughout Frenchman Flat, then radionuclides from the southernmost events have the greatest likelihood of reaching the Lower Carbonate Aquifer.

B.1.3.2.7. Vertical Flow to the Carbonates

The current regional groundwater flow model creates a flow path that is essentially horizontal throughout Frenchman Flat. This produces a long flow path through very low groundwater velocity alluvial material. As a consequence, all but the most long-lived radionuclides decay to a

level that is acceptable. However, if the flow is vertical, radionuclides can reach the Lower Carbonate Aquifer more quickly through a shorter pathway. Simulations were designed to address this question. An estimate of the vertical flux was obtained from estimates of the vertical hydraulic gradient and hydraulic conductivity. The vertical hydraulic gradient is the difference in head divided by the vertical distance. The head difference is conservatively estimated as the head in Well UE-11a (~736 m) minus the head in Water Well C (~725 m), which is 11 m (36 ft). The distance between the base of the alluvium and the Lower Carbonate Aquifer is about 670 m (2,200 ft) in the center of Frenchman Flat. The hydraulic gradient is calculated as 0.016. This number may be too large by a factor of two, but a conservative estimate was desired for this modeling exercise. The vertical hydraulic conductivity is estimated as 10 percent of the largest measured value in Frenchman Flat, which is 2.1 m/d (6.9 ft/d) at Water Well 5A. The vertical specific discharge, calculated as the product of vertical hydraulic conductivity and vertical hydraulic gradient, is 1.26 m/yr (4.1 ft/yr). For the simulations, a value of 1.2 m/yr (3.9 ft/yr) was chosen.

Three locations were chosen for the vertical flow scenario. One location is near the three events in central Frenchman Flat, and the other two locations are in northern Frenchman Flat. The events in northern Frenchman Flat are closer to the top of the Lower Carbonate Aquifer because the bottom of the basin rises rapidly toward the Massachusetts Mountains to the north of Frenchman Flat. The distances from the bottom of the event cavities to the Lower Carbonate Aquifer vary from 350 m (1,150 ft) in northern Frenchman Flat to nearly 1,100 m (3,609 ft) in central Frenchman Flat.

The results for the vertical pathway in central Frenchman Flat are given in Figure B-21. The end of the path is the top of Lower Carbonate Aquifer; therefore, all the results are described in terms of the concentrations that would be expected to enter the Lower Carbonate Aquifer. The concentrations entering the Lower Carbonate Aquifer are about 50 times the 4-mrem/yr level. This suggests that, if flow is as rapid as this example assumed, the concentrations of carbon-14 in the Lower Carbonate Aquifer could be a concern. As noted earlier, there will be additional dilution in the Lower Carbonate Aquifer because of the three-dimensional effects not accounted for in this one-dimensional analysis. Table B-7 indicated that dilution in the Lower Carbonate Aquifer will be greater than a factor of 10 at a distance of 5 km (3.1 mi) and be at least a factor of 80 at 40 km (24.85 mi).

The two other vertical pathways, both in northern Frenchman Flat (presented in Figures B-22 and B-23), also produce elevated carbon-14 concentrations in the Lower Carbonate Aquifer. These simulations suggest that if there is a pathway from the events to the Lower Carbonate Aquifer that is vertical, or at least much shorter than the horizontal flow base case, then the distance to the 4-mrem/yr boundary in the Lower Carbonate Aquifer could be quite large, perhaps tens of kilometers.

B.1.3.2.8. Summary of Scenario Simulations

A base case of horizontal flow of six radionuclides has been examined, and over a period of 25,000 years, the distance to a 4-mrem/yr boundary is primarily due to carbon-14. When the effect of colloidal transport was examined, the sorbing radionuclides migrated further downgradient, as expected, but not as far as carbon-14. Other simulations with matrix diffusion in the alluvial aquifer and correlation of parameters did not produce substantially different results from the base case. The case of two sources in series did produce a further downgradient distance to the 4-mrem/yr boundary, suggesting that the careful inclusion of all the events needs to be part of the corrective action unit scale modeling. Finally, the single most important scenario was a vertical flow case which quickly moves radionuclides along a short circuit pathway to the Lower Carbonate Aquifer. These latter vertical flow scenarios assume a rather large but defensible vertical flux, within the data available. It appears from these simulations that the most important question to answer is whether there is a short path to the Lower Carbonate Aquifer.

B.1.3.3 Uncertainty Analyses on Individual Parameters

As described in Section 2.3.1, uncertainty analyses were performed for each of the simulations presented in Section 2.2. The simulations in the section were designed to identify the specific parameters that created the greatest uncertainty in the distance to the 4-mrem/yr boundary. The discussion focuses on several representative cases rather than providing a complete listing of every outcome.

B.1.3.3.1. Uncertainty Analysis of the Horizontal Flow Base Case

In Figures B-24 and B-25, which represent the uncertainty in the predicted concentration of tritium at a distance of 0.34 km (0.21 mi) downgradient, the primary contributors to uncertainty are recharge, source term, and KH_20_5 (which is the horizontal hydraulic conductivity of the

alluvium). The recharge and KH_20_5 terms represent horizontal flux which is important in the case of tritium.

A similar conclusion can be drawn from the uncertainty analyses of carbon-14 at a distance of 3 km (1.9 mi) (Figures B-26 and B-27). The parameters contributing the most to the predicted uncertainty, in decreasing order of importance, are horizontal flux, source term, dispersivity, and effective porosity. The response of iodine-129 is identical to that of carbon-14.

The base case simulations for cesium-137 and plutonium-239/240 indicated such a short transport distance that the plots do not show any substantial concentration other than in the source area itself. This, of course, indicates that sorption, as parameterized by the distribution coefficient (Kd), is the single most important parameter. For uranium-238 (Figure B-28), the most important parameters are distribution coefficient, horizontal flux, and dispersivity.

B.1.3.3.2. Uncertainty Analyses for the Colloidal Transport Case

Figures B-29, B-30, and B-31 summarize the case of colloidal transport for plutonium-239/240 and uranium-238. At a distance of 1 km (0.62 mi), the parameters contributing to overall prediction uncertainty, in order of importance, are distribution coefficient, source term, and horizontal flux.

B.1.3.3.3. Uncertainty in the Vertical Flow Scenarios

Figures B-32 and B-33 depict the results of uncertainty analyses of the vertical flow path scenarios in central and northern Frenchman Flat, respectively. The greatest distance in each of these figures corresponds to the top of the Lower Carbonate Aquifer. In both cases, the parameter contributing the most to the uncertainty in the prediction is the source, followed by the effective porosity in the case of the flow path in northern Frenchman Flat. The enhanced importance of the effective porosity in the north is due, in large part, to the fact that the bottom of the shot cavity is in what has been treated as fractured, welded tuff in these simulations. Hence, the initial velocity has a major impact on the resulting uncertainty.

