Analysis of Postclosure Groundwater Impacts

for a

Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

RWEV-REP-001

July 2009

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

To ensure a more reader-friendly document, the U.S. Department of Energy (DOE) limited the use of acronyms and abbreviations in this Analysis of Postclosure Groundwater SEIS Impacts. In addition, acronyms and abbreviations are defined the first time they are used in each chapter or appendix. The acronyms, abbreviations, and symbols used in the text of this document are listed below. Acronyms and abbreviations used in tables and figures are listed in footnotes to the tables and figures.

CFR	Code of Federal Regulations
DOE	U.S. Department of Energy (also called the Department)
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
FEIS	final environmental impact statement
FR	*Federal Register*
K_d	partition coefficient
NEPA	*National Environmental Policy Act*
NRC	U.S. Nuclear Regulatory Commission
NWPA	*Nuclear Waste Policy Act*, as amended
RMEI	reasonably maximally exposed individual
SEIS	supplemental environmental impact statement
TAD	transportation, aging, and disposal (canister)
TSPA-LA	Total System Performance Assessment model for the License Application
U.S.C.	United States Code
USGS	U.S. Geological Survey

TERMS AND DEFINITIONS

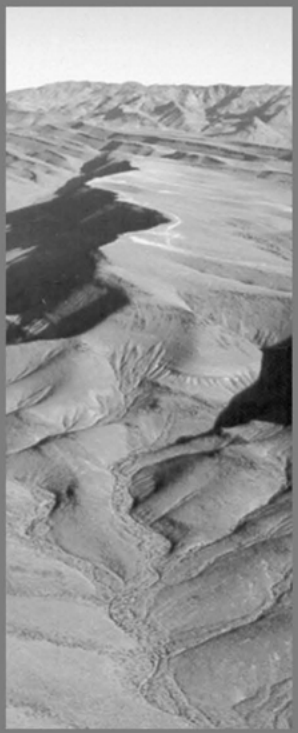
In this document, DOE has italicized terms that appear in the Glossary (Chapter 4) the first time they appear in a chapter.

UNDERSTANDING SCIENTIFIC NOTATION

DOE has used scientific notation in this Analysis of Postclosure Groundwater SEIS Impacts to express numbers that are so large or so small that they can be difficult to read or write. Scientific notation is based on the use of positive and negative powers of 10. The number written in scientific notation is expressed as the product of a number between 1 and 10 and a positive or negative power of 10. Examples include the following:

Positive Powers of 10	Negative Powers of 10
$10^1 = 10 \times 1 = 10$	$10^{-1} = 1/10 = 0.1$
$10^2 = 10 \times 10 = 100$	$10^{-2} = 1/100 = 0.01$
and so on, therefore,	and so on, therefore,
10^6 = 1,000,000 (or 1 million)	10^{-6} = 0.000001 (or 1 in 1 million)

Probability is expressed as a number between 0 and 1 (0 to 100 percent likelihood of the occurrence of an event). The notation 3×10^{-6} can be read 0.000003, which means that there are 3 chances in 1 million that the associated result (for example, a fatal cancer) will occur in the period covered by the analysis.



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S. SUMMARY

S.1 Introduction

S.1.1 BACKGROUND INFORMATION

The U.S. Department of Energy (DOE or the Department) completed the *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F) (Yucca Mountain FEIS) in February 2002. In June 2008, DOE issued the *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F-S1) (Repository SEIS), which addressed modifications to repository design and operational plans.

The Yucca Mountain FEIS addressed the Proposed Action to construct, operate and monitor, and eventually close a geologic repository at Yucca Mountain in Nye County, Nevada, for the disposal of spent nuclear fuel and high-level radioactive waste. The FEIS considered the potential environmental impacts of a repository design for surface and subsurface facilities; a range of canister packaging scenarios, repository thermal operating modes, and repository sizes; and plans for the construction, operation, monitoring, and eventual closure of the repository.

The basic elements of the Proposed Action the Repository SEIS evaluated did not change from those evaluated in the Yucca Mountain FEIS. As described in the Repository SEIS, the surface and subsurface facilities would allow DOE to operate the repository following a primarily canistered approach in which most commercial spent nuclear fuel would be packaged at the reactor sites in transportation, aging, and disposal canisters. The Department would construct the surface and subsurface facilities over a period of several years (referred to as phased construction) to accommodate an increase in spent nuclear fuel and high-level radioactive waste receipt rates as repository operational capability reached its design capacity. The Repository SEIS evaluated potential environmental impacts of the repository design and operational plans as described in the application that DOE submitted on June 3, 2008, to the U.S. Nuclear Regulatory Commission seeking authorization to construct the repository, as required by Section 114(b) of the *Nuclear Waste Policy Act*, as amended.

On September 8, 2008, the NRC staff issued a Notice of Acceptance to the Department informing that the License Application had been accepted for docketing. Included with this notice was the *U.S. Nuclear Regulatory Commission Staff's Adoption Determination Report for the U.S. Department of Energy's Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain*, dated September 5, 2008 (http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/nrc-eis-adr.pdf). In its Adoption Report, the NRC staff conducted a review to determine if it was practicable to adopt the environmental impact statements in accordance with 10 CFR 51.109. Based on its review, the NRC staff concluded that it was practicable to adopt the Yucca Mountain FEIS and supplements prepared by DOE, but that additional supplementation was needed to address the potential impacts of the proposed action on groundwater and from surface discharges of groundwater.

In response to the NRC staff's Adoption Report, DOE has prepared this *Analysis of Postclosure Groundwater Impacts for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level*

Radioactive Waste at Yucca Mountain, Nye County, Nevada (Analysis of Postclosure Groundwater Impacts).

S.1.2 SCOPE OF THE POSTCLOSURE GROUNDWATER SEIS

This Analysis of Postclosure Groundwater impacts addresses the information identified by the NRC staff as needed to supplement DOE's environmental impact statements. It expands on the analysis of postclosure impacts that could arise from potentially contaminated groundwater by considering impacts in areas of the accessible environment farther from Yucca Mountain than that considered in the Repository SEIS.

The NRC staff's Adoption Report identified two areas for supplementation: (1) impacts on groundwater and (2) impacts from surface discharges of groundwater. Within these areas, the NRC specifically identified a need for the following information:

- A description of the full extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) can leave the flow system. For example, the DOE license application describes potential groundwater flow farther to the south of Alkali Flats, into the Southern Death Valley subregion of the regional model domain. This component of the groundwater flow system is not discussed in the EISs.

- An analysis of the cumulative amount of radiological and non-radiological contaminants that can be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time. In its license application, for example, DOE provides calculated cumulative releases of some radionuclides at different stages within the repository system, as intermediate results in TSPA. This type of information, for radiological and non-radiological contaminants could be used in the analysis.

- Estimates of contamination in the groundwater, given potential accumulation of radiological and non-radiological contaminants. One way to analyze the overall impacts on groundwater may be a mass-balance approach that accounts for mass released, the part of the groundwater flow system affected by potential releases, and the expected processes that could affect released contaminants. Such an approach would also show the extent of contamination and possible impacts on water quality.

- A description of the locations of potential natural discharge of contaminated groundwater for present and expected future wetter periods.

- A description of the physical processes at the surface discharge locations that can affect accumulation, concentration, and potential remobilization of groundwater-borne contaminants.

- Estimates of the amount of contaminants that could be deposited at or near the surface. This involves estimates of the amount of groundwater involved in discharge or near-surface evaporation, the amounts of radiological and non-radiological

contaminants in that water, contaminant concentrations in the resulting deposits, and potential environmental impacts (e.g., effects on biota).

S.2 Affected Environment

In the late 1990s, DOE directed the U.S. Geological Survey to improve its groundwater flow model of the Death Valley regional flow system to support DOE programs at the Nevada Test Site and Yucca Mountain. The results of the Survey's work are presented in *Death Valley Regional Ground-Water Flow System, Nevada and California – Hydrogeologic Framework and Transient Ground-Water Flow Model*, and much of the information in this Analysis of Postclosure Groundwater Impacts describing the regional flow system was obtained from that document. It includes a conceptual model of the groundwater flow system within the Death Valley region and describes how the Survey used that information to construct a computer-based numerical model to simulate that flow system. Figure S-1 shows the flow system boundaries (as depicted in the model). In addition, DOE has further developed a site-scale flow model, which represents a smaller area (including Yucca Mountain) at a greater level of detail. This site-scale model was used in the *Total System Performance Assessment Model/Analysis for the License Application* (TSPA-LA).

DEATH VALLEY REGION

In this Analysis of Postclosure Groundwater Impacts, Death Valley region refers to the area described by the outer boundaries in Figure S-2; Death Valley subregion refers to one of the three areas that make up the region. Death Valley or the floor of Death Valley refers to the topographic low area, or structural trough running roughly northwest-to-southeast that is labeled in the western (California) side of the region and is a central element of Death Valley National Park.

The source of groundwater flow in the region is predominantly from recharge due to infiltration of precipitation that falls within the boundaries of the region, most of which originates in the mountainous areas. Water also enters the regional flow system as throughflow from adjoining groundwater basins, predominantly from the north, west, and south, but the amount of water coming into the system laterally is estimated to be relatively small (roughly 10 percent) in comparison with that coming in as recharge from the surface.

The overall direction of groundwater movement is from the source areas (that is, those primary areas of recharge that are often near the margins of the regional flow system) toward the regional hydrologic sink in the floor of Death Valley. The largest volume of groundwater loss in the region is also in Death Valley in the form of spring discharges and evapotranspiration.

EVAPOTRANSPIRATION

Evapotranspiration is the loss of water by evaporation from the soil and other surfaces, including evaporation of moisture emitted or transpired from plants.

The regional flow system is best described in hierarchical terms, which include subregions, basins, and sections, to facilitate discussion and delineate general areas of groundwater recharge, discharge, and movement within the boundaries of the overall flow system. Within the region (Figure S-2), recharge entering the system at Yucca Mountain would be within the central Death Valley subregion.

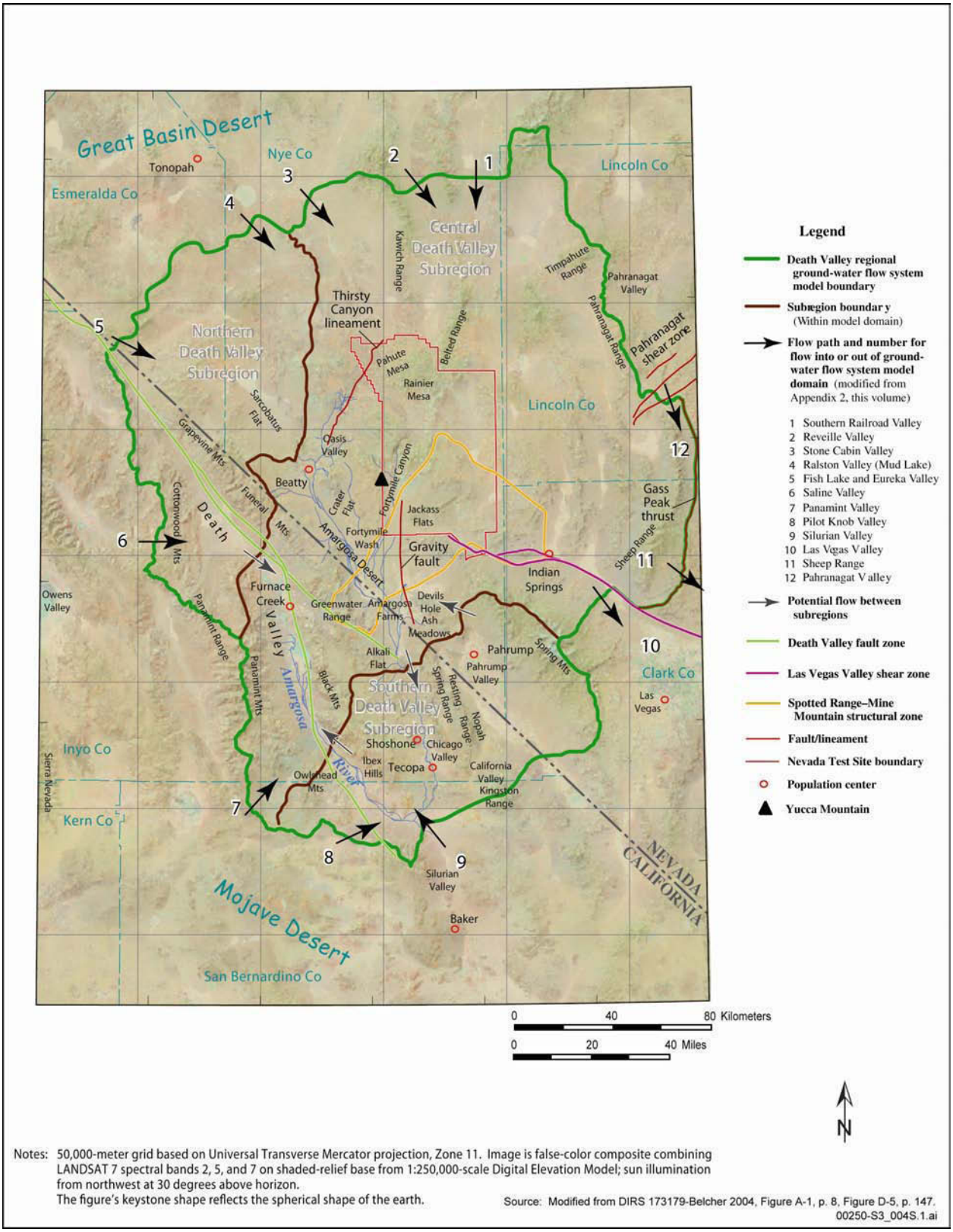


Figure S-1. Boundaries and prominent topographic features of the Death Valley regional groundwater flow system.

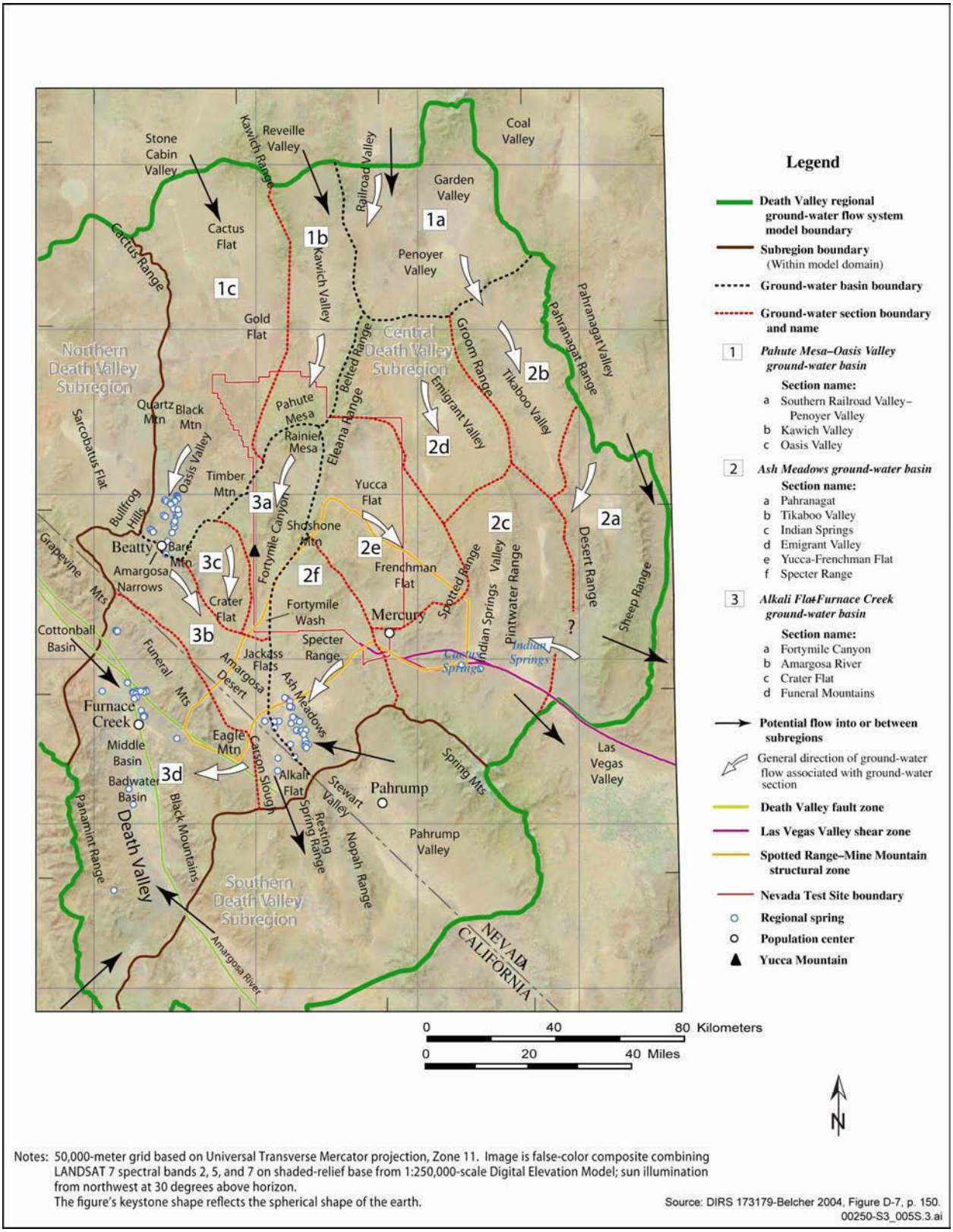
The central Death Valley subregion (Figure S-3) is further divided into three basins: (1) the Pahute Mesa – Oasis Valley groundwater basin; (2) the Ash Meadows groundwater basin; and (3) the Alkali Flat – Furnace Creek groundwater basin, located in the central area of the subregion between the other two basins and extending to the south-southwest. Groundwater in the first two basins generally flows in a southerly direction (and to the southwest in the case of the Ash Meadows groundwater basin), contributing to the Alkali Flat – Furnace Creek groundwater basin, which also generally flows in a southerly direction toward the hydrologic sink that is Death Valley. Yucca Mountain and water infiltrating through the area of the proposed Yucca Mountain Repository are within the Alkali Flat – Furnace Creek basin.

The Alkali Flat – Furnace Creek basin is further divided into four sections (identified by their numbers in Figure S-2): (3a) Fortymile Canyon, (3b) Amargosa River, (3c) Crater Flat, and (3d) Funeral Mountains. The repository at Yucca Mountain would be located within the Fortymile Canyon section, and the natural groundwater flow path from beneath the repository is from that section to the Amargosa River section.

Infiltrating water at Yucca Mountain that reaches the saturated zone, or water table, reaches a volcanic aquifer in the Fortymile Canyon section. The saturated zone at Yucca Mountain is roughly 300 meters (980 feet) below the level of the proposed repository. The lower carbonate aquifer is also present beneath the repository site, but is more than 1,250 meters (4,100 feet) below the repository level. Thus, there is about 950 meters (3,100 feet) between the top of the saturated zone and the top of the lower carbonate aquifer. A well completed to the lower carbonate aquifer at Yucca Mountain indicated a water level, or potentiometric head, in that aquifer about 20 meters (66 feet) higher than the water level in the overlying volcanic aquifer. This demonstrates an upward hydraulic gradient between the lower carbonate aquifer and the volcanic aquifer at this location. The upward gradient, along with the great depth and the intervening confining unit(s), which hinder flow between the aquifers and allow the upward gradient to exist, would prevent any releases from the repository from reaching the lower carbonate aquifer in the area of the repository. Similarly, two other wells, which are farther south than the first well, have been completed to the lower carbonate aquifer. Both of these wells also indicate an upward hydraulic gradient.

At Yucca Mountain, the groundwater in the volcanic aquifer flows to the southeast; then shifts more to the south toward the Amargosa River section. A fault line, the Highway 95 Fault, runs east-to-west in the same general area where the flow system transitions from the Fortymile Canyon section to the Amargosa River section. Subsurface investigations in this area indicate that the Highway 95 Fault is the southern boundary of the volcanic aquifer in the flow path from Yucca Mountain. The volcanic aquifers on the north side of the fault appear to line up with less-permeable Tertiary sedimentary rocks on the south side; thus forcing the southward-flowing groundwater up into the overlying alluvial aquifer system.

Groundwater (both in the alluvial aquifer and in the underlying carbonate aquifer) from the Fortymile Canyon section enters the central part of the Amargosa River section and flows in a southward direction. The majority of the annual groundwater withdrawals in the region (17,600 acre-feet in 2003) occur in the Amargosa River section and are primarily used for irrigation. The largest natural pathway by which groundwater throughflow leaves the Amargosa River section is to the southwest through fractures in the carbonate rocks at the southeastern end of the Funeral Mountains. Throughflow leaving by this route moves into the Funeral Mountains section of the Alkali Flat – Furnace Creek basin, primarily toward the



Notes: 50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Image is false-color composite combining LANDSAT 7 spectral bands 2, 5, and 7 on shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon.
The figure's keystone shape reflects the spherical shape of the earth.

Source: DIRS 173179-Belcher 2004, Figure D-7, p. 150.
00250-S3_005S.3.ai

Figure S-2. Central Death Valley subregion of the Death Valley regional groundwater flow system.

springs in the Furnace Creek area of Death Valley or beyond to the floor of Death Valley. The second largest pathway for groundwater losses in the Amargosa River section is through evapotranspiration, primarily in the area of Alkali Flat and including losses along the Amargosa River and Carson Slough in the same general area.

The Funeral Mountains section encompasses the central, lowest portion of Death Valley (Badwater Basin), the Funeral and Black mountains along the northeast boundary of the section, and the eastern slope of the Panamint Range along the southwest boundary. Since Badwater Basin is the low spot of the regional sink that is Death Valley, groundwater throughflow can reach the section from all directions. This includes groundwater moving in from both the northern and southern Death Valley subregions; however, the primary source of groundwater coming into the section is from throughflow in the lower carbonate aquifer in the southern part of the Funeral Mountains.

Along the primary flowpath, throughflow from beneath the Funeral Mountains first encounters the springs of the Furnace Creek area of Death Valley. Groundwater not discharged at the springs, or discharged and reinfiltrated, then moves southwest toward the floor of Death Valley. There, groundwater is either transpired by stands of mesquite on the lower part of the Furnace Creek fan or evaporated from the playas on the floor of Death Valley. The lowest and largest of these playas is Badwater Basin. Other named playas within the Funeral Mountains section include Middle Basin, which is immediately north of Badwater Basin, and Cottonball Basin, which is north of Furnace Creek.