B.1.3.3.4. Summary of Uncertainty Analyses

The uncertainty analyses presented in Section 2.3.3 can be summarized in terms of vertical and horizontal flow cases. For the vertical flow simulations which were shown in Section 2.3.2 to be of primary importance, the primary source of uncertainty is the source term, followed by the

vertical flux. For the horizontal flow cases, the primary parameters contributing to uncertainty fall into two categories: one for nonsorbing nuclides and one for sorbing nuclides. For nonsorbing nuclides, the horizontal flux seems to be the most important, followed by the source term, dispersivity, and effective porosity. For sorbing nuclides, the distribution coefficient is the most important parameter, followed by the source term and horizontal flux.

Considering the importance of the vertical flow paths, the parameters contributing to overall prediction uncertainty are listed in order of importance as the following: source term, vertical flux, horizontal flux, distribution coefficient, and other parameters, such as effective porosity and dispersivity.

Carbon-14

Figure B-4

Example Plot with Simultaneous Variation of Parameters

Carbon-14
(Distance = 3-Km)

Figure B-5
Example Plot with Uncertainty of Individual Transport Parameters

Carbon-14 (Distance = 3-Km)

Figure B-6
Example Plot with Uncertainty of Individual Flow Parameters

Carbon-14

Figure B-7

Carbon-14, Base Case

Figure B-8
Tritium, Base Case

Iodine-129

B-40

Figure B-9
Iodine-129, Base Case

Uranium-238

Figure B-10
Uranium-238, Base Case

Cesium-137

Figure B-11

Cesium-137, Base Case

Plutonium-239/240

Figure B-12

Plutonium-239/240, Base Case

Cesium-137 Colloid Facilitated Transport

Figure B-13

Cesium-137, Colloid-Facilitated Transport Case

Plutonium 239/240 (Run-2)

Figure B-14
Plutonium-239/240, Colloid-Facilitated Transport Case

Uranium-239 Colloid Facilitated Transport

Figure B-15

Uranium-238, Colloid-Facilitated Transport Case

Carbon-14 Matrix Diffusion in the Alluvium

Figure B-16

Carbon-14, Matrix Diffusion in the Alluvium

Carbon-14 Parameter Correlation, 50%

Figure B-17

Carbon-14, 50 Percent Parameter Correlation

Carbon-14 Parameter Correlation, 90%

Carbon-14 Dual Sources

Figure B-19

Carbon-14, Two Sources in Series

Carbon-14 Flow Path from Northern Frenchman Flat

Carbon-14 Vertical Path - Central Frenchman Flat

Figure B-21

Carbon-14, Vertical Flux from DILUTED WATERS Event

Carbon-14 Vertical Path #1 - Northern Frenchman Flat

Figure B-22
Carbon-14, Vertical Flux from PIN STRIPE Event

Carbon-14 Vertical Path #2, Northern Frenchman Flat

Figure B-23
Carbon-14, Vertical Flux from NEW POINT Event

Tritium
(0.34-Km Downgradient Distance)

Figure B-24
Tritium, Transport Parameter Uncertainty (0.34-km Downgradient Distance)

**Tritium
(0.34-Km Downgradient Distance)**

Figure B-25
Tritium, Hydraulic Parameter Uncertainty (0.34-km Downgradient Distance)

Carbon-14
(Distance = 3-Km)

Figure B-26

Carbon-14, Transport Parameter Uncertainty (3-km Downgradient Distance)

Carbon-14
(Distance = 3-Km)

Figure B-27
Carbon-14, Hydraulic Parameter Uncertainty (3-km Downgradient Distance)

Uranium-239
(Distance = 1-Km)

Figure B-28
Uranium-238, Transport Parameter Uncertainty (0.34-km Downgradient Distance)

Plutonium-239/240
(Distance = 1-Km) Colloid Facilitated Transport

Figure B-29

Plutonium-239/240, Transport Parameter Uncertainty
(1-km Downgradient Distance), Colloid Facilitated Transport

Plutonium-239/240
(Distance = 1-Km) Colloid Facilitated Transport

Figure B-30
Plutonium-239/240, Hydraulic Parameter Uncertainty
(1-km Downgradient Distance), Colloid Facilitated Transport

Uranium-238
(Distance = 1-Km) Colloid Facilitated Transport

Figure B-31
Uranium-238, Transport Parameter Uncertainty
(1-km Downgradient Distance), Colloid Facilitated Transport

Carbon-14
Fast Path to the Carbonates, Central Frenchman Flat

Figure B-32
Carbon-14, Transport Parameter Uncertainty (1-km Downgradient Distance),
DILUTED WATERS Event

Figure B-33
Carbon-14, Transport Parameter Uncertainty
(1-km Downgradient Distance), PIN STRIPE Event

Appendix C

Data Collection and Analysis Options

C.1.0 Data Collection and Analysis Options

C.1.1 Organization of the Data Collection and Analysis Options

In order to apply the value of information analysis process to quantify the reduction of uncertainty that might be achieved and the cost to achieve it, specific packages of activities had to be defined. The activities grouped in each package determine the parameters that would be addressed by the package, and the specifications for the activities provide a fixed point of reference.

Groupings of data types were identified to organize the options to answer specific questions. These questions then serve as the basis for estimating the possible reduction of uncertainty for the option. These groupings, called Option Types, are shown in the second column of Table C-1. Please note the acronym assigned to each Option Type.

The Option Combination Category shown in column three of Table C-1 introduces the functional groupings (discussed in Chapter 4.0), that were used for the decision analysis presented in Chapter 5.0.

Table C-1
Categorization of Data Collection/Analysis Options

Question - Data Type	Data Collection/Analysis Option Type(acronym)	Option Combination Category
Hydrogeology	Geology (G)	Vertical Flux
	Horizontal Gradient (HG)	Horizontal Flux
	Horizontal Hydraulic Conductivity (HHC)	Horizontal Flux
	Vertical Gradient (VG)	Vertical Flux
	Vertical Hydraulic Conductivity (VHC)	Vertical Flux
Source Term	Source Term (ST)	Source Term
Transport Parameters	Alluvium Transport Parameters (ATP)	Transport Parameters
	Volcanic Transport Parameters (VTP)	Transport Parameters
	Carbonate Transport Parameters (CTP)	Transport Parameters
	Distribution Coefficients (DC)	Transport Parameters

Within each option type, the options were subdivided according to the following three levels of work:

- Level 1 - Use existing data for evaluation, analysis, or modeling.
- Level 2 - Conduct nonintrusive data collection, such as analyzing existing samples or test and/or sample existing wells.
- Level 3 - Conduct intrusive data collection, such as drilling new boreholes, constructing new wells, and testing and/or sampling existing wells.

These levels roughly correspond to increasing cost and schedule requirements for accomplishing the option. Proposed options are identified in Table C-2 according to the option type and level.

Table C-2
Matrix of Data Collection and Analysis Option

Data Collection/ Analysis Option Type (Acronym)	Evaluate and/or Model Existing Data	New Analysis of Existing Samples	Test and/or Sample Existing Wells	Construct New Wells, Test and/or Sample
Geology		G2a, G2b, G2c		G3a, G3b
Vertical Gradient	VG1		VG2	VG3c, VG3d
Vertical Hydraulic Conductivity				VHC3
Source Term	ST1	ST2c	ST2a, ST2b	ST3
Horizontal Gradient	HG1		HG2	HG3
Horizontal Hydraulic Conductivity	HHC1		HHC2	HHC3
Alluvium Transport Properties	ATP1		ATP2	ATP3
Volcanic Transport Properties			VTP2	VTP3
Carbonate Transport Properties	CTP1		CTP2	CTP3
Distribution Coefficients	DC1	DC2		DC3

An additional alphabetic designator is added to the option identifier when there are multiple options at the same level under an option type. This Appendix contains data sheets for each option, the question the option is designed to answer, a detailed description of the option, limitations of the option, and a cost estimate of the option.

The options listed in Table C-2 do not include all possibilities for activities. During development of the options, each possibility was evaluated, and some were rejected for various reasons. In some cases it was determined that all worthwhile work in a level had already been done (G1 option type), that no data (VTP1 and VHC1 option types), samples, or wells (VHC2 option type) exist to support an option, or that the cost of the option was too great to consider (more elaborate Level 3 activities).

C.1.2 Cost Estimating

Cost estimates for each option were developed based on the specified scope. The table at the bottom of each option data sheet shows the cost elements that were used to estimate the option cost. The elements and their costs are taken, to the extent possible, from the UGTA Baseline cost estimating for planned and contingent activities. Additional cost elements for other work are included, as necessary, and costs for these elements were estimated using information from various DOE contractor staff involved in similar activities. Complete supporting information is contained in the Frenchman Flat value of information analysis cost estimating documentation file. In most cases, the scope or specifications of the option did not correspond exactly with the baseline assumption used for costing. Consequently, the baseline cost elements were adapted and manipulated using professional judgement to give a representative cost for the value of information analysis option. A rationale for the various manipulations is included in the documentation file.

The cost estimates are meant to be representative for the type of activity and scope, not precise estimates for a proposal. While the costs are reported to the nearest dollar, the cost estimates should be viewed and used in terms of one or two significant digits only. The scope and specifications for the options are not sufficiently developed to base a detailed estimate on them, nor does this analysis require such detail.

VERTICAL GRADIENT

Option VG1: Evaluate Existing Data

Focus: What is the vertical gradient from the alluvium to the carbonate aquifer, both in Frenchman Flat in general and in Areas 11 and 5 specifically?

Description: Identify, organize, and analyze available information. Include the following: locations of existing wells in and around Frenchman Flat and pertinent well information, including well identification, well construction, deviation surveys, effective open intervals, hydrostratigraphic unit(s), land surface elevations, and depth-to-water measurements. This task is essentially identical to Option HG1.

Determine hydraulic heads, and analyze uncertainty in derived head values. Analyze head data to quantify vertical gradients and identify implications for transport. Identify data gaps and specifications for Options G2a,b,c; VG2; and VG3c,d.

Limitations: There is a lack of available wells with appropriate completion intervals at vertically discrete depths in both Frenchman Flat in general and in the specific areas mentioned. There are also large uncertainties in using available water-level measurements due to the accuracy and precision of available well-head elevations; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainties in available information resulting from the accuracy and precision of available measurements are probably much greater than the general limits for the accuracy of head information for a well, which is ± 2 feet, and the uncertainty due to the completion interval. Also, this general amount of uncertainty in determination of the discrete- depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VG1	Evaluate available data	lump	1	50,000.00	50,000

VERTICAL GRADIENT

Option VG2: Collect New Information From Existing Wells

Focus: What is the vertical gradient from the alluvium to the carbonate aquifer, both in Frenchman Flat in general and in Areas 11 and 5 specifically?

Description: Based on analysis of the potential for collecting higher quality or more specific hydraulic head information from existing wells (VG1), identify wells (10 expected) for collecting new information. It is assumed that high quality elevation surveys, deviation surveys, and depth-to-water measurements for each well would be conducted for this activity. The new information would be directly incorporated into the Frenchman Flat analysis. This activity is basically identical to activity G2, although there could be some differences in the wells selected for each task. In application, these two tasks would probably be combined into one task, costing somewhat less than the total of the two individual tasks.

Limitations Encountered: There is a lack of available wells with appropriate completion intervals at vertically discrete depths in both Frenchman Flat in general and in the specific areas mentioned. There are also limiting uncertainties in new information, gathered as previously specified, due to the accuracy and precision of well-head elevation surveys; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainty in new information resulting from the accuracy and precision of the various measurements is generally ± 2 ft/1,000 ft of depth and the uncertainty due to the completion interval. This later uncertainty could be reduced with enough varied information, but there is probably not enough opportunity for information collection from existing wells available to reduce it substantially. Also, this general amount of uncertainty in determination of the discrete-depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VG2	Elevation survey (level survey) - 10 wells	lump	1	24,000.00	24,000
	Deviation survey	ea.	10	19,144.00	191,440
	Water-level measurements, 3/well	ea.	30	273.00	8,190
	Calibrate measurement equipment	lump	1	1,093.00	1,093
				Option Total	224,723

VERTICAL GRADIENT

Option VG3c: Construct New Wells To Obtain Vertical Gradient Information, Area 11

Focus: What is the vertical gradient from the alluvium to the carbonate aquifer, both in Frenchman Flat in general and in Area 11 specifically?

Description: Construct a new multiple-completion well in Area 11 to obtain accurate water levels at one location in the alluvium, volcanics/tertiary sediments, and lower carbonate aquifer. This well, per the UGTA Baseline, would consist of three individual completion wells. Anticipated depths are 1,100 ft, 2,300 ft, and 3,500 ft below land surface, respectively. It is assumed that high quality elevation surveys, deviation surveys, and depth-to-water measurements for each well would be conducted for this activity. Three water-level measurements are planned for each well. Local measurement of horizontal gradient may be incorporated into this task by slightly modifying the well installations. The value of this activity will be determined under the horizontal gradient (construct new wells activity [HG3]), and the well installations would be modified if the two activities are both selected.

Limitations Encountered: There are also limiting uncertainties in new information, gathered as specified, due to the accuracy and precision of well-head elevation surveys; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainty in new information resulting from the accuracy and precision of the various measurements is generally ± 2 ft/1,000 ft of depth and the uncertainty due to the completion interval. This amount of uncertainty in determination of the discrete- depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VG3c	Water-level monitoring well, Area 11 - 1,100 ft	ea.	1	701,665.00	701,665
	Water-level monitoring well, Area 11 - 2,300 ft	ea.	1	1,156,937.00	1,156,937
	Water-level monitoring well, Area 11 - 3,500 ft	ea.	1	1,633,967.00	1,633,967
	Water-level measurements, 3/well	ea.	9	273.00	2,457
				Option Total	3,495,026

VERTICAL GRADIENT

Option VG3d: Construct New Wells To Obtain Vertical Gradient Information, Area 5

Focus: What is the vertical gradient from the alluvium to the carbonate aquifer, both in Frenchman Flat in general and in Area 5 specifically?