The largest spring discharges for the Funeral Mountains section, as well as for the Alkali Flat – Furnace Creek basin, are those of the Furnace Creek area and include the Texas, Travertine, and Nevares springs. The estimated combined discharge of these springs is 2,300 acre-feet (2.8 million cubic meters) per year, of which more than half is from the Travertine Springs. By far the largest groundwater loss in the section, however, is by evapotranspiration. The estimated annual evapotranspiration loss from the floor of Death Valley is 35,000 acre-feet (43.2 million cubic meters). This estimated quantity, however, includes areas of the Death Valley floor that are within the northern and southern Death Valley subregions as well as the central Death Valley subregion.

Groundwater in the Funeral Mountains section supports federal facilities and those of the Timbisha Shoshone Tribe within Death Valley National Park. Most of the water used to support the Tribe and operations within the park comes from the springs in the Furnace Creek area; some water comes from a single production well. Death Valley is within the traditional homeland of the Timbisha Shoshone Tribe, and some members of that Tribe reside on a 314-acre parcel of trust land located on the floor of Death Valley near Furnace Creek. The springs in the Furnace Creek area are of traditional and cultural importance to members of the Tribe, and the purity of water in those springs is important to tribal spiritual beliefs, culture, and heritage.

Under a climate that was cooler and wetter than today, the groundwater flow paths would be basically the same as for the present day. Because of potentially higher water levels, however, there would likely be additional natural discharge locations consistent with identified paleodischarge sites.

S.3 Environmental Impacts of Postclosure Repository Performance

REGULATORY COMPLIANCE POINT

This point is defined as the location over the highest concentration of contaminants in the plume as required by the U.S. Nuclear Regulatory Commission at 10 CFR 63.312(a). The TSPA-LA calculates radiologic dose to a reasonably maximally exposed individual located at a point on the Nevada Test Site boundary (36°40'13.66661" North Latitude) that is approximately 18 kilometers south of the repository. In this Analysis of Postclosure Groundwater Impacts, this location is referred to as the Regulatory Compliance Point.

The Repository SEIS analyzed the transport of radionuclides out of the repository to a location 18 kilometers south of the repository and reported impacts to a hypothetical reasonably maximally exposed individual. The assessments of environmental impacts in this Analysis of Postclosure Groundwater Impacts focus on the effects of long-term transport of radiological and nonradiological contaminants beyond this Regulatory Compliance Point. The analysis starts at the point where contaminants would be released from the unsaturated zone to the saturated zone underneath the repository. For the radionuclides, DOE used results from TSPA-LA to characterize the release from the unsaturated zone, transport of radionuclides in the saturated zone to the Regulatory Compliance Point, and release of the radionuclides into the volcanic-alluvial aquifer beyond the Regulatory Compliance Point. From the Regulatory Compliance Point, DOE performed further analysis to track radionuclides out into the Amargosa Desert and Death Valley. For nonradiological contaminants, DOE used a modified version of the bounding release analysis of these contaminants from the Repository SEIS and used the same methods for saturated zone transport beyond the Regulatory Compliance Point as those used for the radiological contaminants.

The U.S. Nuclear Regulatory Commission staff identified a need for additional evaluations of the impacts of contaminants released from the repository at locations beyond this Regulatory Compliance Point. In response, DOE performed the following analyses:

- Traced the release and movement of contaminants from the repository into the aquifer system up to and beyond the Regulatory Compliance Point, including releases at discharge sites. Assessed the cumulative amounts entering and leaving the aquifer system and the accumulation within the system; and

- Assessed the impacts resulting from the release, movement, and accumulation of contaminants throughout the region;

The analyses followed these steps:

- Used the regional groundwater flow model to define the potential paths contaminants could take after exiting the repository and transporting to the Regulatory Compliance Point and beyond into the region. This modeling also identified natural discharge points;

- Performed transport analyses of contaminants along the flow paths developed from the regional groundwater model to natural discharge or pumped withdrawal points;

- Analyzed human health impacts from radiological and nonradiological contaminants at points where contaminants interact with the biosphere (that is, natural discharge and pumped withdrawal points);

- Analyzed soil concentrations at pumped discharge sites; and
- Evaluated processes that could occur at the natural discharge sites.

S.3.1 ANALYTICAL FRAMEWORK FOR THE ANALYSIS OF POSTCLOSURE GROUNDWATER IMPACTS

DOE developed an analytical method for this document to evaluate the potential range of environmental impacts that could occur within a 1-million-year postclosure period. The analyses assumed that the current population, its distribution, and current land uses would all remain as they are today.

DOE also evaluated other primary variables, such as future climatic conditions and groundwater withdrawals, by establishing a reasonable range of possibilities and preparing a set of analytical constructs that, when evaluated, provide a perspective on the range of impacts that could occur to the environment over the 1-million-year period.

DOE analyzed two separate climate conditions: the present climate and a future, wetter climate. The wetter climate considered in this analysis is consistent with the post-10,000-year climate used in the TSPA-LA, which is almost four times wetter than the present climate. In this Analysis of Postclosure Groundwater Impacts, for each climate condition, DOE held the climate constant for the entire 1 million years.

Groundwater pumping can lead to changes in the hydraulic gradients and therefore alter the direction and rate of groundwater flow in the region. The results of the groundwater modeling show that different flow paths result from different pumping scenarios. In this Analysis of Postclosure Groundwater Impacts, DOE evaluated two pumping scenarios: (1) a pumping scenario that continues the 2003 pumping rates in the Amargosa Farms area for the entire 1-million-year postclosure period, and (2) a no-pumping scenario that analyzes the cessation of all pumping in the region for the entire 1-million-year postclosure period.

To evaluate the effects of these two pumping scenarios, DOE extended flow and transport simulations to physical locations beyond those the TSPA-LA model addressed. Output from the TSPA-LA model was used as input to the Death Valley regional groundwater flow system model to develop contaminant flow paths beyond the Regulatory Compliance Point.

Both the site-scale saturated zone flow model and the Death Valley regional groundwater flow system model include particle-tracking capabilities. This capability allowed a simulation of adding particles (representing contaminants) at locations within the model and then tracking the particles as they moved with the groundwater (that is, assuming there is no adsorption, filtering, decay, or other mechanisms that would prohibit the particles from moving with the water). DOE used the particle-tracking capabilities of the regional model to determine where those particles would move in the regional flow system. DOE repeated this process for the two pumping scenarios to determine how the flow paths would change under differing conditions imposed on the model.

Under the pumping scenario, the model predicts that all of the particles would be withdrawn from the wells at the Amargosa Farms area (Figure S-3). Under the no-pumping scenario, the model shows the particles initially traveling to the south from the Regulatory Compliance Point and essentially all of the particles eventually flow to the west to exit the groundwater flow system at the floor of Death Valley in

the Furnace Creek area on or near the Middle Basin playa (Figure S-4). There is a small particle trace that continues to the south to discharge at Alkali Flat (also referred to as Franklin Lake Playa) and another small particle trace that travels farther south in Death Valley toward Badwater Basin. While the model predicts discharge from the alluvial aquifer on the floor of Death Valley, it cannot be precluded that contaminants could mix with carbonate waters and discharge at the springs in the Furnace Creek area; therefore, this Analysis of Postclosure Groundwater Impacts also evaluates the potential impacts of the complete contaminant plume discharging into these springs.

Considering the variables described above, this document evaluates potential environmental impacts for the following analytical constructs:

- Pumping scenario, present climate, Amargosa Farms area
- Pumping scenario, wetter climate, Amargosa Farms area
- No-pumping scenario, present climate, floor of Death Valley at Middle Basin
- No-pumping scenario, wetter climate, floor of Death Valley at Middle Basin
- No-pumping scenario, present climate, Furnace Creek springs area
- No-pumping scenario, wetter climate, Furnace Creek springs area

In addition, because the particle-tracking analysis indicates that some particles could flow to Alkali Flat, DOE assessed the potential impacts of discharges at that location. These results are presented in comparison with those at Middle Basin.

Under these constructs and the assumptions behind them, there would be no natural discharge of contaminants under the pumping scenario; therefore, there would be no impacts at Death Valley. Similarly, under the no-pumping scenario, there would be no withdrawals and, therefore, no impacts in the Amargosa Farms area. Although it is likely that future events would be a combination of these two scenarios, the analysis of the two extremes ensures this Analysis of Postclosure Groundwater Impacts does not underestimate the impacts at these locations.

For each scenario, DOE estimated the total annual dose from exposure to radionuclides and daily intake of nonradiological contaminants for a full-time resident living at the discharge area. DOE further estimated the annual dose and daily intake for a resident near the Amargosa Farms area for the pumping scenario based on the characteristics of agricultural production in Amargosa Valley and the behaviors and lifestyles of the residents in that area. DOE used similar methods to estimate dose and intake for a resident of Death Valley resulting from the discharge of contaminants at springs in the Furnace Creek area, but did not include exposure pathways related to ingestion of contaminated foodstuffs. These pathways were not included because there is no large-scale agricultural production in Death Valley.

To estimate the annual dose and daily intake for a resident of Death Valley resulting from the discharge of contaminants at the Death Valley floor, DOE calculated the concentration of contaminants in evaporite minerals that would precipitate onto the surface of the wet playa in Middle Basin. At wet playas in Death Valley and the surrounding region (that is, playas where groundwater is near the ground surface), capillary action brings water to the surface, resulting in evaporation of groundwater and deposition of the minerals in that groundwater. Radiological and nonradiological contaminants from a repository at Yucca Mountain would occur as trace amounts in the dissolved solids in groundwater and would precipitate with those dissolved solids. Because there would be no mechanism for preferential precipitation of

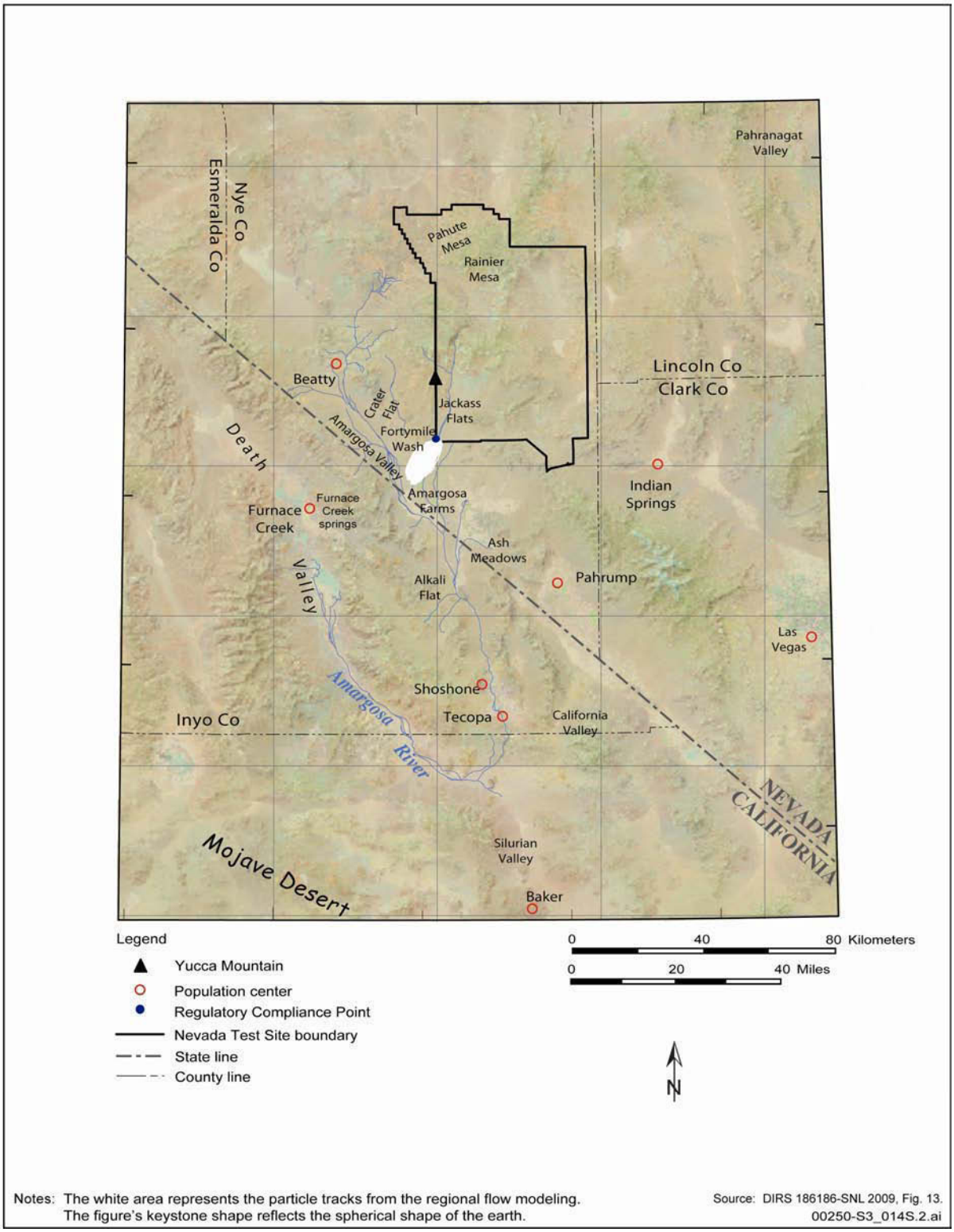


Figure S-3. Groundwater flow paths for the pumping scenario.

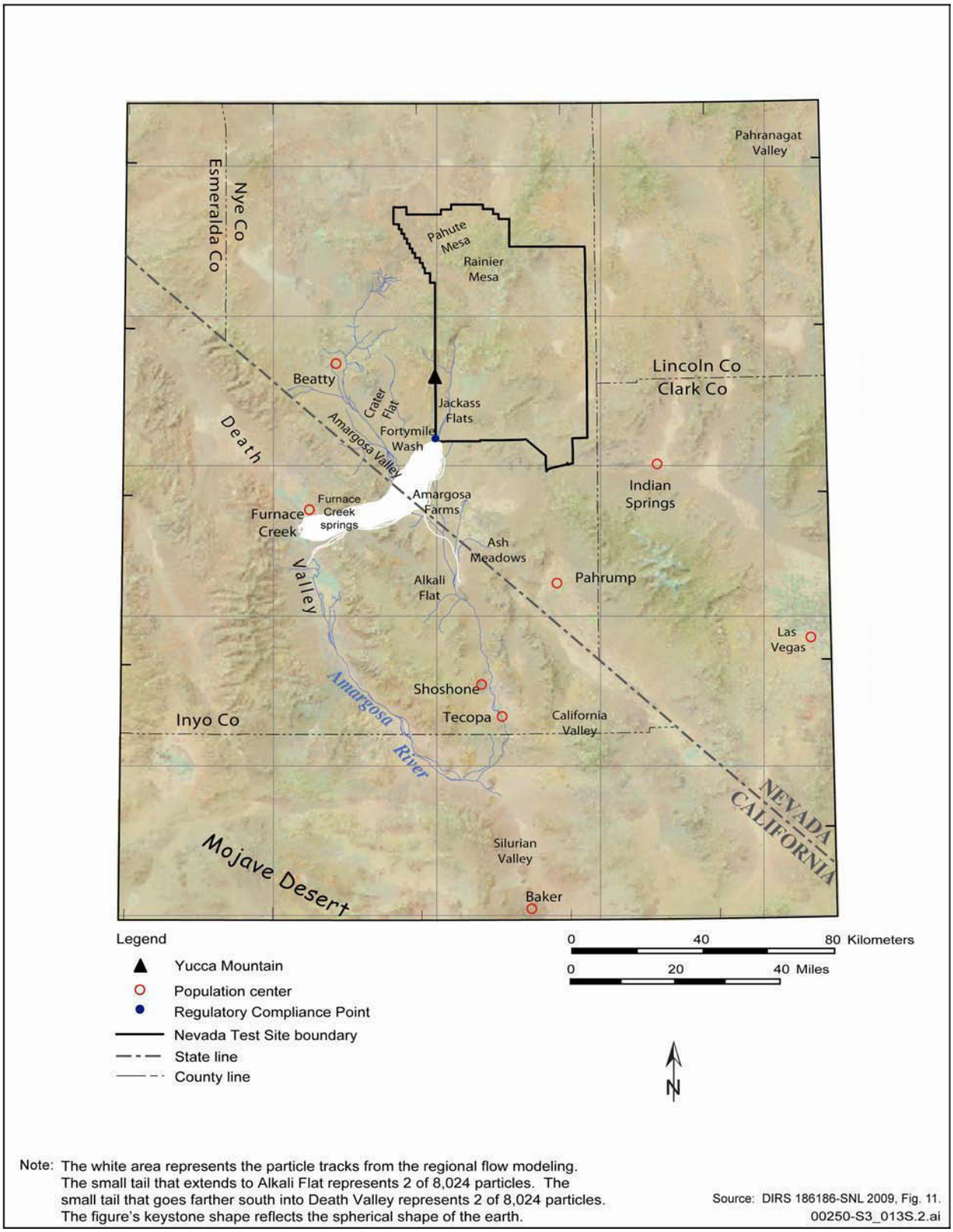


Figure S-4. Groundwater flow paths for the no-pumping scenario.

contaminants, DOE estimated the concentration of contaminants in the evaporite minerals based on the ratio of contaminants to total-dissolved-solids in the groundwater. To estimate the health impact from exposure to contaminants in the evaporite material, DOE considered three pathways: external exposure, inhalation of resuspended particulates, and inadvertent ingestion of soil. The consequences of ingesting water from Middle Basin and using that water for other purposes were not included because that water would be brackish, and better-quality water would be available from the springs and wells in the Furnace Creek area.

S.3.2 ANALYTICAL RESULTS

The results in this Analysis of Postclosure Repository Impacts are segregated by radiological and nonradiological contaminants.

S.3.2.1 Radiological Impacts Health Impacts

DOE estimated the total annual dose for a full-time resident as a function of time for the 1-million-year postclosure period. Table S-1 summarizes the estimated peak annual doses during this time for the radiological contaminants. This table also gives the probability of a latent cancer fatality associated with these individual doses. As recommended by the Interagency Steering Committee on Radiation Standards, this analysis uses a conversion factor of 0.0006 probability of latent cancer fatality per rem of dose for members of the public to estimate the health effects of radiologic doses. This probability represents the chance that a person exposed to the dose for 70 years would die from a cancer induced by that dose. Note that the probabilities in Table S-1 are very small (on the order of 1 chance in a million at the highest level).

As a point of comparison, the mean peak annual dose during 10,000 years after closure presented in the Repository SEIS for the reasonably maximally exposed individual at the Regulatory Compliance Point was 0.24 millirem per year, and the mean peak annual dose during 1 million years after closure was 2.0 millirem per year. All of the doses in Table S-1 are less than or about equal to these doses.

Figures S-5 to S-8 summarize the trends of the total annual dose over time at the three locations; that is, the Amargosa Farms area, Middle Basin, and Furnace Creek springs. In the present climate, radionuclides that have no adsorption to slow their travel (specifically, iodine-129 and technetium-99) dominate dose at the Amargosa Farms area. During the wetter climate, some slower-moving radionuclides, such as plutonium-242, contribute significantly to the total dose at that area (at least for a limited time).

If, for the no-pumping scenario, the entire flow of contaminants were to divert to Alkali Flat, the total annual dose could be as much as twice that calculated for the Middle Basin because the current, measured rate of evapotranspiration at Alkali Flat is about half that at Middle Basin, and the dose would be inversely proportional to the evapotranspiration rate. This qualitative approach is very conservative because if all of the contaminants were to divert to Alkali Flat, the evapotranspiration rate at that location would likely have increased from its current value.

Table S-1. Peak annual dose and probability of latent cancer fatalities for six exposure scenarios.

Scenario	Peak annual dose (millirem per year)		Probability of a latent cancer fatality (per year)	
	10,000 years after closure	1,000,000 years after closure	10,000 years after closure	1,000,000 years after closure
Amargosa Farms area, pumping, present climate	2.2×10^{-1}	1.1	1.3×10^{-7}	6.7×10^{-7}
Amargosa Farms area, pumping, wetter climate	2.5×10^{-1}	1.3	1.5×10^{-7}	8.0×10^{-7}
Middle Basin, no-pumping, present climate	0.0	1.6×10^{-1}	0.0	9.5×10^{-8}
Middle Basin, no-pumping, wetter climate	1.5×10^{-2}	4.2×10^{-2}	8.9×10^{-9}	2.5×10^{-8}
Furnace Creek springs area, no-pumping, present climate	0.0	3.4×10^{-1}	0.0	2.1×10^{-7}
Furnace Creek springs area, no-pumping, wetter Climate	2.3×10^{-2}	8.9×10^{-2}	1.4×10^{-8}	5.4×10^{-8}

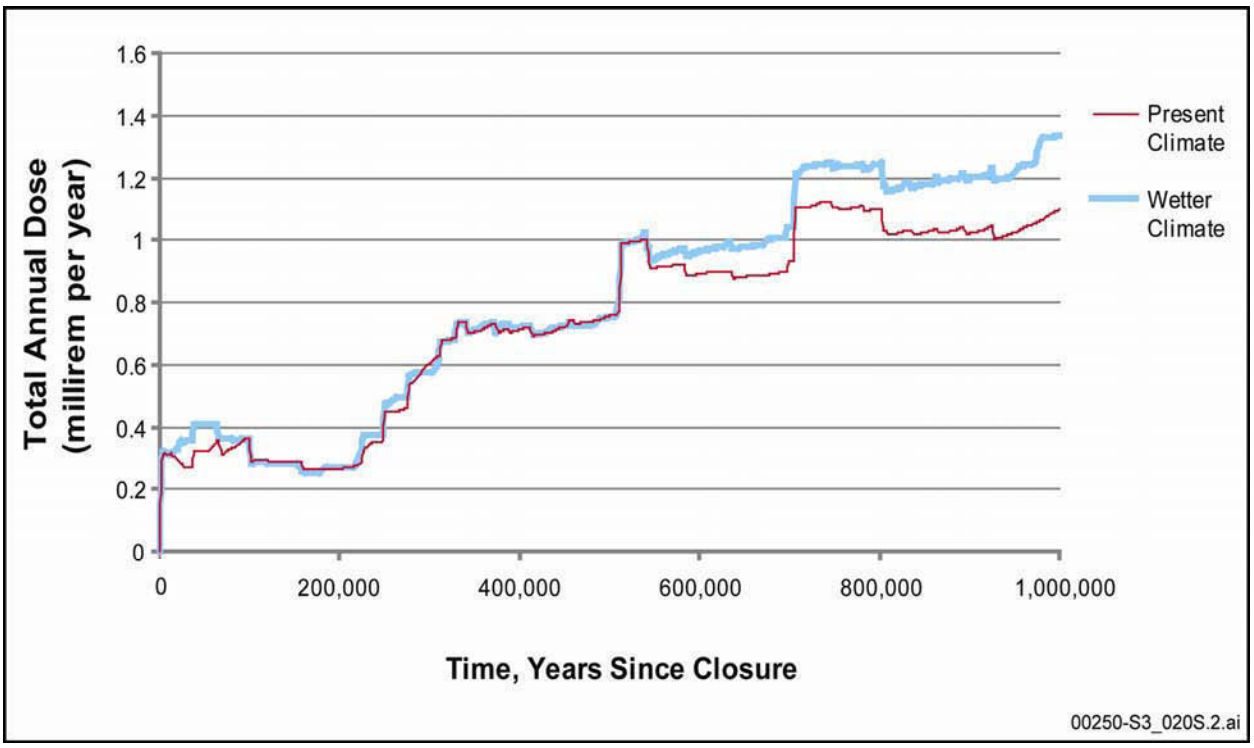


Figure S-5. Total annual dose at the Amargosa Farms area.