Description: Construct a new multiple-completion well in Area 5 to obtain accurate water levels at one location in the alluvium, volcanics/tertiary sediments, and lower carbonate aquifer. This well, per the UGTA Baseline, would consist of three individual completion wells. Anticipated depths are 1,100 ft, 3,050 ft, and 5,000 ft below land surface, respectively. It is assumed that high quality elevation surveys, deviation surveys, and depth-to-water measurements for each well would be conducted for this activity. Three water-level measurements are planned for each well. Local measurements of horizontal gradient may be incorporated into this task by slightly modifying the well installations. The value of this will be determined under the horizontal gradient (construct new wells activity [HG3]), and the well installations would be modified if the two activities are both selected.

Limitations Encountered: There are limiting uncertainties in new information, gathered as specified above, due to the accuracy and precision of well-head elevation surveys; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainty in new information resulting from the accuracy and precision of the various measurements is generally ± 2 ft/1,000 ft of depth and the uncertainty due to the completion interval. This amount of uncertainty in determination of the discrete-depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VG3d	Water-level monitoring well, Area 5 - 1,100 ft	ea.	1	701,665.00	701,665
	Water-level monitoring well, Area 5 - 3,050 ft	ea.	1	1,455,080.00	1,455,080
	Water-level monitoring well, Area 5 - 5,000 ft	ea.	1	2,230,254.00	2,230,254
	Water-level measurements, 3/well	ea.	9	273.00	2,457
				Option Total	4,389,456

HORIZONTAL GRADIENT

Option HG1: Evaluate Existing Data

Focus: What is the horizontal gradient in the alluvium and deeper hydrostratigraphic units in the Frenchman Flat basin and in the underlying carbonate aquifer, both in Frenchman Flat in general and in Areas 11 and 5 specifically?

The horizontal gradient in the alluvium in Frenchman Flat appears to be very low, on the order of several meters head difference at most, over the available baseline. This makes measurement uncertainties a significant problem, since these uncertainties add up to a large fraction of the vertical head change used to calculate the gradient. This problem is exacerbated by the poor distribution of existing wells for the purpose of determining the gradient.

Description: Identify, organize, and analyze available information. Include the following: locations of existing wells in and around Frenchman Flat and pertinent well information, including well identification, well construction, deviation surveys, effective open intervals, hydrostratigraphic unit(s), land surface elevations, and depth-to-water measurements. This task is essentially identical to task VG1.

Determine hydraulic heads, and analyze uncertainty in derived head values. Analyze head data to quantify horizontal gradients and identify implications for transport. Identify data gaps and specifications for Options G2a,b,c; VG2; and VG3c,d.

Limitations: There is a lack of available wells throughout Frenchman Flat with appropriate completion intervals at vertically discrete depths. There are also large uncertainties in using available water-level measurements due to the accuracy and precision of available well-head elevations; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainties in available information resulting from the accuracy and precision of available measurements are probably much greater than the general limits for the accuracy of head information for a well, which is ± 2 ft/1,000 ft of depth and the uncertainty due to the completion interval. Also, this general amount of uncertainty in determination of the discrete-depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
HG1	Evaluate available data	lump	1	50,000.00	50,000

HORIZONTAL GRADIENT

Option HG2: Collect New Information From Existing Wells

Focus: What is the horizontal gradient in the alluvium and deeper hydrostratigraphic units in the Frenchman Flat basin and in the underlying carbonate aquifer, both in Frenchman Flat in general and in Areas 11 and 5 specifically?

The horizontal gradient in the alluvium in Frenchman Flat appears to be very low, on the order of several meters head difference at most, over the available baseline. This makes measurement uncertainties a significant problem, since these uncertainties add up to a large fraction of the vertical head change used to calculate the gradient. This problem is exacerbated by the poor distribution of existing wells for the purpose of determining the gradient.

Description: Based on analysis of the potential for collecting higher quality or more specific hydraulic head information from existing wells (VG1), identify wells (10 expected) for collecting new information. It is assumed that high-quality elevation surveys, deviation surveys, and depth-to-water measurements for each well would be conducted for this activity. The new information would be directly incorporated into the Frenchman Flat analysis. This activity is basically identical to activity VG2, although there could be some differences in the wells selected for each task. In application, these two tasks would probably be combined into one task, costing somewhat less than the total of the two individual tasks.

Limitations Encountered: There is a lack of available wells with appropriate completion intervals at vertically discrete depths in both Frenchman Flat in general and in the specific areas mentioned. There are also limiting uncertainties in new information gathered, as specified, due to the accuracy and precision of well-head elevation surveys; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainty in new information resulting from the accuracy and precision of the various measurements is generally ± 2 ft/1,000 ft of depth and the uncertainty due to the completion interval. This later uncertainty could be reduced with enough varied information, but there is probably not enough opportunity for information collection from existing wells available to substantially reduce it. Also, this general amount of uncertainty in determination of the discrete-depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
HG2	Elevation survey (level survey) - 10 wells	lump	1	24,000.00	24,000
	Deviation survey	ea.	10	19,144.00	191,440
	Water-level measurements, 3/well	ea.	30	273.00	8,190
	Calibrate measurement equipment	lump	1	1,093.00	1,093
				Option Total	224,723

HORIZONTAL GRADIENT

Option HG3: Construct New Wells To Obtain Horizontal Gradient Information

Focus: What is the horizontal gradient in the alluvium and deeper hydrostratigraphic units in the Frenchman Flat basin and in the underlying carbonate aquifer, both in Frenchman Flat in general and in Areas 11 and 5 specifically?

The horizontal gradient in the alluvium in Frenchman Flat appears to be very low, on the order of several meters head difference at most over the available baseline. This makes measurement uncertainties a significant problem, since these uncertainties add up to a large fraction of the vertical head change used to calculate the gradient. This problem is exacerbated by the poor distribution of existing wells for the purpose of determining the gradient.

Description: Construct three new single-completion wells in the alluvium to obtain accurate head information at locations in northeast, southeast, and southwest Frenchman Flat. These wells, per the UGTA Baseline, would consist of small diameter completions with no pumping capability. Nominal depth for the wells is 1,100 ft below land surface. It is assumed that high-quality elevation surveys, deviation surveys, and depth-to-water measurements for each well would be conducted for this activity. Three water-level measurements are planned for each well.

Information on the horizontal gradient in deeper hydrostratigraphic units would be obtained by adding new hydraulic head information for those hydrostratigraphic units obtained from VG3c,d (if done) to existing information from HG1 and HG2. Information on local horizontal gradients in Areas 11 and 5 may be obtained from the VG3c,d task by slightly modifying the well installations. The value of this will be determined under the horizontal gradient (construct new wells activity [HG3]), and the actual well installation will then be modified, if this activity is pursued.

Limitations Encountered: There are also limiting uncertainties in new information, gathered as specified, due to the accuracy and precision of well-head elevation surveys; borehole deviation corrections; measurements of depth-to-water; and the effects of long, open intervals (because water-level measurements reflect composite head across the open interval, presumably where a vertical gradient exists). The uncertainty in new information resulting from the accuracy and precision of the various measurements is generally ± 2 ft/1,000 ft of depth and the uncertainty due to the completion interval. This amount of uncertainty in determination of the discrete-depth head may exceed the size of the gradient that is being measured, resulting in the inability to accurately quantify the gradient.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
HG3	Drill water-level monitoring wells, 1,100 ft deep	ea.	3	701,665.00	2,104,995
	Deviation survey	ea.	3	19,144.00	57,432
	Elevation survey (level survey)	ea.	3	2,400.00	7,200
	Water-level measurements, 3/well	ea.	9	273.00	2,457
				Option Total	2,172,084

GEOLOGY

Option G2b: Nonintrusive Geological Investigation

Focus: What is the thickness of the alluvium; the continuity and thickness of underlying volcanic or clastic aquitards; and the depth to the carbonate throughout Frenchman Flat and, specifically, the vicinities of Area 11 and Area 5? What is the subsurface structure, faulting, displacement, and juxtapositions of Frenchman Flat in the vicinities of Area 11 and Area 5 specifically?

The UGTA geologic model of Frenchman Flat has two alternate interpretations of the subsurface which would affect markedly different groundwater flow and contaminant transport calculations. One interpretation is that the alluvium aquifer is isolated everywhere from the Lower Carbonate Aquifer by a continuous layer of Tertiary sediments and volcanic confining units. The other scenario is that alluvium is locally in contact with the carbonate aquifer either because of local erosion prior to alluvium deposition or by the juxtaposition of the two aquifers across a relatively large displacement fault.

Description: Perform a two-dimensional reflection seismic survey over an area of 120 square kilometers. Seismic surveys in the two-dimensional method consist of a grid of seismic lines which are generally one to a few kilometers apart. Data are processed in two dimensions along individual lines. A grid of two-dimensional seismic lines allows the mapping and orientation of gross structural and stratigraphic features when they are recognized on more than one line. The use of two-dimensional seismic data grids has been a commonly accepted technique in the petroleum industry for prospect delineation and positioning of exploratory boreholes.

Limitations: The two-dimensional seismic survey is expected to achieve much of the results of the three-dimensional survey in Option G2c at substantially lower cost, but could prove to be less definitive under certain circumstances. This case would probably become apparent upon interpretation of the two-dimensional survey, providing the opportunity for additional work if it is deemed necessary rather than leaving some serious problem undiscovered. An additional limitation is the lack of good borehole information to tie the seismic survey to, which would greatly improve the interpretation. The drilling of deep boreholes under other options (such as G3a,b; VG3c,d; or CTP3) would provide much of the required correlation opportunity, and the addition of some specific testing to such drilling for this purpose would be advantageous.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
G2b	2-D seismic grid, 120 sq km	ea.	1	2,000,000.00	2,000,000
	Incorporate data, Executive Staff	hr.	320	115.42	36,934
				Option Total	2,036,934

HYDRAULIC CONDUCTIVITY

Option HHC1: Evaluate Existing Data

Focus: What is the correct horizontal hydraulic conductivity value(s) for use in modeling flow?

Groundwater pore velocity (seepage velocity) and the associated contaminant migration velocity are directly dependent on the hydraulic conductivity characteristic of the hydrogeologic medium. The physical relationship is such that, for a given hydraulic gradient, the flow velocity increases as the hydraulic conductivity increases. For this option, we consider only horizontal hydraulic conductivity; the vertical case is investigated separately. Horizontal hydraulic conductivity may be anisotropic, where the conductivity is greatest in a particular direction and least in the perpendicular direction. Much more information is required to define anisotropic conductivity.

Description: Identify, organize, and analyze available information. Include the following: available well records and geophysical logs for wells in Frenchman Flat or other wells that may be representative of hydrostratigraphic units in Frenchman Flat, available pumping data, pumping test data, other hydraulic test data, the CAMBRIC tracer test data, and any pertinent data relative to the Radioactive Waste Management Area, such as air permeability data.

Limitations: Most of this work has already been done during the Phase I study. The available information is limited as far as the deeper hydrostratigraphic units and areally over the downgradient extent of Frenchman Flat.

Cost: The content of this activity is included in the Environmental Restoration Contractor Task Plans for Fiscal Year 1997 (evaluate available data).

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost\$
HHC1	Evaluate available data	lump	1	50,000.00	50,000

HYDRAULIC CONDUCTIVITY

Option HHC2: Use Existing Wells To Obtain Horizontal Hydraulic Conductivity Information

Focus: What is the correct horizontal hydraulic conductivity value(s) for use in modeling flow? Groundwater pore velocity (seepage velocity) and the associated contaminant migration velocity are directly dependent on the hydraulic conductivity characteristic of the hydrogeologic medium. The physical relationship is such that, for a given hydraulic gradient, the flow velocity increases as the hydraulic conductivity increases. For this option, we consider only horizontal hydraulic conductivity; the vertical case is investigated separately. Horizontal hydraulic conductivity may be anisotropic, where the conductivity is greatest in a particular direction and least in the perpendicular direction. Much more information is required to define anisotropic conductivity.

Description: Conduct flow logging and pumping tests in three existing wells.

Limitations: Locations and depths of existing wells, assuming three are found suitable for testing, are expected to provide only information on the alluvium in a limited area of Frenchman Flat, while information is especially lacking for deeper hydrostratigraphic units and areally over the downgradient extent of Frenchman Flat. It may also be assumed that existing wells will not include observation well(s), limiting the quality of the data obtained and not addressing the question of anisotropy.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
HHC2	Conduct pumping test in 3 existing wells (alluvium)	ea.	3	165,422.00	496,266
	Flow logging	ea.	3	31,010.00	93,030
	Interpretation, Senior Staff - 80 hrs/well	hr.	240	64.37	15,449
	Reporting document	ea.	3	25,000.00	75,000
				Option Total	679,745

HYDRAULIC CONDUCTIVITY

Option HHC3: Construct New Wells To Obtain Horizontal Hydraulic Conductivity Information

Focus: What is the correct horizontal hydraulic conductivity value(s) for use in modeling flow? Groundwater pore velocity (seepage velocity) and the associated contaminant migration velocity are directly dependent on the hydraulic conductivity characteristic of the hydrogeologic medium. The physical relationship is such that, for a given hydraulic gradient, the flow velocity increases as the hydraulic conductivity increases. For this option, we consider only horizontal hydraulic conductivity; the vertical case is investigated separately. Horizontal hydraulic conductivity may be anisotropic, where the conductivity is greatest in a particular direction and least in the perpendicular direction. Much more information is required to define anisotropic conductivity.