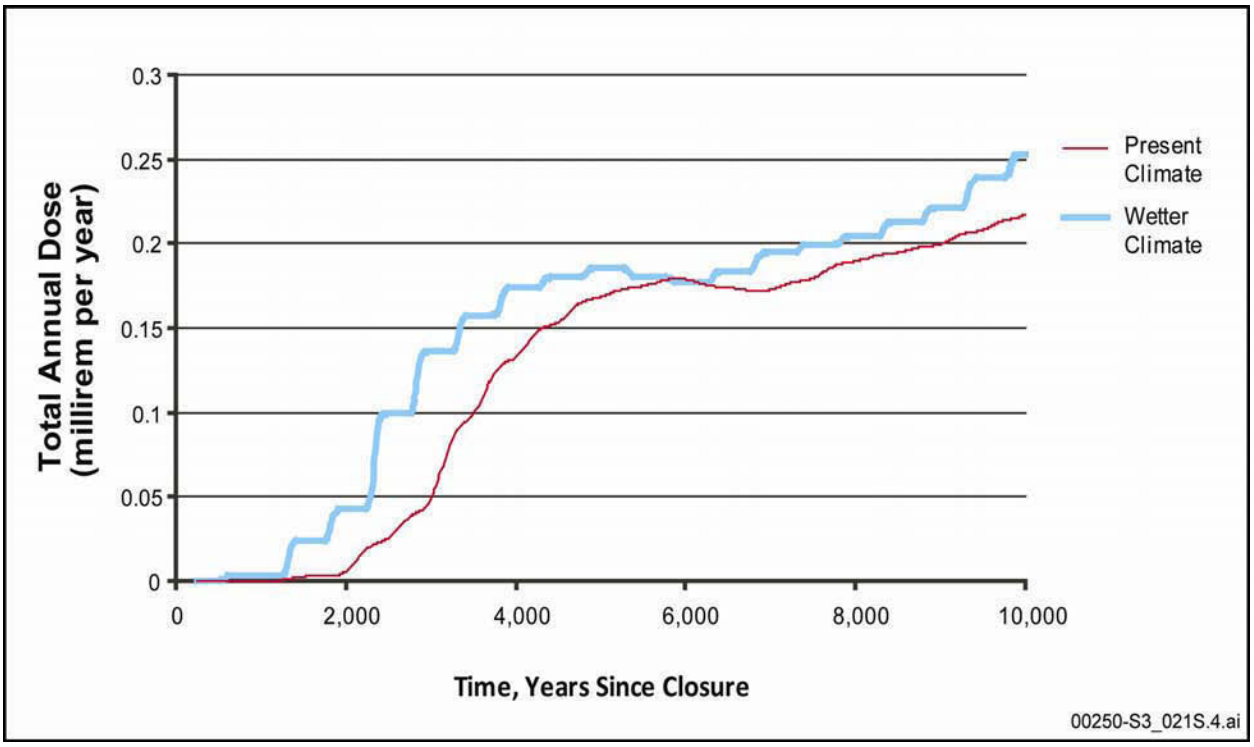


Figure S-6. Total annual dose at the Amargosa Farms area for the first 10,000 years.

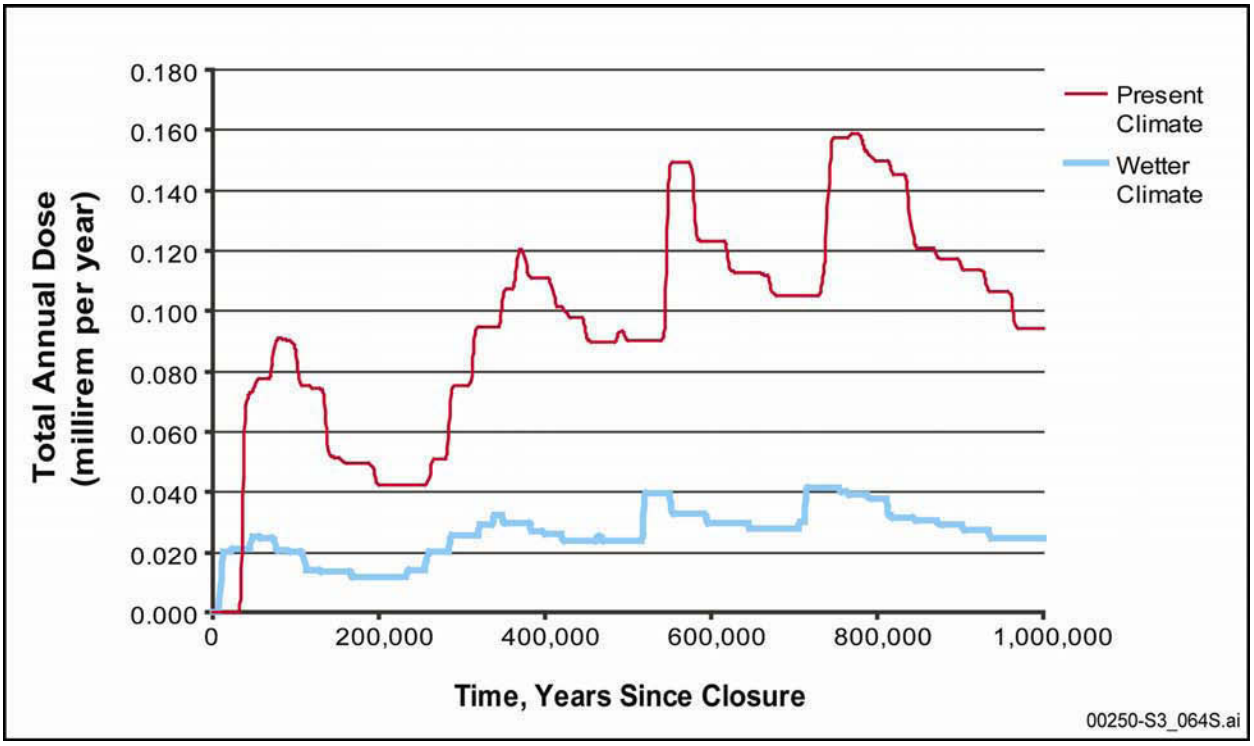


Figure S-7. Total annual dose at Middle Basin.

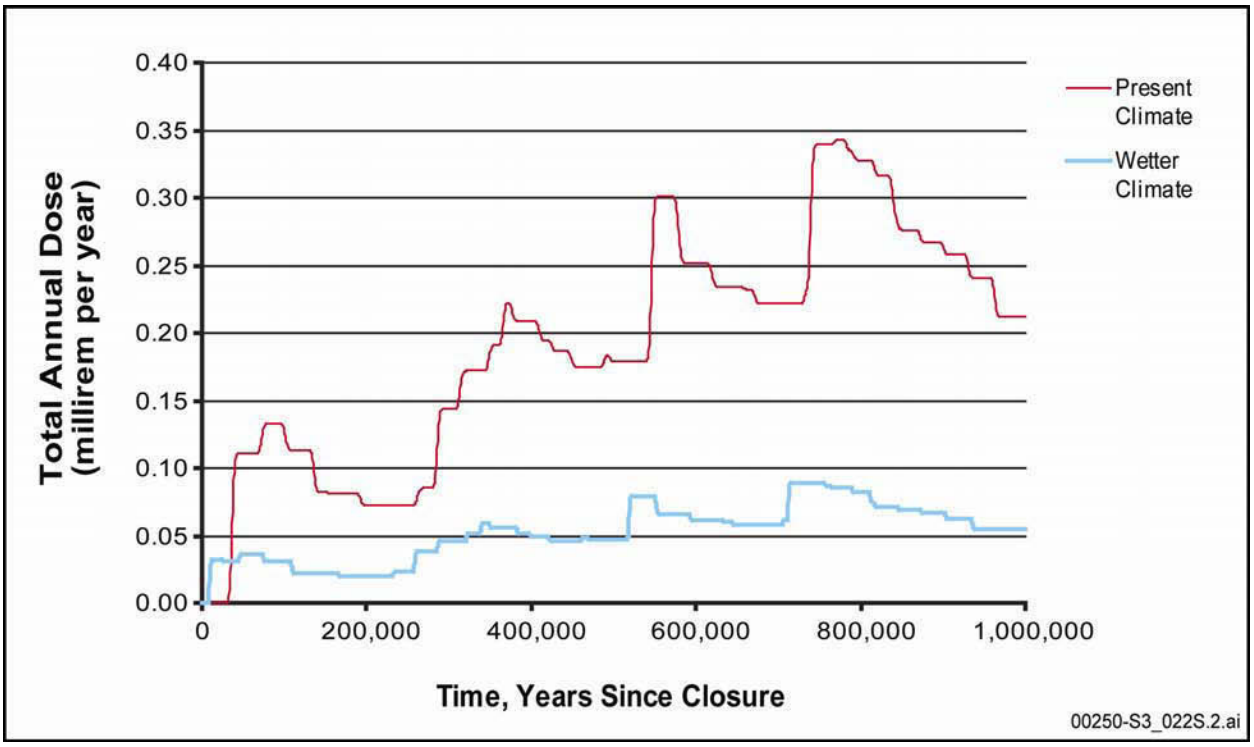


Figure S-8. Total annual dose at the Furnace Creek springs area.

S.3.2.2 Nonradiological Health Impacts

The nonradiological contaminants this Analysis of Postclosure Groundwater Impacts considered include molybdenum, nickel, vanadium, and uranium. Uranium is included as both a radiological and nonradiological contaminant because uranium has a notable toxicity as a heavy metal. The uranium concentrations are a sum of the uranium isotopes from the radionuclide calculations. DOE assessed human health impacts of the nonradiological materials by comparing daily intakes with the U.S. Environmental Protection Agency's Oral Reference Dose standard. For exposure locations involving ingestion of potentially contaminated water (that is, the Amargosa Farms and Furnace Creek springs areas), DOE calculated the daily intake for a 70-kilogram person drinking 2 liters of water per day. For exposure at Middle Basin, DOE calculated the daily intake due to inhalation and inadvertent ingestion of soil. Table S-2 summarizes the estimated daily intakes of the nonradiological contaminants. The bottom row of the table shows EPA's Oral Reference Doses. All intakes are below their associated Oral Reference Dose.

Figures S-9 and S-10 present detailed plots of the daily intakes of nonradiological contaminants for the Amargosa Farms area for the present and wetter climates, respectively. Figures S-11 and S-12 show estimated daily intakes of molybdenum at the Furnace Creek springs area for the present and wetter climates, respectively.

Table S-2. Daily intakes of the nonradiological contaminants.

Scenario	Peak intakes[a] (mg/kg body wt.-day) of metals during 1 million years after closure			
	Molybdenum	Nickel	Vanadium	Uranium
Amargosa Farms area, pumping, present climate[a]	3.00×10^{-3}	1.37×10^{-2}	6.04×10^{-6}	3.47×10^{-6}
Amargosa Farms area, pumping, wetter climate[a]	3.00×10^{-3}	1.37×10^{-2}	6.04×10^{-6}	3.84×10^{-6}
Middle Basin, no-pumping, present climate[b]	6.80×10^{-4}	0.0	0.0	0.0
Middle Basin, no-pumping, wetter climate[b]	1.74×10^{-4}	0.0	0.0	0.0
Furnace Creek Springs area, no-pumping, present climate[a]	2.99×10^{-3}	0.0	0.0	0.0
Furnace Creek Springs area, no-pumping, wetter climate[a]	7.67×10^{-4}	0.0	0.0	0.0
Oral Reference Dose (mg/kg body-wt/day)	5.00×10^{-3}	2.00×10^{-2}	7.00×10^{-3}	3.00×10^{-3}

a. Based on a 70-kilogram person drinking 2 liters of water per day.
b. Based on a 70-kilogram person ingesting and inhaling a given amount of contaminant per day.
mg/kg body-wt/day = milligrams per kilogram body-weight per day.

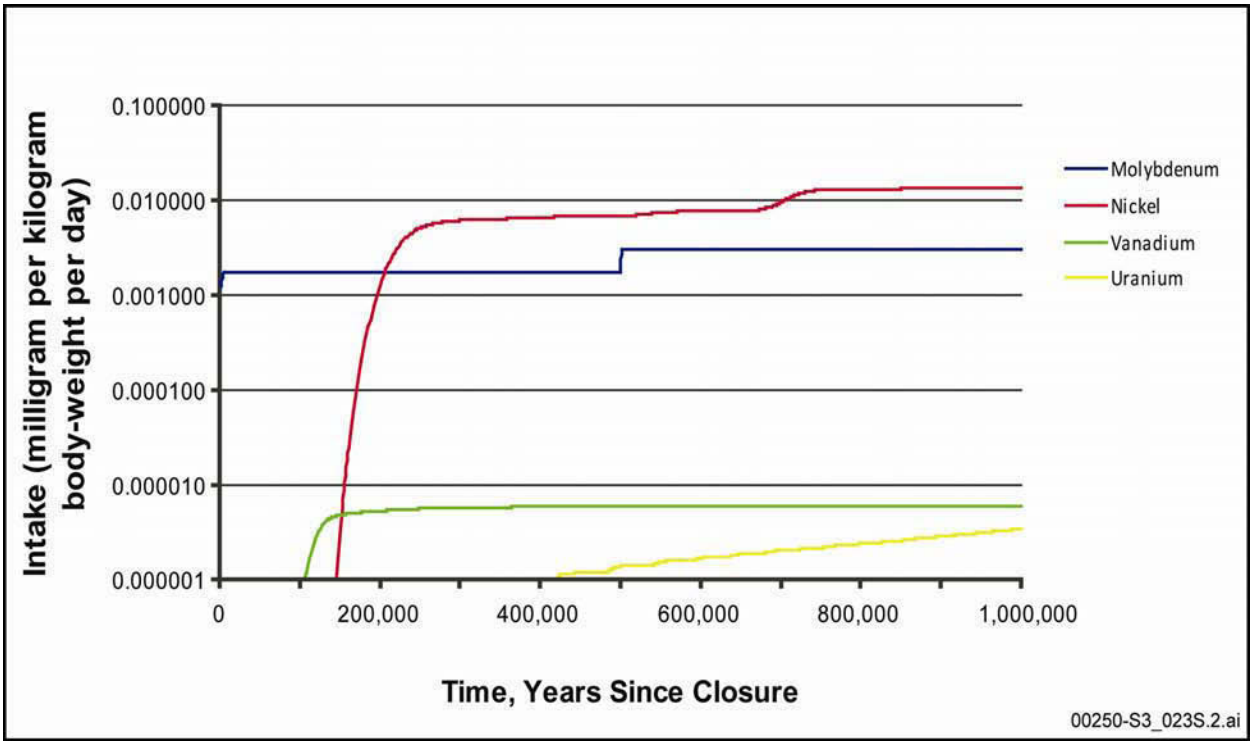


Figure S-9. Daily intakes of nonradiological contaminants at the Amargosa Farms area, present climate.

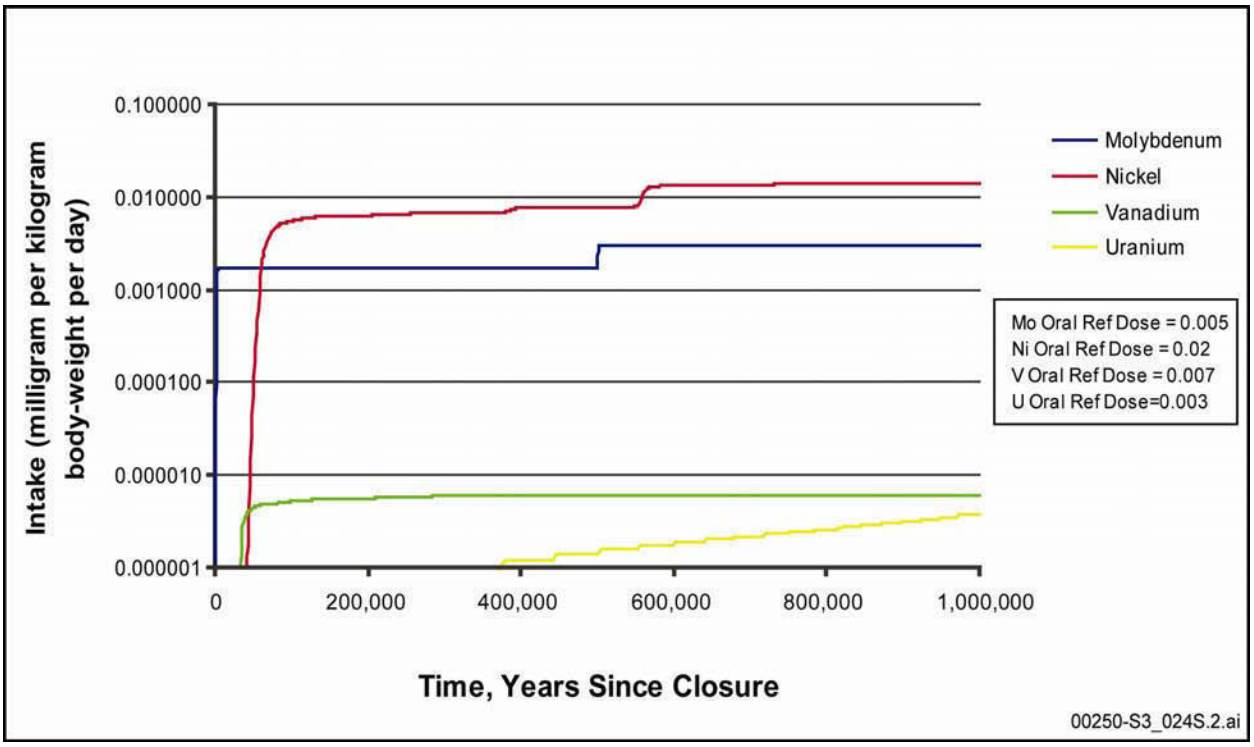


Figure S-10. Daily intakes of nonradiological contaminants at the Amargosa Farms area, wetter climate.

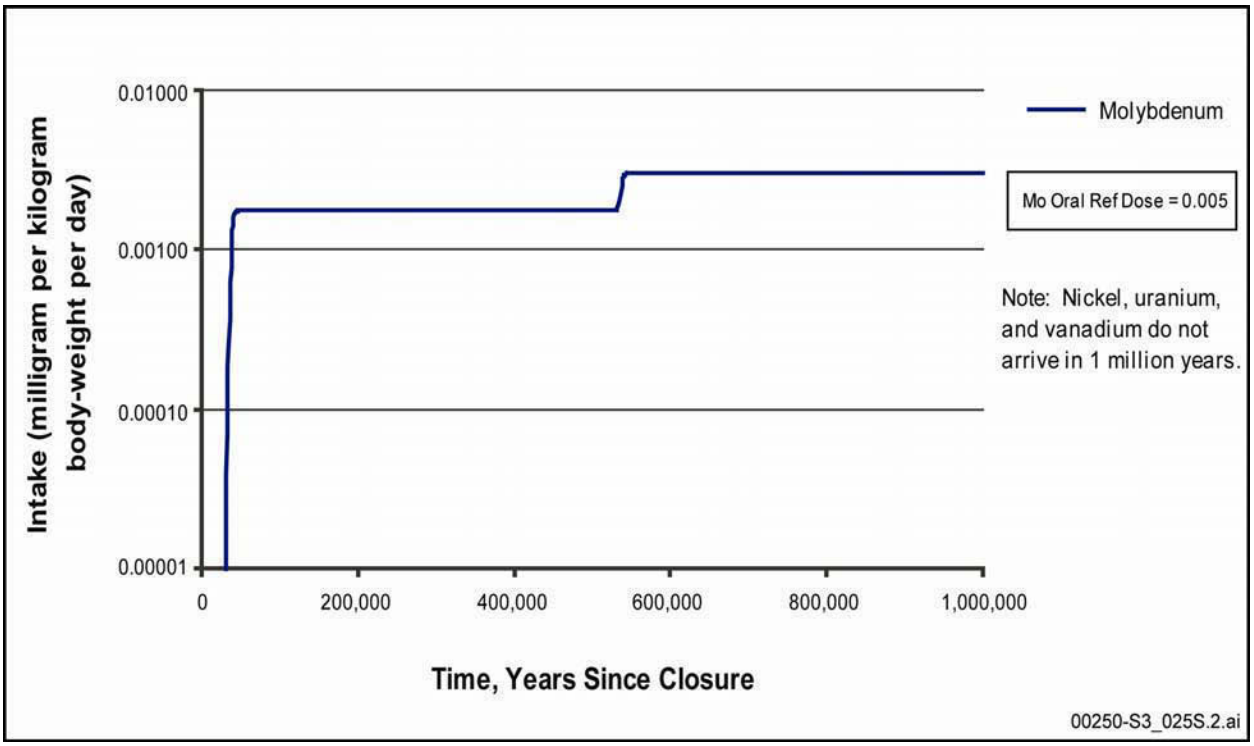


Figure S-11. Molybdenum daily intakes at Furnace Creek springs, no-pumping, present climate.