Description: Construct new wells for testing in the alluvium: one production well and one observation well per location at 1,100-ft depths. Conduct a pumping test and flow logging in the production well.

Limitations: The location of the site for testing may be chosen to provide information in areas where none is available and where there is some question as to the representativeness of existing data. This test only provides direct information on a small area. The option was limited to testing the alluvium because this presented the greatest value for the applicable use of this type of data. Information on deeper hydrostratigraphic units comes into play primarily for vertical transport cases where the vertical hydraulic conductivity is more applicable and other factors are more important. This option is also not designed to provide anisotropy which was not deemed important enough in the alluvium to warrant the cost of additional observation wells.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
HHC3	Drill pumping well, 1,100 ft deep (alluvium)	ea.	1	1,166,858.00	1,166,858
	Flow logging	ea.	1	31,010.00	31,010
	Conduct pumping test	lump	1	165,422.00	165,422
	Interpretation, Senior Staff	hr.	80	64.37	5,150
	Reporting document	lump	1	25,000.00	25,000
				Subtotal	1,393,440
	Drill observation well 1,000 ft deep	ea.	1	701,665.00	701,665
				Option Total	2,095,105

HYDRAULIC CONDUCTIVITY

Option VHC3: Construct New Wells To Obtain Vertical Hydraulic Conductivity Information

Focus: What is the correct vertical hydraulic conductivity value(s) for use in modeling flow? Groundwater pore velocity (seepage velocity) and the associated contaminant migration velocity are directly dependent on the hydraulic conductivity characteristic of the hydrogeologic medium. The physical relationship is such that, for a given hydraulic gradient, the flow velocity increases as the hydraulic conductivity increases. For this option, we consider only vertical hydraulic conductivity; the horizontal case is investigated separately. The volcanic hydrostratigraphic unit has been identified as the primary aquitard through which vertical transport of contaminants would have to occur to reach the carbonates.

Description: Construct new wells for testing in the volcanic hydrostratigraphic unit: one production well and one observation well per location at 2,500-ft and 2,300-ft depths, respectively. Conduct flow logging and a pumping test in the production well.

Limitations: The location of the site for testing may be chosen to provide information where it is most appropriate, but this test only provides direct information on a small area and over a limited vertical distance. The option was designed to test the volcanic hydrostratigraphic unit(s) because this presented the greatest value for the applicable use of this type of data.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VHC3	Drill pumping well, 2,500 ft deep (volcanics)	ea.	1	1,773,192.00	1,773,192
	Flow logging	ea.	1	31,010.00	31,010
	Conduct pumping test	lump	1	165,422.00	165,422
	Interpretation, Senior Staff	hr.	80	64.37	5,150
	Reporting document	lump	1	25,000.00	25,000
				Subtotal	1,999,774
	Drill observation well, 2,300 ft deep	ea.	1	1,156,937	1,156,937
				Option Total	3,156,711

SOURCE TERM

Option ST1: Evaluate Existing Data

Focus: What are the most important radionuclides to include in modeling and the appropriate release models for each radionuclide, including concentrations, mass loading rates, and total inventories?

Some of the corollary questions that would support the answers to the above question are as follows: in what form are the radionuclides, and what is their physical status (i.e., are they in dissolved, colloidal or solid form; what is the physical and chemical nature of the solids; and what is their geochemistry?).

Description: Identify, organize, and analyze available information. Include the following: data about the inventory of radionuclides from each of the shots in Frenchman Flat, data about the concentrations and form of radionuclides in and around shot cavities, and information about the release of radionuclides from cavities and from the solids in which they may be bound. Analyze data from CAMBRIC, BASEBALL, and INGOT sampling. Update the source term database.

Conduct geochemical modeling of the release and transport of radionuclides in and around shot cavities to develop a release model for the hydrologic source term to be used in transport modeling.

Limitations: There appears to be considerable uncertainty in this general topic, including a lack of general data on the complete range of radionuclides that may be present, concentrations of the radionuclides, and information about colloids. Specific data on the particular shots in Frenchman Flat may not be available because of security issues. Long-term release mechanisms, release models, and release rates appear to be very poorly understood.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ST1	Literature search and geochemical modeling	lump	1	830,000.00	830,000
	Data analysis CAMBRIC, BASEBALL, INGOT, etc.	lump	1	399,007.00	399,007
	Incorporate data, Executive Staff	hr.	160	115.42	18,467
				Option Total	1,247,474

SOURCE TERM

Option ST2a: Perform Hot-Well Sampling and Analysis

Focus: What are the most important radionuclides to include in modeling and the appropriate release models for each radionuclide, including concentrations, mass loading rates, and total inventories?

Some of the corollary questions that would support the answers to the above question are as follows: in what form are the radionuclides, and what is their physical status (i.e., are they in dissolved, colloidal or solid form; what is the physical and chemical nature of the solids; what is their geochemistry?). Very little is known about the long-term behavior of cavity glass, the other altered materials surrounding the shot cavities, or about the amount of radionuclides stored in these materials that may be released. What is especially of concern for determining the extreme boundary of radionuclide transport is the concentration in groundwater of each radionuclide, and whether a higher concentration in groundwater leaving the cavity than would be measured by sampling at this time would ever occur.

Description: Sample four "Hot-Wells" (including INGOT and BASEBALL), and analyze the samples.

Limitations: The "Hot Wells" are not specific to Frenchman Flat shots. This activity only provides data on current concentrations of radionuclides in the groundwater.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ST2a	Hot-Well sampling (4 wells), includes INGOT, BASEBALL	lump	1	272,420.00	272,420
	4 sample analyses, Hot Well	lump	1	44,473.00	44,473
	Incorporate data, Executive Staff	hr.	80	115.42	9,234
				Option Total	326,127

SOURCE TERM

Option ST2b: Well Sampling and Sample Analysis

Focus: What are the most important radionuclides to include in modeling and the appropriate release models for each radionuclide, including concentrations, mass loading rates, and total inventories?

Some of the corollary questions that would support the answers to the above question are as follows: in what form are the radionuclides, and what is their physical status (i.e., are they in dissolved, colloidal or solid form; what is the physical and chemical nature of the solids; and what is their geochemistry?). Very little is known about the long-term behavior of cavity glass, the other altered materials surrounding the shot cavities, or about the amount of radionuclides stored in these materials that may be released. What is especially of concern for determining the extreme boundary of radionuclide transport is the concentration in groundwater of each radionuclide, and whether a higher concentration in groundwater leaving the cavity than would be measured by sampling at this time would ever occur.

Description: Sample 10 existing wells, and analyze for radiochemistry and geochemistry.