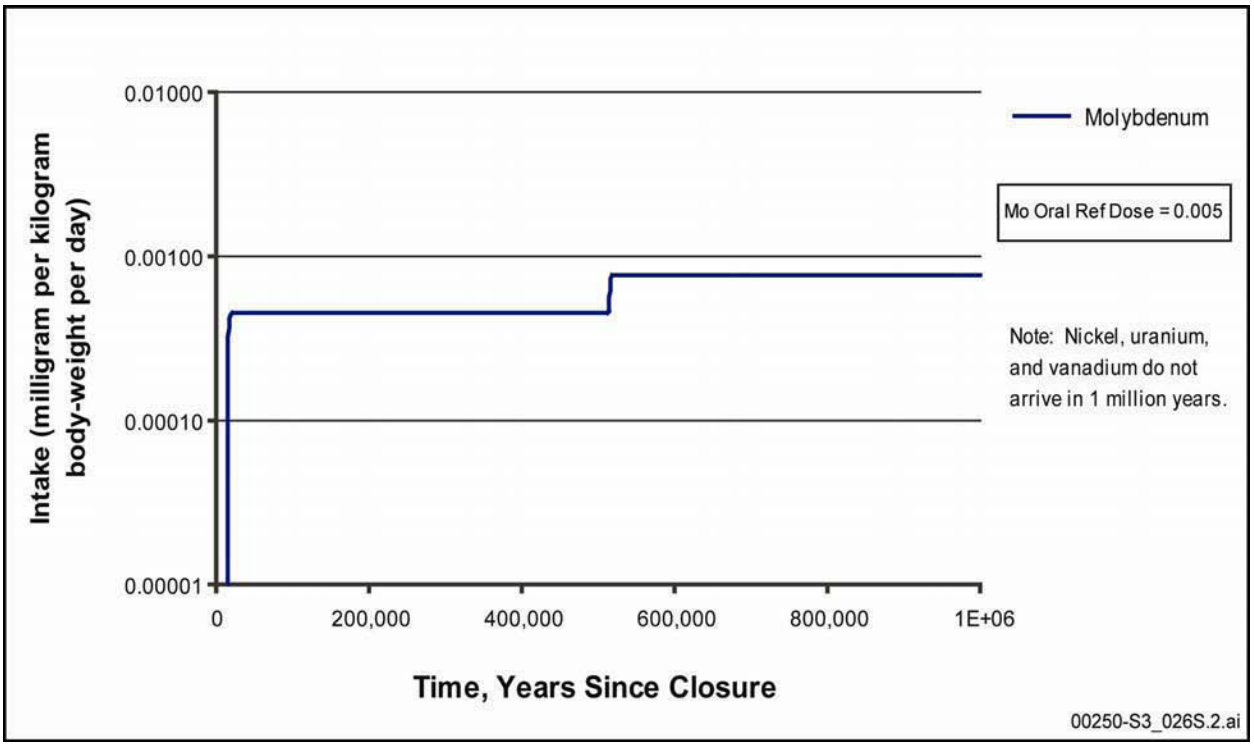


Figure S-12. Molybdenum daily intakes at Furnace Creek springs, no-pumping, wetter climate.

S.3.3 AMERICAN INDIAN CONCERNS

This Analysis of Postclosure Groundwater Impacts describes the possibility that groundwater that flows under Yucca Mountain could discharge at the floor of Death Valley or at springs in the Furnace Creek area of Death Valley. The springs in the Furnace Creek area are of traditional and cultural importance to members of the Timbisha Shoshone Tribe, and the purity of water in those springs is important to Tribal spiritual beliefs, culture, and heritage. Therefore, DOE has further considered potential impacts to cultural resources and American Indian concerns.

The Department acknowledges the sensitivities and cultural practices of the Timbisha Shoshone Tribe concerning the use and purity of springs in the Funeral Creek area; however, the analyses contained in this document demonstrate that the potential concentrations of contaminants in those springs would be so low that there would be virtually no potential health effects associated with the use of the springs. Thus, this document supports the Department's previous conclusion that no disproportionately high and adverse impacts would result from the proposed repository.

S.3.4 CUMULATIVE IMPACTS

The Repository SEIS analyzed the potential environmental impacts of the reasonably foreseeable action of disposing of Inventory Modules 1 and 2 beyond that of the Proposed Action (70,000 metric tons of heavy metal). These inventory modules represent the total projected amount of spent nuclear fuel and high-level radioactive waste (Module 1) and the additional inventory of other radioactive materials, such as Greater-Than-Class C low-level radioactive wastes (Module 2). The Repository SEIS developed scale factors for how the addition of Modules 1 and 2 to the proposed repository inventory would affect the dose and nonradiological impacts at the Regulatory Compliance Point. DOE found that impacts of the

modules would increase linearly relative to the increased number of waste packages. Potential impacts of the Proposed Action at groundwater discharge locations in the region depend directly on the fluxes at the Regulatory Compliance Point; therefore, it is reasonable to assume that the cumulative impacts of the inventory modules at the regional discharge locations would also increase by the linear relationship identified in the Repository SEIS. The scale factors for nonradiological contaminants would be likewise. Because the estimated 1-million-year impacts at the discharge locations evaluated in this analysis are all less than or about equal to the dose estimates presented in the Repository SEIS for the Regulatory Compliance Point, the estimated doses at these locations would also be less than or about equal to the estimated doses presented in the Repository SEIS for the inventory modules. Likewise, the intakes of toxic metals would be less than or about equal to those presented in the Repository SEIS.

The Repository SEIS also evaluated the cumulative impact from Nevada Test Site activities, primarily as a result of past underground weapons testing. After evaluation, the estimated total potential cumulative impact (Yucca Mountain impact plus Nevada Test Site impact) would be 0.24 millirem per year to the reasonably maximally exposed individual for the 1-million-year period. It would be reasonable to expect that the same effect applies to the dose impacts estimated in this Analysis of Postclosure Groundwater Impacts for the regional discharge locations, and would therefore contribute an insignificant amount to the 1-million-year dose.

S.4 Conclusions

S.4.1 MAJOR CONCLUSIONS OF THE ANALYSIS

This Analysis of Postclosure Groundwater Impacts expands the analyses of postclosure impacts from those presented in the Repository SEIS, to include:

- A description of the full extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) could leave the flow system;
- An analysis of the cumulative amount of radiological and nonradiological contaminants that could be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time;
- Estimates of contamination in the groundwater, given potential accumulation of radiological and nonradiological contaminants;
- A description of the locations of potential natural discharge of contaminated groundwater for present and expected future, wetter periods;
- A description of the physical processes at the surface discharge locations that could affect accumulation, concentration, and potential remobilization of groundwater-borne contaminants; and
- Estimates of the amount of contaminants that could be deposited at or near the surface;

This analysis provides estimates of health impacts from exposures to contaminants in Amargosa Valley. DOE found that these exposures would result in very small health impacts, which are about the same as those at the Regulatory Compliance Point. This analysis also provides estimates of health impacts from

exposures to contaminants in Death Valley, either from evapotranspiration from the floor of Death Valley or from the springs at Furnace Creek. DOE found that these exposures would be so low that virtually no potential health effects would be expected.

Based on the above, DOE concludes it has provided the information identified by the U.S. Nuclear Regulatory Commission as needed to supplement the Yucca Mountain FEIS and Repository SEIS and, therefore, has adequately addressed impacts on groundwater, or from surface discharges of groundwater, from the proposed repository.

S.4.2 AREAS OF CONTROVERSY

In both the Yucca Mountain FEIS and the Repository SEIS, DOE acknowledged that areas of controversy exist regarding the Proposed Action and the analyses of its impacts. For this Analysis of Postclosure Groundwater Impacts, the Department identified the areas of controversy that are related to postclosure groundwater impacts and are addressed in this document. These areas reflect differing points of view or irreducible uncertainties.

S.4.2.1 Evaluation of the Lower Carbonate Aquifer

The Inyo County Yucca Mountain Repository Assessment Office raised concerns that DOE has not properly evaluated the full extent of the lower carbonate aquifer, the importance of maintaining the upward hydraulic gradient between the lower carbonate aquifer and the volcanic-alluvial aquifer, and the effects of continued or increased pumping on these aquifers. The Department has addressed these concerns in Appendix A.

S.4.2.2 Impacts to Timbisha Shoshone Tribe

As mentioned in Section S.3.3, the Timbisha Shoshone Tribe considers the waters of the Furnace Creek springs to be of traditional and cultural importance and believes that any effects on the purity of these waters would be detrimental to the Tribe's culture. The analysis DOE included in this document demonstrates that the potential concentrations of contaminants in those springs would be so low that there would be virtually no potential health effects associated with the use of the springs.

1. INTRODUCTION

Spent nuclear fuel and *high-level radioactive waste* are long-lived, highly *radioactive* materials that result from certain nuclear activities. For more than 60 years, these materials have accumulated at commercial power plants and DOE facilities and continue to accumulate across the United States. Because of their nature, spent nuclear fuel and high-level radioactive waste must be isolated from the human environment, and monitored for long periods. The United States has focused a national effort on the siting and development of a *geologic repository* for *disposal* of these materials and on the development of systems for transportation of the materials safely from their present storage locations to the repository. Through the passage of the *Nuclear Waste Policy Act*, as amended (NWPA) (42 U.S.C. 10101 et seq., 1987), Congress found that:

- The Federal Government has the responsibility to provide for the permanent disposal of high-level radioactive waste and spent nuclear fuel to protect the public health and safety and the environment.
- Appropriate precautions must be taken to ensure that these materials do not adversely affect the public health and safety and the environment for this or future generations.

The NWPA directed that the U.S. Department of Energy (DOE or the Department) evaluate the *Yucca Mountain site* in Nye County, Nevada as a potential location for a *geologic* repository. In addition, in 2002, Congress and the President designated the Yucca Mountain site for the development of a repository for the disposal of high-level radioactive waste and spent nuclear fuel (Public Law 107-200; 116 Stat. 735). A geologic repository for spent nuclear fuel and high-level radioactive waste would permanently isolate radioactive materials in a deep *subsurface* location to limit risk to the health and safety of the public.

1.1 Background

DOE completed the *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F; DIRS 155970-DOE 2002, all) (Yucca Mountain FEIS) in February 2002. The *Proposed Action* addressed in the FEIS is to construct, operate and monitor, and eventually close a geologic repository at Yucca Mountain in southern Nevada for the disposal of spent nuclear fuel and high-level radioactive waste. The Yucca Mountain FEIS considered the potential environmental impacts of a repository design for surface and subsurface facilities; a range of *canister* packaging scenarios, repository thermal operating modes, and repository sizes; and plans for the *construction*, *operation*, *monitoring*, and eventual *closure* of the repository. In addition, the FEIS examined various national transportation scenarios and Nevada transportation alternatives for *shipment* of spent nuclear fuel and high-level radioactive waste to the repository.

In June 2008, DOE issued the *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F-S1; DIRS 180751-DOE 2008, all) (Repository SEIS). The basic elements of the Proposed Action evaluated in the Repository SEIS did not change from that evaluated in the Yucca Mountain FEIS. As described in the Repository SEIS, the surface and subsurface facilities would allow DOE to operate the repository following a *primarily canistered approach* in which most

commercial spent nuclear fuel would be packaged at the *reactor* sites in *transportation, aging, and disposal (TAD) canisters*. DOE would repackage any commercial spent nuclear fuel that arrived at the repository in packages other than TAD canisters in TAD canisters. The Department would construct the surface and subsurface facilities over a period of several years (referred to as phased construction) to accommodate an increase in spent nuclear fuel and high-level radioactive waste receipt rates as repository operational capability reached its design capacity. The Repository SEIS evaluated potential environmental impacts of the repository design and operational plans as described in the application that DOE submitted on June 3, 2008, to the U.S. Nuclear Regulatory Commission (NRC) seeking authorization to construct the repository, as required in Section 114(b) of the NWPA (DIRS 185814-DOE 2008, all).

On September 8, 2008, the NRC issued a Notice of Acceptance (letter) to the Department (DIRS 186112-Weber 2008, all) informing that the license application had been accepted for docketing. Included with this notice was the *U.S. Nuclear Regulatory Commission Staff's Adoption Determination Report for the U.S. Department of Energy's Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain* (DIRS 186113-NRC 2008, all) (NRC staff's Adoption Report), dated September 5, 2008 (http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/nrc-eis-adr.pdf). The NRC staff's Adoption Report describes the review the NRC staff conducted to determine if it was practicable to adopt the EISs in accordance with 10 CFR 51.109. The NRC staff concluded that it was practicable to adopt the Yucca Mountain FEIS and supplements prepared by DOE, but that additional supplementation was needed to address the potential impacts of the proposed action on groundwater and from surface discharges of groundwater (the basis for the NRC staff's position is contained in the NRC staff's Adoption Report and summarized in Section 1.2 of this chapter). In the letter, the NRC staff requested that DOE provide a plan for the preparation of a supplement to the Yucca Mountain FEIS and supplements within 30 days.

On October 3, 2008, DOE informed the NRC that it planned to supplement the Yucca Mountain FEIS and supplements as discussed in the enclosure to the NRC letter of September 8, 2008. Accordingly, on October 24, 2008, DOE published a Notice of Intent to prepare a Postclosure Groundwater SEIS and invited comments on the notice (73 FR 63463). In its Notice, DOE described the scope of its analysis:

> The requested supplement will analyze further the repository-related impacts on groundwater, and from surface discharges of groundwater. More specifically, the supplement will describe the extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) can leave the flow system. In addition, the supplement will provide an analysis of the cumulative amount of radiological and non-radiological contaminants that can be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time. This information will be used to estimate contamination in the groundwater, given potential accumulation of radiological and non-radiological contaminants.
>
> The supplement also will provide a discussion of the impacts on soils and surface materials from the processes involved in surface discharges of contaminated groundwater. A description of locations of potential natural discharge of contaminated groundwater for present and expected future wetter periods will be included, as will a description of the physical processes at surface discharge locations that can affect accumulation, concentration, and potential remobilization of groundwater-borne

contaminants. This information will be used to develop estimates of the amount of contaminants that could be deposited at or near the surface, and potential environmental impacts.

In the Notice of Intent, DOE announced a 30-day public comment period, which ended on November 24, 2008. During the 30-day period, DOE received comments from: (1) the Inyo County Yucca Mountain Repository Assessment Office, (2) the Lincoln County Board of County Commissioners, (3) the White Pine County Nuclear Waste Project Office, and (4) the Timbisha Shoshone Tribe. The primary nature of the comments focused on the following:

- Inyo County – requested expansion and/or refinement of the scope of the supplement as defined by the NRC staff. Specifically, the County requests that DOE evaluate perceived flaws in the model used to analyze long-term performance, impacts from continued regional groundwater pumping, impacts to endangered species in springs in Death Valley, and that DOE address cleanup and remediation measures.

- Lincoln County – requested an expansion of the scope of the supplement to include an additional analysis of the potential impacts of a volcanic eruption, specifically addressing how the release of volcanic tephra and radioactive gases might impact human health and the environment in counties northeast of Yucca Mountain.

- White Pine County – requested an expansion of the scope of the supplement to include an additional analysis of the potential impacts of a volcanic eruption, specifically addressing how the release of volcanic tephra and radioactive gases might impact human health and the environment in counties northeast of Yucca Mountain.

- Timbisha Shoshone Tribe – requested that the supplement include analyses of several topics related to groundwater flow, potential transport of nuclear waste, and possible effects in Death Valley National Monument.

DOE has since decided not to supplement the Yucca Mountain FEIS and its supplements, but rather to prepare this *Analysis of Postclosure Groundwater Impacts for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (Analysis of Postclosure Groundwater Impacts). The Analysis of Postclosure Groundwater Impacts addresses the information identified by the NRC staff as needed to supplement DOE's EISs and supplements, and the comments received on the Notice of Intent. The comment documents and DOE's response to these comments are provided as Appendix A to this document.

1.2 Scope of the Postclosure Groundwater Impact Analysis

This Analysis of Postclosure Groundwater Impacts addresses the information identified by the NRC staff as needed to supplement DOE's EISs. Specifically, the NRC staff's Adoption Report identified two areas that needed supplementation, as quoted below (DIRS 186113-NRC 2008, Section 3.2.1.4.2.2, pp. 3-10 through 3-12):

Need for Supplementation 1: Impacts on Groundwater

The EISs have not provided complete and adequate discussion of the nature and extent of the repository's cumulative impact on groundwater in the volcanic-alluvial aquifer. A supplement should include the following information:

- A description of the full extent of the volcanic-alluvial aquifer, particularly those parts that could become contaminated, and how water (and potential contaminants) can leave the flow system. For example, the DOE license application describes potential groundwater flow farther to the south of Alkali Flats, into the Southern Death Valley subregion of the regional model domain (DOE, 2008a, General Information, Section 5.2.2.2). This component of the groundwater flow system is not discussed in the EISs.

- An analysis of the cumulative amount of radiological and non-radiological contaminants that can be reasonably expected to enter the aquifer from the repository, and the amount that could reasonably remain over time. In its license application, for example, DOE provides calculated cumulative releases of some radionuclides at different stages within the repository system, as intermediate results in TSPA (e.g., DOE, 2008a, Safety Analysis Report, Section 2.4.2.2.3). This type of information, for radiological and non-radiological contaminants, could be used in the analysis.

- Estimates of contamination in the groundwater, given potential accumulation of radiological and non-radiological contaminants. One way to analyze the overall impacts on groundwater may be a mass-balance approach that accounts for mass released, the part of the groundwater flow system affected by potential releases, and the expected processes that could affect released contaminants. Such an approach would also show the extent of contamination and possible impacts on water quality.

Need for Supplementation 2: Impacts from Surface Discharges of Groundwater

The EISs have not provided a complete and adequate discussion of the impacts on soils and surface materials from the processes involved in surface discharges of contaminated groundwater. A supplement should include the following additional information:

- A description of the locations of potential natural discharge of contaminated groundwater for present and expected future wetter periods (for example, as discussed in DOE, 2008a, Safety Analysis Report, Section 2.3.1.2).

- A description of the physical processes at the surface discharge locations that can affect accumulation, concentration, and potential remobilization of groundwater-borne contaminants.

- Estimates of the amount of contaminants that could be deposited at or near the surface. This involves estimates of the amount of groundwater involved in discharge or near-surface evaporation, the amounts of radiological and non-radiological

contaminants in that water, contaminant concentrations in the resulting deposits, and potential environmental impacts (e.g., effects on *biota*).

1.3 Document Organization and Contents

This Analysis of Postclosure Groundwater Impacts is organized to address the needs identified in the previous section. Chapter 2 provides descriptions of the volcanic-alluvial aquifer including the current groundwater flow system and evidence of past climates and associated flow systems. Further, Chapter 2 provides summary information from the modeling of the groundwater flow system and how the Repository SEIS and the *Yucca Mountain Repository License Application* (DIRS 185814-DOE 2008, all) used that modeling.

Chapter 3 of this Analysis of Postclosure Groundwater Impacts presents the analytical methodology and results for the estimation of impacts from contaminated groundwater and surface discharges in the accessible environment. Chapter 3 also includes a discussion of potential postclosure impacts to American Indians in the *Death Valley region*.

Appendix A of this analysis presents the comment documents received after DOE's publication of the notice of intent to prepare the SEIS, and DOE's responses to those comments. Appendix B provides analytical details that support the results provided in Chapter 3.

REFERENCES

155970	DOE 2002	DOE (U.S. Department of Energy) 2002. *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada.* DOE/EIS-0250. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020524.0314; MOL.20020524.0315; MOL.20020524.0316; MOL.20020524.0317; MOL.20020524.0318; MOL.20020524.0319; MOL.20020524.0320.
179508	DOE 2002	DOE (U.S. Department of Energy) 2002. *Idaho High-Level Waste and Facilities Disposition, Final Environmental Impact Statement.* DOE/EIS-0287. Idaho Falls, Idaho: U.S. Department of Energy, Idaho Operations Office. ACC: MOL.20070613.0004.

180751	DOE 2008	DOE (U.S. Department of Energy) 2008. *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada.* DOE/EIS-0250F-S1. Las Vegas, Nevada: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20080606.0001.
185814	DOE 2008	DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application.* DOE/RW-0573, Update No. 1. Docket No. 63-001. Las Vegas, Nevada: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20081023.0041.
186113	NRC 2008	NRC (U.S. Nuclear Regulatory Commission) 2008. *U.S. Nuclear Regulatory Commission Staff's Adoption Determination Report for the U.S. Department of Energy's Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain.* Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: LLR.20090203.0020
186112	Weber 2008	Weber, W.F. 2008. "Notice of Acceptance for Docketing of the Department of Energy's License Application for Authority to Construct a Geologic Repository at a Geologic Repository Operations Area at Yucca Mountain, Nevada." Letter from W.F. Weber (NRC) to E.F. Sproat, (DOE/OCRWM), September 8, 2008, 0908083756, Docket No.: 63-001, with enclosures. ACC: CCU.20080908.0004.

2. AFFECTED ENVIRONMENT

This chapter presents baseline environmental conditions associated with the supplemental evaluation needs posed by U.S. Nuclear Regulatory Commission (NRC) staff in the *U.S. Nuclear Regulatory Commission Staff's Adoption Determination Report for the U.S. Department of Energy's Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain* (NRC staff's Adoption Report) (DIRS 186113-NRC 2008, all). The topical areas identified by NRC staff include elements of baseline environmental conditions as well as additional impact evaluations. The supplemental environmental conditions identified in the NRC staff's Adoption Report are: (1) a description of the full extent of the volcanic-alluvial *aquifer*, particularly those parts that could become contaminated, and how water (and potential *contaminants*) can leave the flow system; and (2) a description of the locations of potential natural *discharge* of contaminated *groundwater* for present and expected future wetter periods. Chapter 1of this Analysis of Postclosure Groundwater Impacts provides more information about the NRC staff's requests. The scope of this chapter is to provide the supplemental information on baseline environmental conditions and to provide information needed to understand the supplemental impact evaluations presented in Chapter 3 of this analysis.