Limitations: Existing wells are generally not located optimally for providing direct information on the sources (cavities), but the information is useful for evaluating if the estimated source terms are reasonable.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ST2b	Sample 10 Frenchman Flat wells	lump	1	53,775.00	53,775
	Analysis of a set of 10 samples, radionuclides	lump	1	111,182.50	111,183
	Non-CLP char. analysis of samples	ea.	10	2,700.00	27,000
	Incorporate data, Senior Staff	hr.	120	64.37	7,724
				Option Total	199,682

SOURCE TERM

Option ST2c: Leach Tests on Existing Cavity Glass Samples

Focus: How much of the radionuclide inventory is stored in the cavity glass, and how is it released?

Very little is known about the long-term behavior of cavity glass, the other altered materials surrounding the shot cavities, or about the amount of radionuclides stored in these materials that may be released. What is especially of concern for determining the extreme boundary of radionuclide transport is the concentration in groundwater of each radionuclide and whether a higher concentration in groundwater leaving the cavity than would be measured by sampling at this time would ever occur.

Description: Conduct leach tests on six samples of cavity glass.

Limitations: The representativeness of existing cavity glass samples is not known. The long-term nature of the release mechanism may not provide data on a timely schedule or be a good predictor of long-term future behavior.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ST2c	Leach tests on cavity glass - 6 sample set	month	6	20,000.00	120,000
	Incorporate data, Executive Staff	hr.	160	115.42	18,467
				Option Total	138,467

SOURCE TERM

Option ST3: New Drillback into a Shot Cavity

Focus: What are the most important radionuclides to include in modeling and the appropriate release models for each radionuclide, including concentrations, mass loading rates, and total inventories?

Some of the corollary questions that would support the answers to the above question are as follows: in what form are the radionuclides, and what is their physical status (i.e., are they in dissolved, colloidal or solid form; what is the physical and chemical nature of the solids; and what is their geochemistry?). Very little is known about the long-term behavior of cavity glass and the other altered materials surrounding the shot cavities or about the amount of radionuclides stored in these materials that may be released. What is especially of concern for determining the extreme boundary of radionuclide transport is the concentration in groundwater of each radionuclide and whether a higher concentration in groundwater leaving the cavity than would be measured by sampling at this time would ever occur.

Description: Drill into a shot cavity (estimated 1,100-ft depth), and collect cavity glass and cavity water samples. Perform leach tests on cavity glass (six samples for six months), and analyze four cavity water samples.

Limitations: The long-term nature of the cavity glass release mechanism may not provide data on a timely schedule or be a good predictor of long-term future behavior.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ST3	Drillback, 1,100 ft deep	ea.	1	1,258,405.00	1,258,405
	Leach tests on cavity glass - 6 sample sets	month	6	20,000.00	120,000
	Sample and analyze cavity water - 4 samples	lump	1	44,473.00	44,473
	Incorporate data, Executive Staff	hr.	160	115.42	18,467
	Reporting document	lump	1	50,000.00	50,000
				Option Total	1,491,345

ALLUVIUM TRANSPORT PROPERTIES

Option ATP1: Evaluate Existing Data

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion.

Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Reevaluate CAMBRIC tracer test data for additional information about alluvium transport parameters, and evaluate available data from the Radioactive Waste Management Site (RWMS) for pertinent transport parameter data.

Limitations: This data represents a limited number of locations which do not necessarily provide representative data for all of Frenchman Flat. It is not known what may be available from the RWMS.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ATP1	Review CAMBRIC data, Executive Staff	hr.	320	115.42	36,934
	Evaluate RWMS data, Senior Staff	hr.	800	64.37	51,496
	Reporting document	lump	1	25,000.00	25,000
				Option Total	113,430

ALLUVIUM TRANSPORT PROPERTIES

Option ATP2: Collect New Data using Existing Core and Existing Wells

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Conduct geophysical logging for porosity and density in seven wells, and conduct laboratory tests on 12 existing core samples (three each for the four sediment types that have been identified).

Limitations: Existing wells are not well distributed throughout Frenchman Flat to provide a full representation of the alluvium. A good selection of existing core providing the desired range of sediment types may not be available for Frenchman Flat. These activities do not directly address effective porosity or dispersion.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ATP2	Geophysical logging (porosity, density), 7 wells	ea.	7	27,088.00	189,616
	Lab tests on existing core, 4/sed. type x 3 sed. types	ea.	12	1,000.00	12,000
	Incorporate data, Executive Staff	hr.	80	115.42	9,234
	Reporting document	lump	1	25,000.00	25,000
				Option Total	235,850

ALLUVIUM TRANSPORT PROPERTIES

Option ATP3: Collect New Data Using New Wells

Focus: What are the correct transport parameter values to use in transport modeling?

The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Construct two 1,100-ft-deep pumping wells, and perform a doublet-type tracer test.

Limitations: This test provides very good data for one location, but is not necessarily representative of Frenchman Flat alluvium in general. Additional tests would provide more representative data.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
ATP3	Drill 1,100 ft pumping wells	ea.	2	1,166,858.00	2,333,716
	Conduct doublet-type tracer test	lump	1	839,268.00	839,268
	Interpretation, Executive Staff	hr.	480	115.42	55,402
	Reporting document	lump	1	50,000.00	50,000
				Option Total	3,278,386

VOLCANIC TRANSPORT PROPERTIES

Option VTP2: Collect New Data Using Existing Core and Existing Wells

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Conduct geophysical logging for porosity and density in three wells, and conduct laboratory testing of nine existing cores.

Limitations: Existing wells are not well distributed throughout Frenchman Flat to provide a full representation of the volcanic hydrostratigraphic unit. A good selection of existing core providing the desired range of samples may not be available for Frenchman Flat. These activities do not directly address effective porosity or dispersion.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VTP2	Geophysical logging (porosity, density), 3 wells	ea.	3	27,088.00	81,264
	Lab tests on existing core, 3/well x 3 wells	ea.	9	1,000.00	9,000
	Incorporate data, Executive Staff	hr.	80	115.42	9,234
	Reporting document	lump	1	25,000.00	25,000
				Option Total	124,498

VOLCANIC TRANSPORT PROPERTIES

Option VTP3: Collect New Data, Requiring Construction of New Wells

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Construct two 3,500-ft-deep pumping wells, and perform a doublet-type tracer test.

Limitations: This test provides very good data for one location, but is not necessarily representative of the Frenchman Flat volcanic hydrostratigraphic unit in general. Additional tests would provide more representative data.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
VTP3	Drill 3,500-ft pumping wells	ea.	2	2,206,287.00	4,412,574
	Conduct doublet-type tracer test	lump	1	839,268.00	839,268
	Interpretation, Executive Staff	hr.	480	115.42	55,402
	Reporting document	lump	1	50,000.00	50,000
				Option Total	5,357,244

CARBONATE TRANSPORT PROPERTIES

Option CTP1: Evaluate Existing Data

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Review Amargosa tracer test data, and review C-well complex tritium data.