The environmental conditions described in this chapter and the impact evaluations of Chapter 3 are supplemental to those presented in the *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F; DIRS 155970-DOE 2002, all) (Yucca Mountain FEIS) and the *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F-S1; DIRS 180751-DOE 2008, all) (Repository SEIS) for the long-term performance of the proposed *repository* at Yucca Mountain. In order to support the impact evaluations in Chapter 3, this chapter includes the following additional descriptive information on the *affected environment*:

- A description of the current groundwater flow system, addressing each of the groundwater basins or sections through which groundwater from beneath Yucca Mountain could pass. The basin or section descriptions include identification of the aquifers, locations of natural discharge, and direction of *subsurface* flow.

- A discussion of past (ancient) climates and hydrological conditions that provide the basis for possible future conditions as addressed in the Yucca Mountain FEIS, Repository SEIS, and in Chapter 3 of this analysis.

- A description of the numerical modeling performed to simulate the regional groundwater flow system for past, present, and future climate conditions.

- A discussion of the groundwater modeling performed in the local area of Yucca Mountain and the associated evaluations of impact for the *reasonably maximally exposed individual* (RMEI) as was presented in the Repository SEIS. This discussion, along with the descriptions of the regional flow system modeling efforts, provides the basis for the current modeling and evaluation approach described in Chapter 3 of this analysis, which evaluates potential contaminant flow paths and potential impacts beyond the RMEI location.

2.1 Current Groundwater Flow System

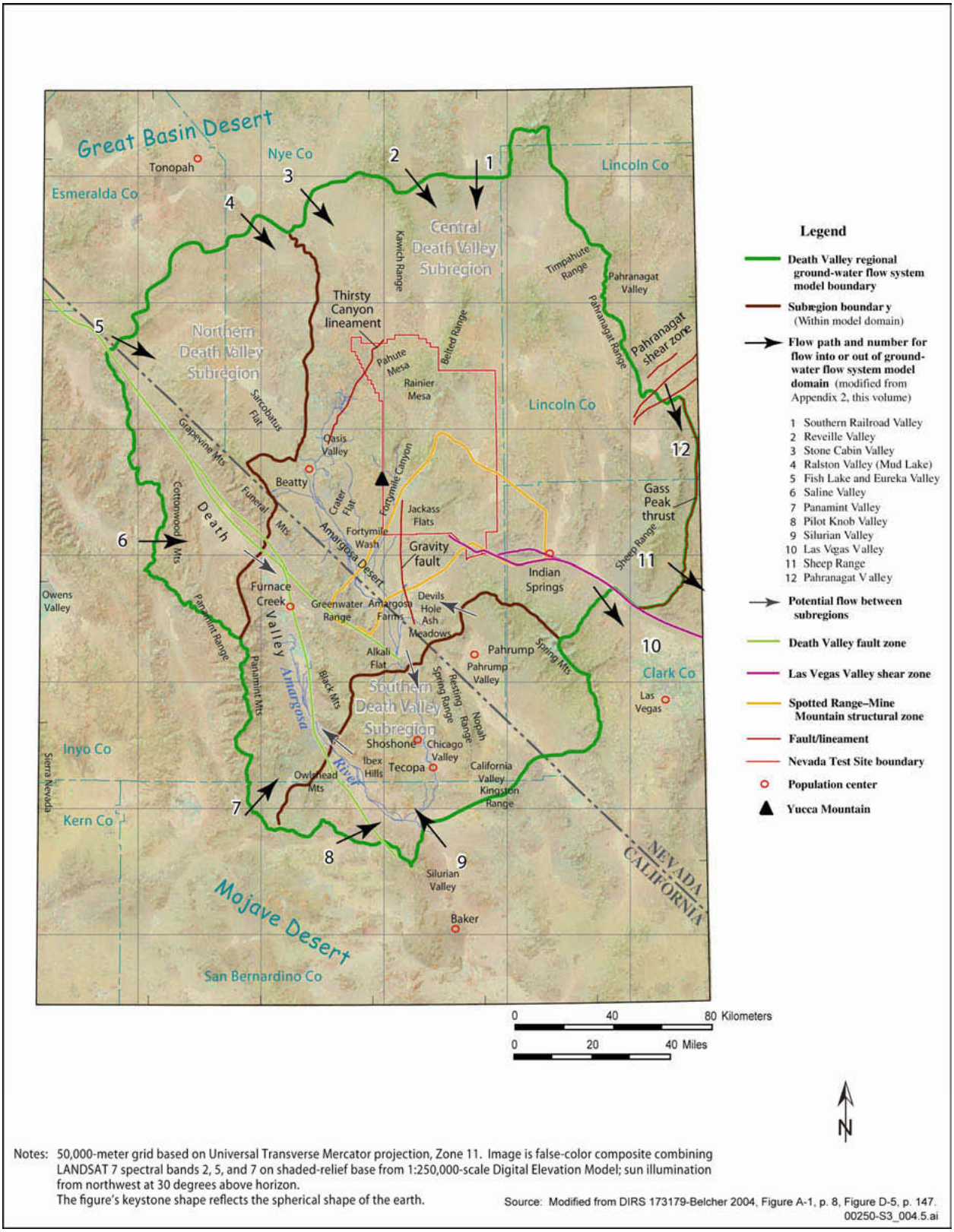
This section presents general information on the *Death Valley regional groundwater flow system*, illustrated in Figure 2-1, which is then followed by more specific detail on the portions of the regional flow system that the proposed repository at Yucca Mountain could affect.

DEATH VALLEY REGION

In this section, Death Valley region refers to the area described by the outer boundaries in Figure 2-1; Death Valley subregion refers to one of the three areas that make up the region. Death Valley or the floor of Death Valley refers to the topographic low area, or structural trough running roughly northwest-to-southeast that is labeled in the western (California) side of the region and is a central element of Death Valley National Park.

In the late 1990s, DOE directed the U.S. Geological Survey (USGS) to improve its groundwater flow model of the Death Valley regional flow system to support DOE programs at the Nevada Test Site and Yucca Mountain. The results of the USGS's work are presented in *Death Valley Regional Ground-Water Flow System, Nevada and California – Hydrogeologic Framework and Transient Ground-Water Flow Model* (DIRS 173179-Belcher 2004, all), and much of the information in this section comes from that document. The USGS technical report presents a hydrologic conceptual model of the groundwater flow system within the *Death Valley region* as well as a description of the construction of a computer-based numerical model to simulate that flow system. The conceptual model is an interpretation or working description of how the flow system works. It was developed based on data that had been measured (such as *water table* elevations), calculated (for instance, estimates of *recharge* and discharge), or otherwise collected (such as groundwater hydrochemistry characteristics) to represent the regional flow system. The numerical model was then developed to simulate flow in the regional system and provide additional information. The flow paths for groundwater from beneath Yucca Mountain are contained within the flow system boundaries of the numerical model. The information presented in this section, unless specifically noted as coming from the numerical model, is based on the conceptual model of the Death Valley regional groundwater flow system. Modeling results are left primarily for discussion in Chapter 3.

The source of groundwater flow in the region is predominantly from recharge due to *infiltration* of precipitation that falls within the boundaries, and most of the recharge originates in the mountainous areas. The major recharge areas include: (1) along the eastern boundary (the Timpahute, Pahranagut, and Sheep ranges and the Spring Mountains); (2) along the western part of the boundary (Panamint Range and the Cottonwood Mountains); (3) the northern area of the Nevada Test Site (Kawich and Belted ranges and Rainier Mesa), and (4) along the eastern margin of Death Valley (Grapevine and Funeral mountains) (DIRS 173179-Belcher 2004, pp. 117 and 118). Areas of recharge are generally reflected by mounds in the water table or *potentiometric surface*, and the largest mound in the region is associated with the Spring Mountains (DIRS 169734-BSC 2004, pp. 8-9 and 8-10), located southeast of Yucca Mountain. Water also enters the regional flow system as *throughflow* from adjoining groundwater basins, predominantly from the north, west, and south, but the amount of water coming into the system laterally is estimated to be relatively small (roughly 10 percent) in comparison with that coming in as recharge from the surface (DIRS 173179-Belcher 2004, pp. 330 and 331; DIRS 169734-BSC 2004, p. 8-42).



Notes: 50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Image is false-color composite combining LANDSAT 7 spectral bands 2, 5, and 7 on shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon.
The figure's keystone shape reflects the spherical shape of the earth.

Source: Modified from DIRS 173179-Belcher 2004, Figure A-1, p. 8, Figure D-5, p. 147.
00250-S3_004.5.ai

Figure 2-1. Boundaries and prominent topographic features of the Death Valley regional groundwater flow system.

One can conceptualize groundwater flow in the region as including a set of relatively shallow, localized flow systems superimposed on deeper intermediate and regional flow systems. A localized flow system can be visualized as consisting of a single basin or valley between mountain ridges; an intermediate flow system would be at a greater depth, supporting flow beneath two or more valleys. The overall direction of groundwater movement is from the source areas (that is, those primary areas of recharge generally near the margins of the regional flow system) toward the regional hydrologic sink (that is, the area to which groundwater flows) in the *floor of Death Valley*.

EVAPOTRANSPIRATION

Evapotranspiration is the loss of water by evaporation from the soil and other surfaces, including evaporation of moisture emitted or transpired from plants.

The largest volume of groundwater loss in the region is also in Death Valley in the form of spring discharges and *evapotranspiration*. In this discussion, sites of evapotranspiration losses are locations where groundwater is naturally at or close enough to the surface of the ground to be susceptible to evaporation or uptake by plants. Losses from pumping and subsequent use of the water are identified separately. There are numerous additional discharge locations along flow paths toward Death Valley. By volume of water lost, the largest of these is represented by the spring discharges and evapotranspiration at Ash Meadows. Other areas of notable water loss (all by evapotranspiration and occasionally with spring discharges) include Sarcobatus Flat, Oasis Valley, Pahrump Valley, and Tecopa Basin (DIRS 173179-Belcher 2004, pp. 330 and 331). As with water coming laterally into the regional flow system, there is throughflow that leaves the system laterally into adjoining groundwater systems. Again, the amount of water that leaves the regional flow system in this manner, primarily along the east and southeast boundaries, is estimated to be relatively small (less than 10 percent) in comparison with the volume lost within the boundaries (DIRS 173179-Belcher 2004, pp. 330 and 331; DIRS 169734-BSC 2004, p. 8-42).

Another pertinent factor in describing the general nature of groundwater in the regional flow system is the nature of the *geologic* material through which it passes. The eastern and southern parts of the region lie within the carbonate-rock province of the Great Basin, which is characterized by thick sequences of carbonate rock. The northwest part of the region generally is underlain by volcanic rocks that are part of the southwest Nevada volcanic field (DIRS 169734-BSC 2004, p. 8-4). In characterizing this region, the USGS identified 25 different hydrogeologic units in five different groupings that begin with the youngest unconsolidated Cenozoic basin-fill (or alluvial) deposits along with younger volcanic rocks. The groupings then incorporate the consolidated Cenozoic basin-fill deposits; the Cenozoic volcanic rocks of the southwestern Nevada volcanic field; the Mesozoic, Paleozoic, and late Proterozoic sedimentary rocks (including the carbonate rock); and finally the lowest units, the crystalline metamorphic rocks of the Proterozoic Era and the intrusive rocks of all ages. Units within these groupings can be aquifers or *confining units*. A confining unit is a rock or sediment unit of relatively low *permeability* that retards the movement of water in or out of adjacent aquifers, whereas an aquifer is a permeable water-bearing unit of rock or sediment that yields water in a usable quantity to a well or spring. Within the 25 hydrogeologic units, the USGS characterized 9 as aquifers, 8 as confining units, and another 8 as units that can function either as aquifers or confining units. It is noted that these are general characterizations because the hydrogeologic units vary in material and hydraulic properties over the extent of the regional groundwater flow system (DIRS 173179-Belcher 2004, pp. 39 and 40), which is the reason some units are identified as either aquifers or confining units.

Simplifying the hydrogeologic units presented in the USGS model (and in almost any other groundwater study of the region), the principal aquifers of the region can be characterized as basin-fill (or alluvial),

volcanic, and carbonate. The basin-fill is the eroded, or otherwise broken down material deposited in between mountains and ridges. These bodies of sand, silt, gravel, and other materials can be very thick, and when they extend below the water table, permeable portions serve as aquifers. *Volcanic aquifers* are in permeable units of igneous rock (of volcanic origin), and *carbonate aquifers* are in permeable units of limestone or dolomite (carbonate rock). (The carbonate aquifer is more appropriately termed the carbonate-rock aquifer, but this document refers to it as simply the carbonate aquifer and uses "carbonate rock" to reference the geologic strata.) Consistent with the location of the southwest Nevada volcanic field identified previously, the mountainous area of the north-central portion of the Death Valley region is often underlain by volcanic rocks and the associated volcanic aquifers. Consistent with the location of the carbonate-rock province of the Great Basin, carbonate aquifers are regionally extensive, particularly in the east and southern portions of the region, and are often at great depths below volcanic and *alluvial aquifers*. When all three aquifers are present, the volcanic rocks are generally in hydraulic connection with the overlying basin-fill and may be in hydraulic connection with underlying carbonate rocks as well as laterally from one basin to another (DIRS 169734-BSC 2004, p. 8-4). It should be noted that two carbonate aquifers are recognized in the region: the *upper* and *lower carbonate aquifer*s. The upper unit is generally only of local importance (that is, it is not significant in the regional flow system) and is not present in the flow path from Yucca Mountain, and, accordingly, is not discussed further.

The regional flow system is divided into subregions, basins, and sections to facilitate discussion and delineate general areas of groundwater recharge, discharge, and movement within the boundaries of the overall flow system. Within the region (Figure 2-1) are the northern *Death Valley subregion*, the central Death Valley subregion, and the southern Death Valley subregion. The regional flow system is divided into these subregions for descriptive purposes only, with delineation of the subregion boundaries based on several different physical attributes including discharge locations in Death Valley. Recharge entering the system at Yucca Mountain would be within the central Death Valley subregion and, based on the primary discharge locations within that subregion, will likely never leave it as groundwater. The focus of the discussion in this Analysis of Postclosure Groundwater Impacts is, therefore, the central Death Valley subregion; specifically, that portion of the subregion that contains the groundwater flow paths from Yucca Mountain. This discussion includes the southern Death Valley subregion because it is possible that some throughflow, including flow paths from Yucca Mountain, occurs between the central and southern subregions. Flow paths from Yucca Mountain do not extend toward the northern Death Valley subregion, but throughflow from the northern subregion into the central subregion does occur.

The subsections that follow begin with descriptions of the applicable subregions and provide a broad view of the overall subregion before moving to the discussion of the applicable basin, the next category down in the hierarchy used to define the flow system. Similarly, the basin is discussed in broad terms before focusing on the applicable groundwater section, the lowest category in the hierarchy. In this manner, each of the groundwater sections through which groundwater from Yucca Mountain could pass is addressed beginning beneath Yucca Mountain and following the general flow path to the low point of the regional flow system, which is Death Valley. Death Valley extends in a northwest-to-southeast direction across all three of the subregions (that is, the northern, central, and southern Death Valley subregions). The lowest area of Death Valley, Badwater Basin, is within the central Death Valley subregion.

Defining the Death Valley regional groundwater flow system included estimating the amount of water moving through the system. In most cases, the USGS's technical report (DIRS 173179-Belcher 2004, all) presents this information in the form of estimates of quantities of water lost from the system through spring discharges, evapotranspiration, and pumping. Thus the report does not generally provide estimates

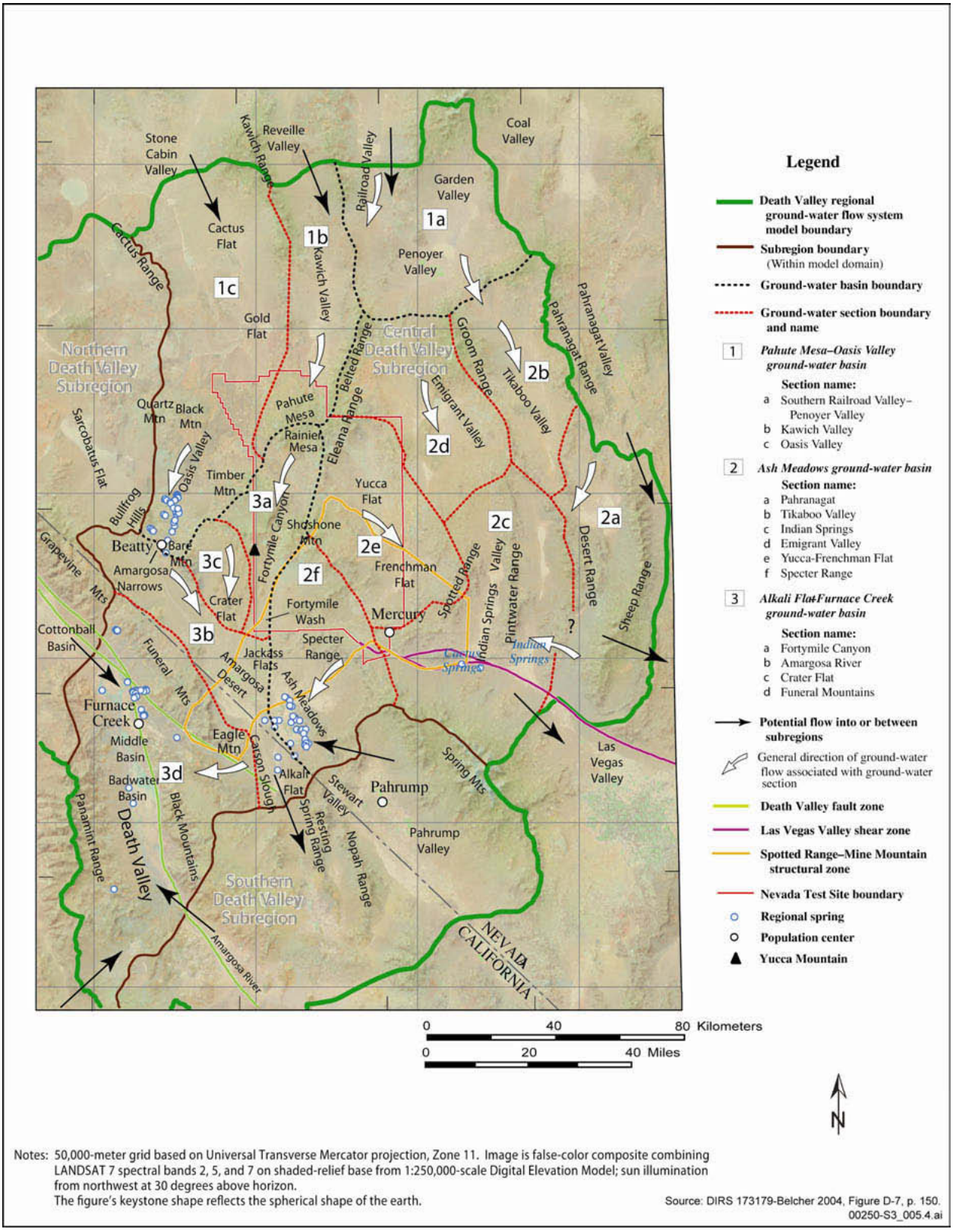
for quantities of groundwater moving through any specific location within the flow system. However, if it is assumed that the system is reasonably in balance (that is, there are no areas where reservoirs of surface or subsurface water are growing or being depleted), then the estimates of water losses along the flow paths provide an indication of at least the minimum amount of groundwater that is moving along those flow paths. It is recognized that some portions of the regional system are currently not in balance (for example, as indicated by lowered water levels in some areas due to pumping), but the water loss values are still of use in describing the movement in the system. Table 2-1 provides estimates of water losses along the sections of the regional flow system that are described in the discussions that follow. That is, the table presents information for those sections of the flow system that could involve flow paths for groundwater that originates beneath Yucca Mountain. The USGS's technical report identifies and describes numerous other significant areas of the flow system where groundwater is lost from the system, which are not included in Table 2-1 since they are not applicable to the analysis in this Analysis of Postclosure Groundwater Impacts.

Table 2-1. Estimates of water losses along select sections of the regional flow system.

	Annual groundwater losses/discharges (acre-feet)		
Flow path section	Specific spring discharges[a]	Losses from evapotranspiration[b]	Groundwater pumping in 2003[c]
Central Death Valley subregion			
Alkali Flat – Furnace Creek basin			
Fortymile Canyon section			92
Amargosa River section		1,350[d]	17,600
Funeral Mountains section	2,300[e]	23,700[f]	55
Southern Death Valley subregion			
Shoshone – Tecopa section		2,530[g]	27[h]
California Valley section		6,400	(h)
Ibex Hills section		3,420[i]	

Note: To convert acre-feet to cubic meters, multiply by 1,233.49.

a. Source: DIRS 173179-Belcher 2004, p. 109.
b. Source: DIRS 173179-Belcher 2004, p. 107.
c. Source: DIRS 185968-Moreo and Justet 2008, database.
d. Evapotranspiration losses from the Amargosa River section include those from the Franklin Well area and those from the Alkali Flat (also known as Franklin Lake Playa) area.
e. The spring discharge shown for the Funeral Mountains section is the total for the Texas, Travertine, and Nevares springs. The data source describes the discharge value for Travertine Springs (1,370 acre-feet per year) as being the total of 10 springs in the same area, and the discharge for Nevares Spring (560 acre-feet per year) is described as including nearby Cow and Salt springs.
f. The evapotranspiration loss shown for the Funeral Mountains section is the total annual loss from the following areas (from north to south): Cottonball Basin (3,030 acre-feet per year), Furnace Creek Ranch (3,410 acre-feet per year), Middle Basin (1,960 acre-feet per year), Badwater Basin (5,950 acre-feet per year), west side vegetation (5,390 acre-feet per year), and Mormon Point (3,950 acre-feet per year).
g. Evapotranspiration losses from the Shoshone – Tecopa section include those from areas along the Amargosa River bed and those from the Chicago Valley playa.
h. The groundwater pumpage volume for the Shoshone – Tecopa section includes pumpage from the California Valley section. The data source does not provide a breakdown of the two sections.
i. The evapotranspiration loss shown for the Ibex Hills section is the total annual loss from the following areas (from north to south): Confidence Mill site (960 acre-feet per year) and Saratoga Springs (2,460 acre-feet per year).



Notes: 50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Image is false-color composite combining LANDSAT 7 spectral bands 2, 5, and 7 on shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon.
The figure's keystone shape reflects the spherical shape of the earth.

Source: DIRS 173179-Belcher 2004, Figure D-7, p. 150.
00250-S3_005.4.ai

Figure 2-2. Central Death Valley subregion of the Death Valley regional groundwater flow system.

2.1.1 CENTRAL DEATH VALLEY SUBREGION

The central Death Valley subregion (Figure 2-2) is divided into three basins: (1) the Pahute Mesa – Oasis Valley groundwater basin, which incorporates northern and northwestern portions of the subregion; (2) the Ash Meadows groundwater basin, which consists of the east portion of the subregion; and (3) the Alkali Flat – Furnace Creek groundwater basin, located in the central area of the subregion between the other two basins and extending to the south-southwest. In general terms, groundwater in the first two basins flows southward (and to the southwest in the case of the Ash Meadows groundwater basin), contributing flow to the Alkali Flat – Furnace Creek groundwater basin. Conversely, groundwater in the Alkali Flat – Furnace Creek basin does not move into either of the other two basins of the Central Death Valley subregion.

The three basins of the central Death Valley subregion were named based on major discharge areas. As Figure 2-2 shows, groundwater flow in the Pahute Mesa – Oasis Valley basin is generally toward an area having spring discharges and evapotranspiration losses in Oasis Valley near Beatty. Some of the flow may also go west toward Sarcobatus Flat in the northern Death Valley subregion, and some may flow to the east toward Crater Flat. Finally, groundwater not discharging within Oasis Valley flows through the thin layer of alluvium or the low-permeability basement rocks at Amargosa Narrows and into the Alkali Flat – Furnace Creek basin (DIRS 173179-Belcher 2004, p. 150).

Groundwater flow in the Ash Meadows basin, the largest of the basins in the central Death Valley subregion, generally moves toward the discharge area of Ash Meadows. In Ash Meadows, groundwater encounters a northwest-to-southeast trending fault where water coming in primarily from the east in the lower carbonate aquifer hits less permeable fine-grained basin-fill sediments. The result is about 30 springs along a 16-kilometer (10-mile) long spring line that generally follows the trace of the fault (DIRS 173179-Belcher 2004, p. 152). Although earlier conceptual models of the Ash Meadows basin had much of the flow at Ash Meadows originating in Pahranagat Valley, more recent evidence suggests that most, if not all, of the water discharging at Ash Meadows originated in the Spring Mountains. Most of the discharged water likely infiltrates and recharges the alluvial aquifers, with much of this discharging as evapotranspiration along the Amargosa River, Carson Slough, and Alkali Flat (DIRS 173179-Belcher 2004, p. 152), located just to the south-southwest of Ash Meadows. (Alkali Flat is also referred to as Franklin Lake Playa.)

Yucca Mountain and water infiltrating through the area of the proposed *Yucca Mountain Repository* are within the Alkali Flat – Furnace Creek basin. Since groundwater in this basin does not contribute flow to either of the other two basins in the central Death Valley subregion, and because of the significance of this basin with respect to groundwater flow from the proposed repository, the remaining discussion of this subregion is limited to the Alkali Flat – Furnace Creek basin.

2.1.1.1 Alkali Flat – Furnace Creek Groundwater Basin

The northern boundary of the Alkali Flat – Furnace Creek groundwater basin is in the area of Pahute Mesa in the central area of the regional flow system. The basin extends to the southwest, encompassing Fortymile Canyon, Crater Flat, the Amargosa Desert, the Funeral Mountains, the central portion of Death Valley, and the eastern slope of the Panamint Range (on the west side of Death Valley) (Figure 2-2). Groundwater in the basin moves through volcanic aquifers in the north and alluvial and carbonate

aquifers in the south. As with the regional flow system in general, the direction of flow is toward the regional sink of Death Valley.

The primary recharge areas for the Alkali Flat – Furnace Creek basin are Pahute Mesa and the Timber and Shoshone mountains in the north, the Grapevine and Funeral mountains (separating Amargosa Desert from Death Valley) in the center, and the Panamint Range on the southwestern boundary. Additional water sources for the Alkali Flat – Furnace Creek basin are in the form of groundwater throughflow, possibly from the Sarcobatus Flat and Oasis Valley areas in the north and from the Ash Meadows area in the east.

The main surface discharge area in the basin is the springs in Death Valley, specifically those in the Furnace Creek area, including the Texas Springs, Travertine Springs, and Nevares Springs. The largest losses in the basin, however, are attributed to evapotranspiration losses over the floor of Death Valley. In the south-central part of the basin, near the Nevada-California border, there are also discharge areas along the Amargosa River, Carson Slough, and Alkali Flat. Throughflow may also result in groundwater leaving the basin and entering the southern Death Valley subregion by following the general course of the Amargosa River past Alkali Flat and through a veneer of alluvium near Eagle Mountain.

The Yucca Mountain FEIS described the flow in the alluvial aquifer of the southern Amargosa Desert as moving toward the primary discharge area of Alkali Flat, with a small portion potentially moving toward the springs in the Furnace Creek area of Death Valley (DIRS 155970-DOE 2002, pp. 3-40 and 3-46). The subsequent Repository SEIS also described the predominant flow in the alluvial aquifer of the southern Amargosa Desert as moving toward Alkali Flat, but the SEIS cited more recent studies as showing evidence that a portion of the flow likely goes to the Furnace Creek area, with some minor amounts also potentially going beyond Alkali Flat and following the general course of the Amargosa River into Death Valley (DIRS 180751-DOE 2008, pp. 3-34 and 3-35). These are relatively minor changes in the conceptual model of the groundwater flow system in the Amargosa Desert. However, this Analysis of Postclosure Groundwater Impacts reaches different conclusions about the direction of flow. As Chapter 3 of this analysis describes, DOE used the Death Valley regional flow system model to simulate flow conditions in the absence of any significant pumping in the region, so the simulation included no effects from pumping in the Amargosa Desert on flow paths from Yucca Mountain. Results of the simulation for this *no-pumping scenario* show flow paths from Yucca Mountain going primarily toward the Furnace Creek area and the floor of Death Valley beyond, with only a small portion going to Alkali Flat. Although the Death Valley regional groundwater flow system model is considered the best representation of the regional flow system developed to date, there are still uncertainties inherent in its use. Since the model predicts a portion (albeit small) of the flow going to Alkali Flat, it does not preclude that flow path as a possibility. Further, groundwater reaching as far south as Alkali Flat might, under at least some conditions, continue southward into the southern Death Valley subregion. As a result, even though the modeling scenario in this case predicts a dominant flow path toward the Furnace Creek area, the conceptual model for purposes of this evaluation conservatively continues to identify other possible flow paths to the south, toward Alkali Flat and beyond.

The Alkali Flat – Furnace Creek basin is divided into four sections (identified by their numbers in Figure 2-2): (3a) Fortymile Canyon, (3b) Amargosa River, (3c) Crater Flat, and (3d) Funeral Mountains. The proposed repository at Yucca Mountain would be located within the Fortymile Canyon section, and the natural groundwater flow path from beneath the repository is from that section to the Amargosa River section. In the southern portion of the Amargosa River section, groundwater moves to the west to

discharge points in the Funeral Mountains section, further south to discharge in the area of Alkali Flat, or past Alkali Flat into the southern Death Valley subregion. The following sections describe in more detail the groundwater pathway from the Yucca Mountain area.

Table 2-2 provides a summary of the sample results from a series of water quality samples collected from springs in the Furnace Creek area and from wells in the Amargosa Farms area. These are primary areas of impact Chapter 3 evaluates, so the data are presented here to provide an indication of the baseline condition of groundwater in these two areas. The table also shows drinking water standards for comparison purposes. It is recognized that these samples represent groundwater and were not collected from drinking water systems, so the standards are not directly applicable. However, the standards do provide a recognized benchmark. As can be seen in Table 2-2, with the exception of arsenic in three locations, and lead and fluoride in one location (indicated by shading in the table), the groundwater samples represent water of good quality. Relatively high concentrations of natural arsenic are a recognized problem for groundwater in this area, and since the U.S. Environmental Protection Agency (EPA) lowered the drinking water standard from 0.05 to 0.01 milligrams per liter in 2006, many of the groundwater sources in the area exceed the standard.

2.1.1.1.1 *Fortymile Canyon Section*

Recharge and Movement

Recharge and throughflow from volcanic rocks of the eastern Pahute Mesa and the western part of Rainier Mesa are the sources for groundwater flow in the Fortymile Canyon section. Infiltration of runoff in the upper reaches of Fortymile Canyon and Fortymile Wash during moderate to intense precipitation events may also be a significant source of recharge in the section (DIRS 173179-Belcher 2004, p. 152). The amount of water infiltrating at Yucca Mountain is small in comparison with these other areas and is not a significant contributor to recharge. Infiltrating water at Yucca Mountain that reaches the *saturated zone* reaches a volcanic aquifer. As indicated in the Repository SEIS (DIRS 180751-DOE 2008, p. 3-42), the saturated zone at Yucca Mountain is roughly 300 meters (980 feet) below the level of the repository. The lower carbonate aquifer is also present beneath the repository site, but it is more than 1,250 meters (4,100 feet) below the repository level (DIRS 180751-DOE 2008, p. 3-42). Thus, there is about 950 meters (3,100 feet) between the top of the saturated zone, or water table, and the top of the lower carbonate aquifer. As noted in the Repository SEIS, a well (well UE-25 p-1) completed to the lower carbonate aquifer at Yucca Mountain indicated a water level, or potentiometric head, in that aquifer about 20 meters (66 feet) higher than the water level in the overlying volcanic aquifer. This demonstrates an upward *hydraulic gradient* between the lower carbonate aquifer and the volcanic aquifer at this location. The upward gradient, along with the great depth and the intervening confining unit(s), which hinder flow between the aquifers and allow the upward gradient to exist, affects the movement of groundwater in this area. Infiltrating water (and potential releases from the repository) that reached the saturated zone in this area would remain in the overlying volcanic aquifer and move laterally rather than down into the lower carbonate aquifer. (Note: Under natural conditions, a separating confining unit or a zone of low permeability would generally be necessary for an upward hydraulic gradient to exist between a low aquifer and an overlying aquifer, otherwise the heads in the aquifers would equalize.) At Yucca Mountain, the groundwater in the volcanic aquifer flows to the southeast. This condition is localized, in that by the time the flow reaches the Fortymile Wash area, the general direction of flow shifts to the south and into the Amargosa River section.

Table 2-2. Water quality of springs in the Furnace Creek area and of wells in the Amargosa Farms area.

Constituent	Units	Drinking water standard	Select springs of the Furnace Creek area[a]			Select wells of the Amargosa Farms area	
			Navel Spring[a]	Texas Spring[a,b]	Nevares Spring[c]	NDOT Well[d]	Gilgans South Well[d]
Number of observations			2 to 3	1 to 4	1	1	1
Inorganics							
Arsenic	mg/L	0.010	Not analyzed	0.024	Not analyzed	0.022	0.011
Barium	mg/L	2	0.032	0.039[e]	0.042	0.010	0.0022
Beryllium	mg/L	0.004	Not analyzed	(0.003)[e]	0.0006	(0.001)[e]	(0.001)[e]
Cadmium	mg/L	0.005	(0.01)[e]	0.0038[f]	(0.001)[e]	(0.001)[e]	(0.001)[e]
Chloride (secondary)[g]	mg/L	250[g]	75[e]	37.3	37	13	7.2
Chromium (total)	mg/L	0.1	0.0035	0.00075[f]	(0.005)[e]	0.0065	0.0043
Copper	mg/L	1.3[h]	(0.01)[e]	0.0083[f]	(0.001)[e]	(0.001)[e]	(0.001)[e]
Fluoride	mg/L	4.0	1.7	4.7	3.2	1.8	1.6
Iron (secondary)[g]	mg/L	0.3[h]	0.098[e]	0.0039[f]	0.004	0.0064	(0.003)[e]
Lead	mg/L	0.015[g]	(0.10)[e]	0.038[f]	(0.001)[e]	(0.001)[e]	(0.001)[e]
Manganese (secondary)[g]	mg/L	0.05[g]	(0.001)[e]	0.0016[f]	0.004	(0.001)[e]	(0.001)[e]
Mercury	mg/L	0.002	(0.0001)[e]	(0.0001)[e]	Not analyzed	(0.001)[e]	(0.001)[e]
Molybdenum	mg/L	None	Not analyzed	(0.030)[e]	0.018	0.007	0.0032
Nitrate (as N)	mg/L	10	6.6	0.2	(0.050)[e]	2.17	1.68
Nitrite (as N)	mg/L	1	(0.01)[e]	(0.01)[e]	(0.050)[e]	(0.01)[e]	(0.01)[e]
Selenium	mg/L	0.05	(0.001)[e]	(0.001)[e]	Not analyzed	(0.001)[e]	(0.001)[e]
Silver (secondary)[g]	mg/L	0.10[g]	(0.001)[e]	(0.001)[e]	(0.001)[e]	(0.001)[e]	(0.001)[e]
Sulfate (secondary)[g]	mg/L	250[g]	113	160	170	110	28
Vanadium	mg/L	None	Not analyzed	(0.01)[e]	(0.001)[e]	Not analyzed	Not analyzed
Zinc (secondary)[g]	mg/L	5[g]	0.0115	0.0093[f]	0.004	0.027	0.0016
Organics							
Organochlorine and organonitrogen compounds		Varies	(varies)[e]	(varies)[e]	Not Analyzed	(varies)[e]	(varies)[e]
Volatile organic compounds		Varies	(varies)[e]	(varies)[e]	Not Analyzed	(varies)[e]	(varies)[e]
Semi-volatile organic compounds		Varies	(varies)[e]	(varies)[e]	Not Analyzed	(varies)[e]	(varies)[e]

Table 2-2. Water quality of springs in the Furnace Creek area and of wells in the Amargosa Farms area (continued).

Constituent	Units	Drinking water standard	Select springs of the Furnace Creek area[a]			Select wells of the Amargosa Farms area	
			Navel Spring[a]	Texas Spring[a,b]	Nevares Spring[c]	NDOT Well[d]	Gilgans South Well[d]
Number of observations			2 to 3	1 to 4	1	1	1
Radionuclides							
Alpha particles	pCi/L	15	2.3	3.15	Not analyzed	(3.0)[e]	(3.0)[e]
Radium 226 and Radium 228	pCi/L	5	0.37	0.47	Not analyzed	0.04	0.03
Uranium	ug/L	30	3.4	4.4	Not analyzed	2.6	(1.0)[e]
Gross beta[i]	pCi/L	None[i]	13	16	Not analyzed	5.7	6.1
Radon-222	pCi/L	None	37	38.5	Not analyzed	612	600

Note: Shaded areas designate sample results that exceed the applicable drinking water standard.

a. Source: DIRS 186228-NPS 1994, pp. 113 to 116, 127 to 130

b. Source: DIRS 186230-USGS 2009, all

c. Source: DIRS 186229-USGS 2009, all

d. Source: DIRS 104828-Covay 1997, all.

e. This constituent was not detected at the detection limit shown in parentheses. As applicable, the *Baseline Water Quality Data Inventory and Analysis Death Valley National Monument* (DIRS 186228-NPS 1994, all) reported a value in these cases, but also reported that the average value was computed with 50 percent or more of the total observations that were half the detection limit (that is, half or more of the observations were reported as not detected, so the "half the detection limit" convention was employed). If there were only two observations in such cases and the minimum and maximum values were the same, then both observations were reported as not detected.

f. This average value was computed with 50 percent or more of the total observations that were half the detection limit. Use of half of the detection limit is a common convention when a value is reported as not being detected.

g. This constituent and the applicable drinking water standard are not from the primary drinking water standards (that is not from 40 CFR Part 141); rather, they are secondary standards from 40 CFR Part 143, which were set to ensure the aesthetic quality of the drinking water. The secondary standards are not federally enforceable.

h. Values shown for copper and lead are action levels that, when exceeded, require the water distribution system to take addition steps to control the corrosiveness of their water (that is, copper and lead are primary concerns with respect to those elements being leached from the distribution system materials).

i. Primary drinking water standards include a standard for beta particles and photon emitters, albeit in terms of dose per year (specifically, 4 millirem per year) from average exposure rates. In order to calculate the dose, speciation of the beta particles is required and the analytical results here are only in terms of gross beta values.

mg/L = milligrams per liter.

NDOT = Nevada Department of Transportation.

pCi/L = picocuries per liter.

ug/L = micrograms per liter.

The Highway 95 Fault runs east-to-west in the same general area where the flow system transitions from the Fortymile Canyon section to the Amargosa River section. Subsurface investigations performed by Nye County in this area have led the County to conclude that the Highway 95 Fault is the southern boundary of the volcanic aquifer in the flow path from Yucca Mountain (DIRS 182194-NWRPO 2005, p. 20). Drilling results show volcanic aquifers on the north side of the fault lining up with less-permeable Tertiary sedimentary rocks on the south side. The Nye County evaluation suggests that the contact with the less-permeable rocks forces the southward-flowing groundwater up into the overlying alluvial aquifer system.

Nye County installed another exploratory well (well NC-EWDP-2DB) to the lower carbonate aquifer in the same area of the boundary between the Fortymile Canyon and Amargosa River sections, just south of the Highway 95 Fault and about 19 kilometers (12 miles) south of the repository site. This well also shows an upward gradient from the lower carbonate aquifer to the overlying alluvial aquifers. In this case, water in the deep well rose 7.2 meters (24 feet) higher than the surrounding water table (DIRS 169734-BSC 2004, p. T8-11). At this location, the Paleozoic rock of the lower carbonate aquifer is at a depth of about 820 to 910 meters (2,700 to 3,000 feet) below the ground surface (DIRS 156115-Nye County Nuclear Waste Repository Office 2001, pp. 31-32). (The range in depth below ground surface is the result of different interpretations of the *lithology* in the well and the depth at which the Paleozoic rock was first encountered.) Since the water table is about 80 meters (260 feet) below the surface in this area, the top of the lower carbonate aquifer is about 740 to 830 meters (2,400 to 2,700 feet) below the top of the water table.

Discharges or Losses

There are no identified natural discharges of groundwater (springs or evapotranspiration sites) within the Fortymile Canyon section of the flow system (Table 2-1). Pumping occurs in the section, but the quantity removed is relatively minor. Water supply wells jointly used by the Nevada Test Site and the Yucca Mountain Project are located near Yucca Mountain in the portion of Jackass Flats that is adjacent to Fortymile Wash. As described in the Yucca Mountain FEIS (DIRS 155970-DOE 2002, p. 3-66), water withdrawals from 1992 through 1997 were as high as 400 acre-feet (490,000 cubic meters) per year in this section. As described in the Repository SEIS (DIRS 180751-DOE 2008, p. 3-50), water use in this area has decreased since that time. By the years 2000 and 2001, the quantity used had dropped to about 140 acre-feet (170,000 cubic meters) per year, and from 2002 through 2004, withdrawals dropped further, ranging from 46 to 67 acre-feet (57,000 to 83,000 cubic meters) per year. The latest update to the groundwater withdrawal rates developed for the regional flow system (DIRS 185968-Moreo and Justet 2008, all) estimates the total groundwater withdrawal in 2003 from both Jackass Flats and the Buckboard Mesa area to the north to be 93 acre-feet (114,000 cubic meters) (Table 2-1).

2.1.1.1.2 *Amargosa River Section*

Recharge and Movement

Recharge to the Amargosa River section is primarily by throughflow from adjoining sections. The alluvial aquifer receives flow from the Oasis Valley, Crater Flat, and Fortymile Canyon sections to the north and from the Ash Meadows area (labeled as the Specter Range section in Figure 2-2) to the east. The underlying lower carbonate aquifer also receives throughflow from the Fortymile Canyon section and from the Ash Meadows area.

Groundwater (both in the alluvial aquifer and in the underlying carbonate aquifer) from the Fortymile Canyon section enters the central part of the Amargosa River section and flows in a southward direction. In the northwestern part of the section (and northwest of the flow path from Yucca Mountain), the USGS described groundwater movement in the alluvial aquifer as being dominantly lateral and downward toward the regional, lower carbonate aquifer flow paths. In the south-central part of the section, near the Nevada-California border, flow characteristics change and become dominated by upward flow from the carbonate rocks (DIRS 173179-Belcher 2004, p. 155).

Since the Death Valley regional groundwater flow system report (DIRS 173179-Belcher 2004, all) was completed, Inyo County installed an additional well to the lower carbonate aquifer. The County installed this deep well on the California portion of the Amargosa River section, almost directly west of Ash Meadows, and it also has an upward hydraulic gradient from the lower carbonate aquifer to the overlying alluvial aquifer. The well is about 50 kilometers (31 miles) south of the deep well at Yucca Mountain and about 31 kilometers (19 miles) south of the deep well Nye County installed. Water in the Inyo County well rose to an elevation 3.3 meters (almost 11 feet) higher than in an adjacent well [only 6 meters (20 feet) away] installed in the overlying alluvial aquifer (DIRS 185423-ICYMRAO n.d., pp. 4 to 8). Assuming that the bottom of the cased portion of the well represents about the top of the lower carbonate aquifer, the depth to the lower carbonate aquifer in this area is about 750 meters (2,500 feet) below the ground surface (DIRS 185423-ICYMRAO n.d., p. 8). The water table in this area is at about 32 meters (105 feet) below the ground surface, so the top of the lower carbonate aquifer is about 720 meters (2,400 feet) below the top of the water table.

The *hydrogeology* of the southern portion of the Amargosa River section is particularly complex. On the east side of the section, the lower carbonate aquifer is close to the surface and feeds springs in Ash Meadows. On the west side, the carbonate rocks are lifted and exposed in the southern end of the Funeral Mountains. Moving to the south, the basin-fill deposits narrow (laterally) and become thinner as they encounter hills and mountains. In addition to the thinned basin-fill deposits in this area, groundwater flow to the south is hindered, or at least deflected, by the low-permeability quartzites of the Resting Spring Range (DIRS 173179-Belcher 2004, p. 155).

The Ash Meadows area is not included in Table 2-1 because it is not part of the flow path from Yucca Mountain, but groundwater movement in Ash Meadows is significant to the Amargosa River section. As noted in Section 2.1, the estimated amount of water discharged and lost to evapotranspiration at Ash Meadows is second only to the amount lost from the floor of Death Valley within the entire regional flow system. Estimates put groundwater losses from the Ash Meadows area at over 18,000 acre-feet (22.2 million cubic meters) per year (DIRS 173179-Belcher 2004, p. 155). Most of the spring discharge (not lost to evapotranspiration) reinfiltrates and recharges the alluvial aquifer of the Amargosa River section; however, much of this is believed to discharge as evapotranspiration from the alluvium along the Amargosa River bed, Carson Slough, and Alkali Flat (DIRS 173179-Belcher 2004, p. 152).