Limitations: The Amargosa tracer test is not judged to be very representative for Frenchman Flat. It is not known if the C-well complex data would provide much applicable information.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
CTP1	Review Amargosa tracer test data, Executive Staff	hr.	320	115.42	36,934
	Review C-Well 3H data, Executive Staff	hr.	320	115.42	36,934
	Reporting document	lump	1	25,000.00	25,000
				Option Total	98,869

CARBONATE TRANSPORT PROPERTIES

Option CTP2: Collect New Data using Existing Core and Existing Wells

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Conduct geophysical logging for porosity and density in three wells, and conduct laboratory testing of six existing cores.

Limitations: Existing wells are not well distributed throughout Frenchman Flat to provide a full representation of the carbonate. A good selection of existing core providing a representative range of samples may not be available for Frenchman Flat. These activities do not directly address effective porosity or dispersion.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
CTP2	Geophysical logging (porosity, density), 3 wells	ea.	3	27,088.00	81,264
	Lab tests on existing core, 2/well x 3 wells	ea.	6	1,000.00	6,000
	Incorporate data, Executive Staff	hr.	80	115.42	9,234
	Reporting document	lump	1	25,000.00	25,000
				Option Total	121,498

CARBONATE TRANSPORT PROPERTIES

Option CTP3: Collect New Data, Requiring Construction of New Wells

Focus: What are the correct transport parameter values to use in transport modeling? The transport parameters in question are effective porosity, dispersion, and matrix diffusion. Knowledge of bulk density is also required for calculating retardation and is included here.

Description: Construct two 5,000-ft-deep pumping wells, and perform a doublet-type tracer test.

Limitations: This test provides very good data for one location, but is not necessarily representative of Frenchman Flat in general. Additional tests would provide more representative data.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
CTP3	Drill 5,000-ft pumping wells	ea.	2	2,855,931.00	5,711,862
	Conduct doublet-type tracer test	lump	1	839,268.00	839,268
	Interpretation, Executive Staff	hr.	480	115.42	55,402
	Reporting document	lump	1	50,000.00	50,000
				Option Total	6,656,532

DISTRIBUTION COEFFICIENTS

Option DC1: Evaluate Existing Data

Focus: What are the correct distribution coefficients to use in transport modeling for the various radionuclides for each hydrostratigraphic unit?

Description: Conduct a literature search, and review the existing data.

Limitations: Not much is available for many of the radionuclides.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
DC1	Literature and existing data review, Executive Staff	hr.	160	115.42	18,467
	Literature and existing data review, Senior Staff	hr.	480	64.37	30,898
				Option Total	49,365

DISTRIBUTION COEFFICIENTS

Option DC2: Collect New Information Using Existing Core

Focus: What are the correct distribution coefficients to use in transport modeling for the various radionuclides for each hydrostratigraphic unit?

Description: Perform laboratory tests on 10 existing cores.

Limitations: A good selection of existing core for Frenchman Flat may not be available, and available existing wells are not well distributed throughout Frenchman Flat.

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
DC2	Lab tests on existing core - 10 sample set	lump	1	57,444.00	57,444
	Reporting document	lump	1	25,000.00	25,000
	Incorporation data, Executive Staff	hr.	80	115.42	9,234
				Option Total	91,678

DISTRIBUTION COEFFICIENTS

Option DC3: Collect New Data Using New Wells

Focus: What are the correct distribution coefficients to use in transport modeling for the various radionuclides for each HSU?

Description: Drill five core holes in the contaminant flowpath from the CAMBRIC shot (estimated at 1,100 ft deep), and conduct laboratory analysis on three core samples per hole. This activity only addresses distribution coefficients for the alluvium.

Limitations: None

Cost:

Options	Option Elements	Units	Quantity	Unit Cost \$	Total Cost \$
DC3	Core holes in CAMBRIC, flowpath, 1,100 ft deep	ea.	5	561,112.00	2,805,560
	Analyze 3 core/hole x 5 holes	lump	1	86,166.00	86,166
	Incorporate data, Executive Staff	hr.	160	115.42	18,467
	Reporting document	lump	1	50,000.00	50,000
				Option Total	2,960,193

Appendix D

Analytical Flow and Transport Solution Used in the Decision Model

D.1.0 Analytical Flow and Transport Solution Used in the Decision Model

In the decision model, DPL sends a seepage velocity to an EXCEL spreadsheet that implements the one-dimensional analytical solute transport model (ODAST). Ogata and Banks (1961) originally developed ODAST and van Genuchten and Alves (1982) modified it to calculate the concentration from the partial differential equation:

$$D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} - \lambda R C = R \frac{\partial C}{\partial t}$$

where:

C = solute concentration (mass/volume) and with the constant coefficients;

D = dispersion coefficient (length²/time);

V = seepage velocity (length/time);

R = retardation factor (dimensionless);

x = vertical distance (length);

t = time (time); and

λ = solute decay factor (time⁻¹).

The solution must satisfy the initial and boundary conditions:

$$C(x,0) = 0$$

$$-D \frac{\partial C}{\partial x} + VC \Big|_{x=0} = \begin{cases} VC_o e^{-\alpha t}, & 0 \leq t \leq \tau_o \\ 0, & t > \tau_o \end{cases}$$

$$\frac{\partial C}{\partial x} \Big|_{x \rightarrow \infty} = 0$$

where the constants:

C_o = initial source concentration (mass/vol);

α = source depletion factor (time⁻¹); and

τ_o = source depletion time (time).

The solution uses a Laplace transform technique and involves products of exponential and complementary error functions (van Genuchten and Alves, 1982). The solution divides C by C_o to yield normalized concentrations. Because the coefficients in the governing equations stay constant, the solution must satisfy a zero concentration gradient condition as x approaches infinity. Because this is a flux-type boundary condition as opposed to the pulse concentration boundary condition used by MC-TRANS, ODAST was modified to "turn off" the decaying source at a time corresponding to the passage of the contaminant pulse out of the shot cavity modeled by MC-TRANS.

ODAST calculates the source depletion time and factor from inputs of initial mass and concentrations of a particular constituent (ODAST must analyze different constituents separately). ODAST uses an exponentially declining source leachate concentration defined as follows:

$$C = C_o \text{Exp}(-\alpha t)$$

$$\alpha = qAC_o/M$$

where:

q = infiltration rate (in/year);

A = area of the grid cell (ft²);

C_o = initial leachate concentration (mg/L); and

M = initial mass of the contaminant constituent (mg).

The source depletion factor varies inversely to the depletion half-life. To simulate a pulse source, we calculate the initial source mass required to maintain the flux boundary condition for the time corresponding to the movement of the mass out of a distance equal to four times the cavity radius (250 m), which corresponds to nodal spacing used in MC-TRANS for the source.

The MC-TRANS analyses also assumed a mechanical longitudinal dispersivity of 250 meters. With these data, a benchmark comparison between the ODAST implementation of the pulse boundary condition and the MC-TRANS results was performed.

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