The largest natural pathway by which groundwater throughflow leaves the Amargosa River section is to the southwest through fractures in the carbonate rocks at the southeastern end of the Funeral Mountains. Throughflow leaving by this route moves into the Funeral Mountains section of the Alkali Flat – Furnace Creek basin, primarily toward the springs in the Furnace Creek area of Death Valley or beyond to the floor of Death Valley. As described in the Repository SEIS (DIRS 180751-DOE 2008, pp. 3-34 and 3-35), the evaluation of naturally occurring chemical and isotopic constituents in the water of the Furnace Creek springs link those discharges to the lower carbonate aquifer and, further, have shown them to be

very similar to the water in springs in Ash Meadows. This suggests that groundwater in the lower carbonate aquifer that feeds Ash Meadows is the primary source of the spring discharge in the Furnace Creek area almost directly to the west. However, these same studies suggest there are other contributors to the Death Valley spring discharges, including the volcanic aquifers to the north of Amargosa Desert that contribute to the alluvial aquifer. The evidence indicates the carbonate rocks beneath the Funeral Mountains provide conduits for flow from both the alluvial and lower carbonate aquifers beneath the Amargosa Desert toward the springs in the Furnace Creek area and beyond to the floor of Death Valley.

In summary, groundwater can reach the southern area of the Amargosa River section from several pathways. In the lower carbonate aquifer, groundwater flows in from the north, as well as from the east by way of throughflow from beneath Ash Meadows. In the overlying alluvial aquifer, groundwater can move in as throughflow from the north, as recharge from spring or near surface flows at Ash Meadows, and as upward flow from the lower carbonate aquifer. Once groundwater reaches the southern area of the Amargosa River section, it can leave by one of three identified routes. From the largest to smallest, based on the estimated volume of water involved, these exit routes are as follows: (1) as throughflow to the west via the fractured carbonate rocks beneath the southern Funeral Mountains and into the Funeral Mountains section of the Alkali Flat – Furnace Creek basin; (2) as evapotranspiration, primarily in the area of Alkali Flat and including losses along the Amargosa River and Carson Slough in the same general area; and (3) as throughflow to the south, following the general course of the Amargosa River and through a thin layer of alluvium near Eagle Mountain and into the southern Death Valley subregion (DIRS 173179-Belcher 2004, p. 154). The USGS regional flow model (DIRS 173179-Belcher 2004, all) does not characterize the quantity of flow that might move into the southern Death Valley subregion, other than describing it as minor. The amount of groundwater and quantity of contaminants that could bypass Alkali Flat, while characterized as minor, is not critical for purposes of this Analysis of Postclosure Groundwater Impacts. This is because Chapter 3 of this analysis evaluates discharge areas closer to the repository and assumes discharge of the entire contaminant plume at those areas. Since the types of discharges, water usage, and associated exposure pathways in the southern Death Valley subregion would reasonably be expected to be similar to those Chapter 3 evaluates, exposure scenarios would be the same but with a lower quantity of contaminants. As a result, if some amount of contaminants were to bypass Alkali Flat, there would be a decrease of impacts from those that Chapter 3 presents for the floor of Death Valley and the springs of the Furnace Creek area.

Discharges or Losses

Natural discharges within the Amargosa River section are characterized as the evapotranspiration resulting from groundwater seeps and near surface water in the Franklin Well area of the Amargosa River bed and the evapotranspiration from Alkali Flat. The Franklin Well area is an 8-kilometer (5-mile) stretch of the Amargosa River bed in California that runs on the west side of California State Highway 127 (that joins Nevada State Highway 373) near the south end of the Funeral Mountains (DIRS 165609-Laczniak et al. 2001, pp. 14 and 20). It is estimated that 350 acre-feet (432,000 cubic meters) of groundwater are lost each year from the Franklin Well area of the Amargosa River (DIRS 173179-Belcher 2004, p. 107). Alkali Flat is a large playa area located near the southern boundary of the Amargosa River section. Estimates of evapotranspiration losses from this area include not only standing water or near surface water in the main playa area, but also aboveground flow and groundwater seeps along Carson Slough from where the slough leaves the Ash Meadows area to where it joins the Amargosa River bed at the main playa (DIRS 165609-Laczniak et al. 2001, p. 19). It is estimated that 1,000

acre-feet (1.23 million cubic meters) of groundwater are lost each year from the Alkali Flat area (DIRS 173179-Belcher 2004, p. 107).

There are also significant groundwater losses in the Amargosa River section as a result of pumping. Notable irrigation activities began in the Amargosa Desert in the 1970s and continue in the western Amargosa Desert. Groundwater withdrawals in the Amargosa River section have caused local water level declines. This includes the farmed area of Amargosa Desert in the central portion of the section as well as in the northwest portion of the section as a result of mining operations south of Beatty. In the Yucca Mountain FEIS (DIRS 155970-DOE 2002, p. 3-48) groundwater withdrawals in the Amargosa Desert were reported to average about 14,000 acre-feet (17 million cubic meters) per year from 1995 to 1997. The Repository SEIS (DIRS 180751-DOE 2008, p. 3-37) reported that this yearly withdrawal rate decreased to an average of about 13,000 acre-feet (16 million cubic meters) per year from 2000 to 2004. The USGS regional flow model incorporates groundwater withdrawal rates that are slightly different than those reported in the FEIS and SEIS. For example, the latest update to the groundwater withdrawal rates developed for the regional flow system (DIRS 185968-Moreo and Justet 2008, all) estimates a total groundwater withdrawal from the Amargosa Desert of 17,600 acre-feet (21.7 million cubic meters) in 2003. This is compared with a 2003 groundwater withdrawal of about 13,800 acre-feet (17 million cubic meters) from the reference (DIRS 178692-La Camera et al. 2005, pp. 72 and 73) the Repository SEIS cited. Accurate pumping records are not available for all irrigation activities in the area and the differences in published values are attributed to differences in the factors used to generate estimates for unavailable data.

DIFFERENCES IN GROUNDWATER PUMPING ESTIMATES

Groundwater pumping estimates for the Amargosa Desert, as identified in previous DOE environmental impact evaluations, are different from those the USGS used in developing the Death Valley regional groundwater flow system model. The primary groundwater use in the area is irrigation. Both estimates are based on documents published by the USGS, but those cited in the earlier DOE documents used irrigation estimates the State of Nevada generated, whereas the regional flow system model used irrigation estimates the USGS generated. Both estimates are based on reliable data on the amount of land under irrigation, but when pumping data are missing, there are differing opinions on what water application rate (amount per acre) should be used to generate an estimate. The regional groundwater flow system model incorporates the larger values of the two approaches. Total annual groundwater withdrawals, as used in the model, averaged 16,800 acre-feet (20.7 million cubic meters) from 1994 through 2003, with a minimum and maximum of 14,100 and 21,200 acre-feet (17.4 and 26 million cubic meters) (DIRS 185968-Moreo and Justet 2008, p.4).

Groundwater pumping described in the preceding paragraph is limited primarily to the west-central portion of the Amargosa Desert. As described in the Repository SEIS (DIRS 180751-DOE 2008, p. 3-38), a 1976 U.S. Supreme Court decision (DIRS 148102-Cappaert et al. v. United States et al. 1976, all) restricted groundwater withdrawal in the Ash Meadows area to protect the water level in Devils Hole and the endangered Devils Hole pupfish. In November 2008, the Nevada State Engineer took further action to protect the federally reserved water rights at Devils Hole. According to Nevada State Engineer Order 1197, any water rights applications within 25 miles (40 kilometers) of Devils Hole, and change applications that place the point of diversion to within 25 miles of Devils Hole, will be denied (with some exceptions) (DIRS 186145-Taylor 2008, all). This 25-mile radius incorporates the Amargosa Farms area of the Amargosa River section and, as a result, the State Engineer's order could curtail future pumping

rates in areas more distant from Devils Hole than Ash Meadows. As a result of these actions and restrictions, current pumping rates at the Amargosa Farms area may not be sustainable in the long term.

On an annual basis, the natural groundwater discharges in and near the Amargosa River section consist of the 1,350 acre-feet (1.66 million cubic meters) lost to evapotranspiration within the section, over 18,000 acre-feet (22.2 million cubic meters) lost to evapotranspiration at Ash Meadows, and the minimum of 2,300 acre-feet (2.8 million cubic meters) of throughflow to the Furnace Creek section (discussed further in Section 2.1.1.1.3 below). Based on these values and, more importantly, on the fact that groundwater levels are declining, it is reasonable to conclude that 17,600 acre-feet (21.7 million cubic meters) of annual groundwater pumping in the Amargosa Desert (primarily in the Amargosa Farms area) plays a significant role in the water budget of the section and of the central Alkali Flat – Furnace Creek basin.

2.1.1.1.3 *Funeral Mountains Section*

Recharge and Movement

As Figure 2-2 shows, the Funeral Mountains section encompasses the central, lowest portion of Death Valley (that is, Badwater Basin), the Funeral and Black mountains along the northeast boundary of the section, and the eastern slope of the Panamint Range along the southwest boundary. Recharge to the section from precipitation is primarily from these mountainous areas, but surface runoff can reach Badwater Basin via Salt Creek from the north or Amargosa River from the south during large precipitation or runoff events within the drainage systems. Since Badwater Basin is the low spot of the regional sink that is Death Valley, groundwater throughflow can reach the section from basically all directions. This includes groundwater moving in from both the northern and southern Death Valley subregions, but a primary source of groundwater coming into the section is from throughflow in the lower carbonate aquifer in the southern part of the Funeral Mountains (DIRS 173179-Belcher 2004, p. 155).

Based on the flow paths described previously for the southern portion of the Amargosa River section, the most likely flow path for groundwater originating from beneath Yucca Mountain to reach the Funeral Mountains section would be through the southern part of the Funeral Mountains. A much less likely route would be a round-about way through the southern Death Valley subregions along the general path of the Amargosa River. Along the primary route, throughflow from beneath the Funeral Mountains would first encounter the springs of the Furnace Creek area of Death Valley. Groundwater not discharged at the springs, or discharged and reinfiltrated, then moves in a southwesterly direction toward the floor of Death Valley. There, groundwater is either transpired by stands of mesquite on the lower part of the Furnace Creek fan or evaporated from the playas on the floor of Death Valley (DIRS 173179-Belcher 2004, p. 154). The lowest, and largest, of these playas is Badwater Basin. Other named playas within the Funeral Mountains section include Middle Basin, which is immediately to the north of Badwater Basin, and Cottonball Basin, which is north of Furnace Creek.

The Death Valley floor is surrounded by alluvial fans and numerous springs fringed with vegetation. Groundwater is generally shallow at the bottoms of the fans sloping from the mountains that ring Death Valley. The source of the water in these fans is often local recharge from the mountains, but as in the case of the Furnace Creek area, the source may also be throughflow from adjacent basins.

Discharges or Losses

Natural groundwater losses in the Funeral Mountains section are in the form of spring discharges and evapotranspiration. The largest spring discharges of the section, as well as for the Alkali Flat – Furnace

Creek basin, are those of the Furnace Creek area and include the Texas, Travertine, and Nevares springs. The combined discharge of these springs is estimated at 2,300 acre-feet (2.8 million cubic meters) per year (Table 2-1), of which more than half is from the Travertine springs (DIRS 173179-Belcher 2004, p. 109). By far the largest groundwater loss in the section, however, is by evapotranspiration. The estimated annual evapotranspiration loss from the portion of the *Death Valley floor* within the Funeral Mountains section is 23,700 acre-feet (29.2 million cubic meters) (DIRS 173179-Belcher 2004, p. 276) (see Table 2-1 above). This value for the central portion of the Death Valley floor represents 68 percent of the 35,000 acre-feet (43.2 million cubic meters) per year of evapotranspiration losses estimated for the entire Death Valley floor (DIRS 173179-Belcher 2004, p. 107).

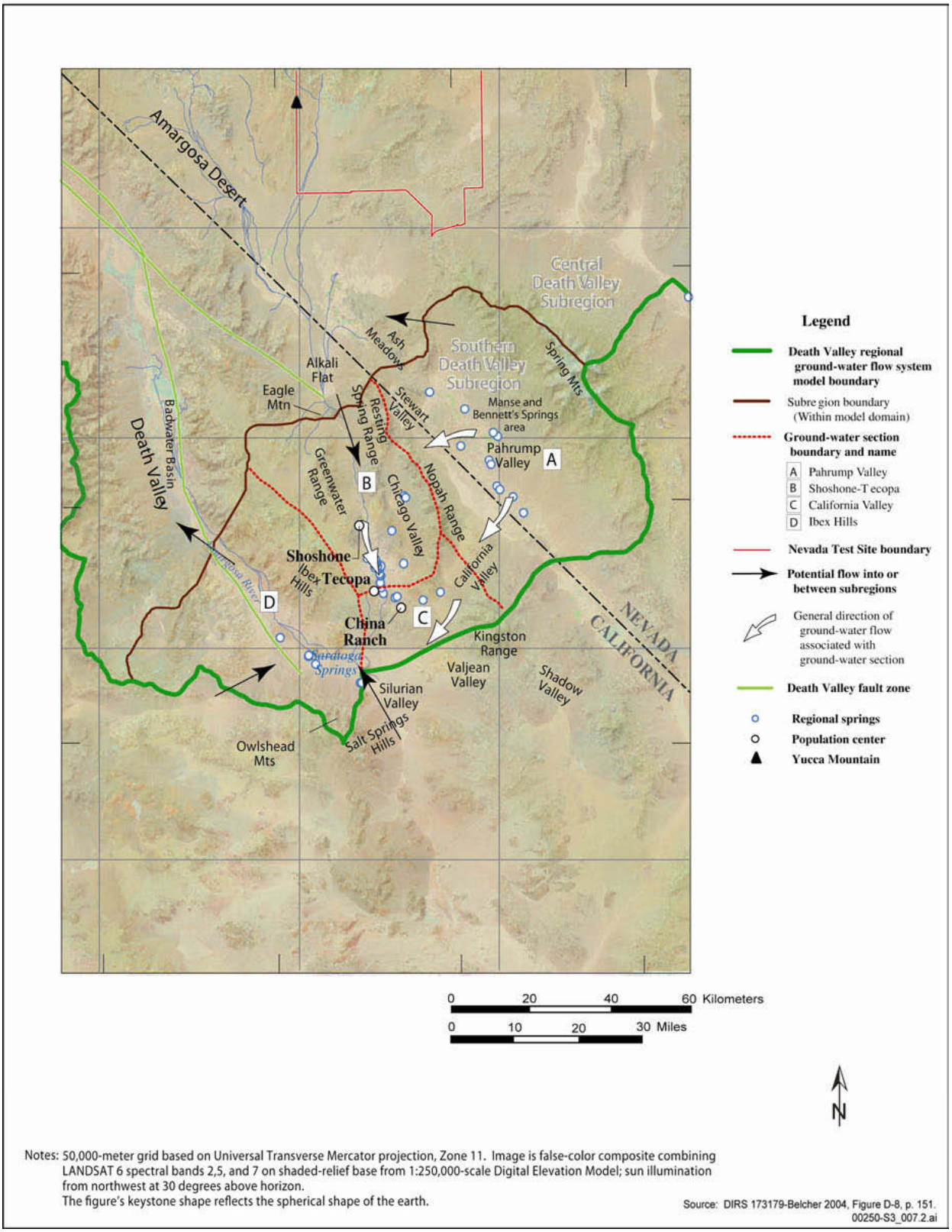
Groundwater in the Funeral Mountains section supports federal facilities and those of the Timbisha Shoshone Tribe within Death Valley National Park. Most of this water is obtained from the springs of the Furnace Creek area, but there is also a single production well (DIRS 168008-Moreo et al. 2003, p. 20) near the northwestern boundary of the section, in the Stovepipe Wells Village area of Death Valley. The amount of groundwater withdrawn from this well is minor; the 2003 withdrawal was about 55 acre-feet (68,000 cubic meters) (DIRS 185968-Moreo and Justet 2008, database) (Table 2-1).

Death Valley Springs and the Timbisha Shoshone Tribe

Death Valley is within the traditional homeland of the Timbisha Shoshone Tribe, and some members of that tribe reside on a 314-acre parcel of trust land located on the floor of Death Valley near Furnace Creek. The springs in the Furnace Creek area are of traditional and cultural importance to members of the Tribe, and the purity of water in those springs is important to tribal spiritual beliefs, culture, and heritage (DIRS 186231-NRC 2009, pp. 28 to 30). Representatives of the Timbisha Shoshone Tribe have stated that the DOE should evaluate the impacts of the contamination of the Death Valley springs on Timbisha cultural, historic, religious, and other interests, including the Tribe's rights to continued traditional tribal religious and cultural activities associated with the springs and on the consumptive water rights granted by the *Timbisha Homeland Act of 2000* (16 U.S.C. 410aaa) (DIRS 186231-NRC 2009, p. 5). Section 3.5 of this Analysis of Postclosure Groundwater Impacts evaluates the potential impacts to cultural resources and American Indian concerns in that area.

2.1.2 SOUTHERN DEATH VALLEY SUBREGION

The southern Death Valley subregion (Figure 2-3) is divided into four sections, with no basins. The four sections are: (A) the Pahrump Valley section making up the northeast portion of the subregion, (B) the Shoshone-Tecopa section in the north-central portion of the subregion, (C) the California Valley section in the south-central portion, and (D) the Ibex Hills section making up the southwest portion of the subregion. Recharge from the Spring Mountains at the northeast boundary provides groundwater flow in the subregion. Precipitation in the Nopah and Greenwater ranges within the central area of the subregion and in the Kingston Range on the southeastern boundary contribute recharge to a lesser degree (DIRS 173179-Belcher 2004, p. 155). Groundwater throughflow may also enter the southern boundary of the subregion by way of the basin-fill materials in Silurian Valley and in valleys adjacent to the Owlshead Mountains. A small amount of throughflow into the subregion may also occur across the boundary with the Alkali Flat – Furnace Creek basin of the central Death Valley subregion. As described in Section 2.1.1.1.2, this area of possible groundwater inflow is through a thin layer of alluvium near Eagle Mountain, south of Alkali Flat.



Notes: 50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Image is false-color composite combining LANDSAT 6 spectral bands 2,5, and 7 on shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon.
The figure's keystone shape reflects the spherical shape of the earth.

Source: DIRS 173179-Belcher 2004, Figure D-8, p. 151.
00250-S3_007.2.ai

Figure 2-3. Southern Death Valley subregion of the Death Valley regional groundwater flow system.

As with the rest of the regional flow system, groundwater in the southern Death Valley subregion generally moves toward the low floor area of Death Valley. Most of the subregion's land area is to the northeast of the Death Valley floor (Figure 2-3), so groundwater in most of the region moves generally in a southwesterly direction. A portion of the subregion's land area, however, is on the southwest side of the Death Valley floor; in this area, groundwater flows generally toward the north and northeast.

Pahrump Valley is the largest discharge area in the subregion. Before extensive development in the Pahrump Valley, the broad playa area had several springs, and the Manse Springs and Bennetts Springs discharged at the base of the broad alluvial fans at the foot of the Spring Mountains. This area now has by far the largest pumping withdrawals in the subregion and flow has ceased in many of the springs. Other areas of natural discharge are along the Amargosa River in the Shoshone and Tecopa areas and in the Saratoga Springs area of Death Valley. Some groundwater may leave the subregion in the northernmost portion, contributing flow to Ash Meadows, and in the southwestern portion, moving past the Saratoga Springs area toward Badwater Basin of the central Death Valley subregion (DIRS 173179-Belcher 2004, p. 155).

The only potential groundwater flow path from beneath Yucca Mountain to the southern Death Valley subregion is across the boundary with the Alkali Flat – Furnace Creek basin in the area south of Alkali Flat and into the Shoshone-Tecopa section of the southern subregion. From the Shoshone-Tecopa section, the primary groundwater flow path basically follows the bed of the Amargosa River to the south into the California Valley section, then to the west into the Ibex Hills section. Since the potential pathway from Yucca Mountain does not include the Pahrump Valley section, that section is not discussed further. The discussion that follows provides additional detail on the three sections of the southern Death Valley subregion that could be involved in the groundwater flow path from Yucca Mountain.

2.1.2.1 Shoshone – Tecopa Section

Recharge and Movement

Groundwater flow in the Shoshone – Tecopa section is primarily a result of throughflow from adjacent sections with some contribution from recharge in the Nopah Range on the northeastern boundary of the section. Groundwater in the Pahrump Valley section that is not lost in that section moves either to the north of the Nopah Range and into the Shoshone – Tecopa section, or to the south of the Nopah Range and into the California Valley section. That groundwater entering the Shoshone – Tecopa section at the northern end of Chicago Valley joins with groundwater flowing south from the Alkali Flat area and moves southward following the path of the Amargosa River.

Discharges or Losses

Groundwater discharge in the Shoshone – Tecopa section is primarily from springs and evapotranspiration along the flood plain of the Amargosa River between the towns of Shoshone and Tecopa, California. Estimates of the amount of groundwater lost to spring discharges and evapotranspiration in the area are about 2,100 acre-feet (2.6 million cubic meters) per year (Table 2-1). The Chicago Valley playa on the east side of the Shoshone – Tecopa section also has evapotranspiration losses. It is estimated that about 430 acre-feet (530,000 cubic meters) of groundwater are lost each year from the Chicago Valley playa (DIRS 173179-Belcher 2004, p. 107).

Documentation for the regional flow system model also identifies some minor pumping withdrawals from the area. Estimates for the Shoshone – Tecopa and California Valley sections are minor and involve only

27 acre-feet (33,000 cubic meters) from two wells in 2003 (DIRS 185968-Moreo and Justet 2008, database; DIRS 173179-Belcher 2004, p. 111) (Table 2-1).

Groundwater not lost to spring discharges, evapotranspiration, or pumping continues flowing south in the alluvium along the Amargosa River and into the California Valley section. Some of the throughflow may also move to the southwest through faulted and fractured crystalline rocks into the Ibex Hills section (DIRS 173179-Belcher 2004, p. 156).

2.1.2.2 California Valley Section

Recharge and Movement

Sources of groundwater flow in the California Valley section are attributed to throughflow from the Shoshone – Tecopa section to the north and from the Pahrump Valley section to the northeast. Recharge from precipitation also occurs on the Kingston Range on the southeast boundary of the section. Groundwater movement in the section is primarily to the south and southwest into the Ibex Hills section.

Discharges or Losses

A structural uplift south of Tecopa brings groundwater to the surface, feeding a *perennial* stretch of the Amargosa River. As a result, water leaves the section both as surface flow in the Amargosa River and as throughflow in the alluvium along the river. The annual water loss estimate resulting from spring discharges and evapotranspiration along the Amargosa River in the California Valley section is 6,400 acre-feet (7.89 million cubic meters) (DIRS 173179-Belcher 2004, p. 107) (Table 2-1). The minor amount of pumping that occurs in this section was included in the Shoshone – Tecopa section above.

2.1.2.3 Ibex Hills Section

Recharge and Movement

The Ibex Hills section receives groundwater from several directions. In addition to receiving throughflow from the Shoshone – Tecopa section to the north and the California Valley section to the east, the Ibex Hills section likely receives throughflow from outside the regional flow system. As described in Section 2.1.2, groundwater throughflow can enter the southern boundary of the section by way of the basin-fill materials in Silurian Valley to the southeast and in valleys adjacent to the Owlshead Mountains to the south. Groundwater discharge from the lower carbonate aquifer also feeds the area of Saratoga Springs at the southern tip of the Ibex Hills. Groundwater movement is toward the low central area of the section where the Amargosa River bed runs from the southeast to the northwest.

Discharges or Losses

Groundwater discharge in the Ibex Hills section is primarily in the form of spring discharges in the Saratoga Springs area, from evapotranspiration along the Amargosa River and shallow groundwater (that is, groundwater close enough to the land surface that it is subject to evapotranspiration) along the flood plain of the river. A minor amount of groundwater may also leave the Ibex Hills section as throughflow into the central Death Valley subregion to the north, toward the discharge area of Badwater Basin (DIRS 173179-Belcher 2004, p. 156). The estimate of total annual evapotranspiration losses from the portion of the Death Valley floor within the Ibex Hills section is 3,420 acre-feet (4.2 million cubic meters) (DIRS 173179-Belcher 2004, p. 277) (see Table 2-1 above). This value for the southern portion of the Death Valley floor includes losses from Saratoga Springs and is only a minor portion (about 10 percent) of the

35,000 acre-feet (43.2 million cubic meters) per year of evapotranspiration losses estimated for the entire Death Valley floor (DIRS 173179-Belcher 2004, p. 107).

2.2 Evidence of Past Climates and the Associated Groundwater Flow System

2.2.1 PALEOCLIMATOLOGY

The Yucca Mountain FEIS briefly described DOE's study and analysis of the evidence of ancient climates (DIRS 155970-DOE 2002, pp. 3-15 and 3-16) in order to gain insight into potential future climates. This study of ancient climates is termed *paleoclimatology*. DOE's efforts have looked at time scales in the hundreds of thousands of years. This section briefly describes the natural phenomena that drive long-term climate changes. It then describes results of efforts to characterize past climates in the Yucca Mountain region based on these natural phenomena and on evidence of past climates found in geologic evidence in the region.

2.2.1.1 Forcing Mechanisms

To understand how climate has changed over this geologic time scale, DOE's evaluations, along with those of other investigators, have looked at the forcing mechanisms that drive climate changes. Two of the primary forcing mechanisms have been characterized as *astronomical changes* and *terrestrial changes*.

Astronomical changes are extraterrestrial changes that affect the *solar radiance* received by the earth and include changes in the solar radiance put out by the sun and those due to changes in the way the earth receives that radiance due to its proximity and tilt in relation to the sun. Changes in solar radiance are attributed to sunspot cycles and increasing and decreasing radiance trends of low magnitude over long periods (DIRS 169734-BSC 2004, pp. 6-4 and 6-5). Earth changes are attributed to slight changes in the shape of its orbit around the sun and to changes in the earth's axis in relation to the plane of the orbit. These cyclical changes in the amount and manner in which the earth receives solar radiance are small, but based on long-term climate records, they show a relationship with *glacial* and *interglacial* periods.

Terrestrial changes refer to the manner in which the earth's components, consisting of the atmosphere, the water bodies, the solid earth, and life forms, respond to the changes in solar radiance the earth receives. Among these components, the primary forcing mechanisms for climate change, in simple terms, are the interactions between the atmosphere and the oceans as they attempt to minimize temperature differences caused by unequal solar radiance. These interactions and other terrestrial forcing mechanisms, including unpredictable events such as volcanism and asteroid impacts, represent additional critical elements in characterizing ancient climates (DIRS 169734-BSC 2004, pp. 6-7 to 6-9).

Developing an understanding of the natural mechanisms that drive climate changes coupled with physical evidence of past climates has allowed DOE to develop estimates of the climates that could occur in the future and how those climates could affect the performance of the proposed repository.

2.2.1.2 Characterization of Past Climates

A variety of information sources have contributed to an understanding of the paleoclimate in the Yucca Mountain area. The primary sources consist of stratigraphic successions of plant and animal fossils, and the presence of stable isotopes of oxygen and carbon that can be measured and dated. Paleoclimatology studies routinely incorporate numerous other contributing information sets that are not specifically mentioned here. These sources of information of interest are often referred to as climate proxy data because some climate-related parameter, or parameters, can be interpreted.

Information sources, or natural records, covering long periods of time within the Yucca Mountain region consist primarily of Devils Hole in Ash Meadows, Nevada and Owens Lake and Death Valley in California—all within about 160 kilometers (100 miles) of Yucca Mountain. Other sources of information used in the evaluations include plant *macrofossil* data collected from packrat middens and wetland and spring deposits, which often provide significant information detail, even if it is only applicable to relatively short periods of time (DIRS 169734-BSC 2004, p. 6-26).

DOE evaluated other climate evidence that shows climate episodes similar in magnitude and timing to the Owens Lake and Death Valley data. These included lake and glacial records in the region and records as far away as Greenland, Antarctica, Siberia, and Europe. These records show that climate varied substantially over time and that the timing of those changes is strikingly similar, which provides added support to the concept that climate responds to global forcing mechanisms (DIRS 169734-BSC 2004, pp. 6-40 to 6-44). One of the other records, mentioned below, is the ice core recovered from the Russian Vostok station in East Antarctica. This was a 1998 joint effort among Russia, the United States, and France and resulted in the deepest ice core ever recovered, reaching a depth of 3,623 meters (2.25 miles). Evaluation of data from the ice core indicated that the ice is slightly older than 400,000 years and represents a record extending through four climate cycles (DIRS 109450-Petit et al. 1999, all).

2.2.1.2.1 *Devils Hole*

Devils Hole, Nevada, is a large fracture within the lower carbonate aquifer that has existed over the past 600,000 years. Calcite that precipitated on rock surfaces over time has left a stable isotope record of the water in the aquifer. The concentrations of isotopes of hydrogen and oxygen deposited in calcite have been shown to vary depending on temperature. As a result, measurements of the isotopes in the calcite provide a climate change chronology, tracking a progression of glacial and interglacial climates. The Devils Hole isotopic data compare well with similar data, including composite records from global oceans and values in ice from cores taken in Antarctica and Greenland. The Devils Hole data provide a good indication of the timing for global climate changes, but do not provide a clear picture of the magnitude of the changes in air temperature and precipitation that were associated with the climate changes (DIRS 169734-BSC 2004, p. 6-28 and 6-29).

INTERGLACIAL CLIMATE

In the cyclic nature of climate, interglacial refers to the relatively dry, warm climate (as in the present day) that is at the opposite end of the spectrum from the cooler and wetter glacial climate.

2.2.1.2.2 *Owens Lake*

Owens Lake is a present-day playa in Inyo County, California, about 160 kilometers (100 miles) west-southwest of Yucca Mountain. Over its long history, Owens Lake has varied between being a flow

through lake; a stagnant, saline lake; and a primarily dry playa bed. The playa contains a thick sequence of lake deposits, which include several plant, animal, and geochemical proxies (that is, they provide evidence for specific conditions) for both *paleohydrology* and climate, and which have been studied extensively in the form of several drill cores collected from the lake bed. These lake deposits provide a record of snow pack in the Sierra Nevada mountains and a measure of the nature, rate of change, and duration of past glacial and interglacial periods (DIRS 169734-BSC 2004, p. 6-30). The chronology of the sediment layers is derived primarily from a model of the sediment accumulation rate. This chronology was subsequently augmented with a radiometric evaluation of pollen profiles that covered 230,000 years of the lake sediment history (DIRS 169734-BSC 2004, p. 6-30).

The geochemistry of the Owens Lake sediments provides significant information on the water that moved through the system. In simple terms, water moving through the system had low concentrations of chemical constituents during glacial periods when runoff was dominated by melt from an extensive snowpack and was higher in geochemical concentrations during interglacial periods (DIRS 169734-BSC 2004, p. 6-31). Fossil diatoms and ostracodes (tiny crustaceans whose remains are commonly preserved in aquatic environments) in the sediments also reflect the range of water chemistry that was in the drainage feeding Owens Lake. The *microfossil* record shows a chronological progression of climate-induced changes in the hydrochemistry as well as in plant and animal life. One set of species becomes rare or disappears and another set appears and becomes common. The Owens Lake record is relatively continuous and can be interpreted in terms of the global climate changes that are correlated with *orbital parameters* (DIRS 169734-BSC 2004, p. 6-37).

2.2.1.2.3 *Death Valley*

Sediments in Death Valley, California, also provide evidence of past climate events. During glacial periods, there was a deep lake present in Death Valley and based on evaluations of sediments there and in nearby areas, the Amargosa River was a primary source for that lake. Since flow in the Amargosa River is not supported by runoff from high mountains like the Sierra Nevada, the very presence of the ancient lake at Death Valley appears to support the likelihood that Fortymile Wash, a primary contributor to the Amargosa River, was a permanent stream requiring a groundwater system to support it (DIRS 169734-BSC 2004, p. 6-37). Silver Lake Playa, to the south of Death Valley, was another Pleistocene lake in the region and provides additional evidence that storm tracks may have been displaced southward (compared with the current climate) during glacial episodes.

Other paleohydrologic and paleoclimatic data from Death Valley have been obtained primarily from a 186-meter (610-foot) core taken from the lowest area (Badwater Basin) of the Death Valley floor. The core consists of sediments and evaporites deposited over the last 200,000 years. The core layers were dated using isotopic dating techniques and evaluated for various geochemical constituents to gain an understanding of the physical and climatic conditions under which they were deposited. The core contains halite crystals with fluid inclusions that can be evaluated for the temperature at which the halite precipitated. Based on the strata dating and the fluid inclusion evaluations, investigators have been able to identify periods of time when maximum summer and winter temperatures were similar and how those temperatures compare with those of the current climate. For example, investigators have been able to conclude that temperatures for the majority of the last 100,000 years were lower than temperatures for the modern climate (DIRS 169734-BSC 2004, p. 6-40), which began about 12,000 years ago (DIRS 169734-BSC 2004, p. T6-30).

2.2.1.2.4 *Conclusion*

DOE's evaluation of paleoclimatology focused on the relatively short-term history of climate of the tens and hundreds of millennia because that is the time scale of significance to the performance of the proposed repository at Yucca Mountain. The forcing mechanisms described above are expected to function in the future in the same manner as they functioned during the past. Conditions that existed during extremely different climates (such as global aridity during the Triassic period or tropical humidity during the Cretaceous period) involved very different land and ocean configurations. These types of changes in land, mountain, and ocean configurations have not occurred over the past 500,000 years and are expected to change little over the next 500,000 years (DIRS 169734-BSC 2004, p. 6-26); climate swings or perturbations during the past 500,000-year time frame were suppressed in comparison with what the earth experienced during times even further removed from the present, and the climates typical of the recent past likely are representative of those in the future. There is some evidence of earlier (before 500,000 years ago) climate shifts that suggests the long-term earth-based (terrestrial) climate-forcing functions have remained relatively constant only over the past 500,000 years (DIRS 169734-BSC 2004, pp.6-57 to 6-60).

The various sets of paleoclimatology data collected from the local Yucca Mountain region have been compared with each other to develop the best possible picture of what climate types affected the area and when. These data have also been compared with records of the southwestern United States beyond the Owens Lake – Death Valley region and with various locations around the world, including Greenland, Antarctica, Siberia, and Europe. The evaluations have shown that climate has changed significantly over time and that major changes around the world were synchronized (DIRS 169734-BSC 2004, p. 6-40). The paleoclimatology studies have identified four basic climate types as occurring within the period represented by the Owens Lake record (DIRS 169734-BSC 2004, p. 6-54). These climate types, or states, are as follows:

- Interglacial – A climate comparable to the present, relatively warm climate.
- *Monsoon* – A climate characterized by hotter summers with increased summer rainfall relative to today.
- *Intermediate* – A climate (sometimes referred to as the glacial-transition climate) that has cooler and wetter summers and winters relative to today.
- Glacial – A climate that is substantially cooler and wetter relative to today.

The sequencing of these climate states is cyclical, moving from interglacial to glacial and back again. The transitions are termed the intermediate climate state. Monsoonal activity occurs as relatively short bursts within the longer periods of interglacial or intermediate climates.

Figure 2-4 provides a graphical representation of the different climate states and when they occurred during the past 425,000 years. The climate states are largely based on the Owens Lake climate proxies because of the quality of record and the proximity of Owens Lake to Yucca Mountain. However, information from Devils Hole and the Vostok (Antarctica) ice core, which shows a strong similarity to the Devils Hole data, was used extensively to help set the timing of the climate changes depicted in the figure (DIRS 169734-BSC 2004, p. 6-55).

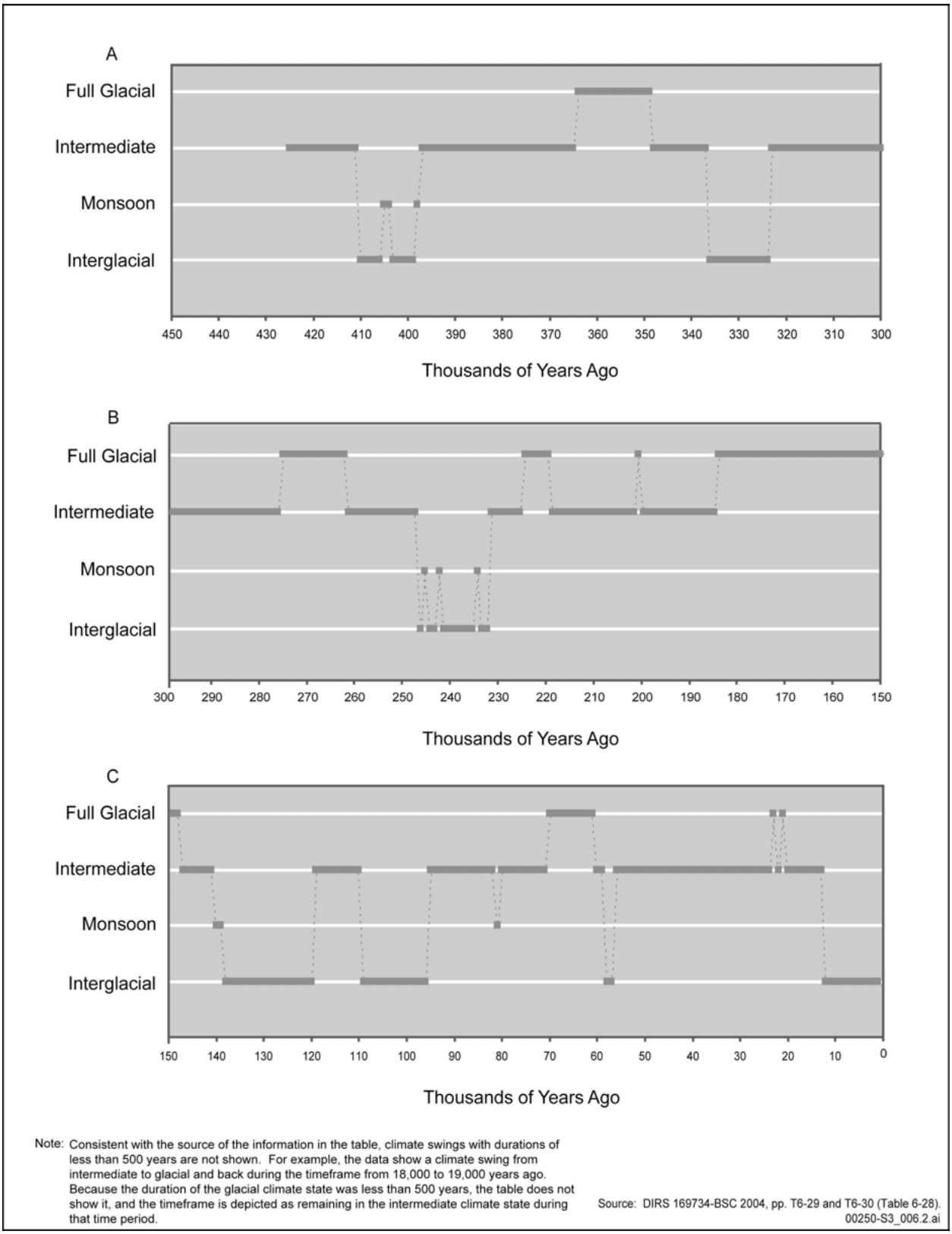


Figure 2-4. Summary of climate occurrences during the past 425,000 years as derived from Owens Lake climate proxies.

Table 2-3 provides a summary of the information presented in Figure 2-4 in terms of the total duration of each climate state. As can be seen in the figure and the table, the Yucca Mountain region experienced the intermediate climate state for the greatest amount of time at almost 60 percent of the past 425,000 years.

Table 2-3. Summary of years and percentage for each climate state.

Climate State	Total duration during the past 425,000 years	Percentage[a]
Interglacial	82,000	19
Monsoon	9,000	2
Intermediate	248,000	58
Glacial	86,000	20

Sources: DIRS 169734-BSC 2004, pp. T6-29 and T6-30, and Figure 2-4 of this Analysis of Postclosure Groundwater Impacts.
a. The percentage total does not sum to 100 percent due to rounding of the individual percentage values.

The data linked well with global circulation patterns and orbital parameters, thus demonstrating the cyclic nature, *process*, timing, and potential drivers of past climate. The climate proxy data suggest the following (from DIRS 169734-BSC 2004, p. 6-52):

- Numerous climate states occurred during the last 500,000 years ranging from warm interglacial periods (modern climate) to cool or cold and wet glacial periods. The half-million-year span contained glacial periods of different magnitudes ranging from cold and very wet to cool and dry. The maximum temperature during the glacial states of 20,000 to 22,000 years ago is estimated to have been between 4 and 8 degrees Celsius (7 to 14 degrees Fahrenheit) colder than present, with a mean annual precipitation between 1.8 to 2.4 times that of present. This glacial period is considered to have been cool and dry compared with previous glacial periods.

- Past climate states contained periods of high variability with warmer periods occurring in glacial states and cool episodes occurring in warm climate states.

- The modern climate has less *effective-moisture* compared with other climate states.

- Past climates resulted in infiltration and percolation within Yucca Mountain.

2.2.2 PALEOHYDROLOGY

Concurrent with its evaluation of paleoclimates, DOE evaluated paleohydrologic evidence. This evaluation of ancient hydrologic conditions in the region of Yucca Mountain has, like the paleoclimatic data, provided insight for assessing the long-term performance of the proposed repository. The paleoclimatology studies described above identified periods of higher effective-moisture (compared with modern conditions) that dominated the last 425,000 years. Similarly, the paleohydrology studies have shown that the low groundwater levels of today might be typical for only the relatively short, drier interglacial periods and that the water table has been higher in the past and would likely rise during future glacial cycles.

The higher effective-moisture of past climate states resulted in the Death Valley region's lakes, perennial drainage systems, some large wetlands, and many small seeps and minor wetlands (DIRS 120425-D'Agnese et al. 1999, p. 5). Shallow lakes existed in the Gold Flat, Kawich, and Emigrant basins to the

north and northeast of the Nevada Test Site. Both the Amargosa River and its major tributary, Fortymile Wash, were likely perennial streams helping supply Lake Manly in Death Valley. Cactus Springs, Corn Creek Springs, and Tule Springs, all on the northeast, Las Vegas side of the Spring Mountains, were supported by both groundwater and surface water systems. The higher amounts of recharge in the Spring Mountains and the Sheep Range likely resulted in spring discharge from the alluvial fans at the foot of the mountains (DIRS 120425-D'Agnese et al. 1999, p. 5). This picture of past hydrologic conditions has been obtained through the evaluation of natural features, isotopic data, and mineralogical data, all of which provide evidence of past groundwater levels.

The paleohydrologic information of interest for this Analysis of Postclosure Groundwater Impacts is the identification of areas along potential groundwater flow paths from Yucca Mountain where past conditions may have resulted in groundwater discharge locations not considered in the Section 2.1 discussion of the current groundwater flow system.

2.2.2.1 Ancient Groundwater Discharge Locations

Evidence of ancient, or fossil, spring discharges can take several forms in the southern Great Basin. In areas where water from the lower carbonate aquifer fed the springs, fossil spring deposits are in the form of calcite that forms tufa mounds, travertine terraces, and stratiform deposits. These are all calcium carbonate deposits typical of the Ash Meadows basin and eastern Death Valley, where current discharges are from the lower carbonate aquifer. Deposits in Crater Flat and the Amargosa Desert are from discharges of the alluvial aquifer that were derived primarily from volcanic aquifers, and the amount of carbonate materials is less. Based on the evaluation of fossil spring deposits, the water table might have been from 15 to 70 meters (50 to 230 feet) higher during the Pleistocene (the epoch that lasted from about 1.6 million to 10,000 years ago) than at present (DIRS 169734-BSC 2004, p. 8-97). The discussions that follow address the various *paleodischarge* sites found in the Yucca Mountain region. Figure 2-5 depicts these ancient discharge sites.

2.2.2.1.1 *Ash Meadows*

At Devils Hole, evaluation of *calcite deposits* has shown that the water level was more than 5 meters (16 feet) higher than at present between 116,000 and 53,000 years ago, and fluctuated between about 5 and 9 meters (16 to 30 feet) higher than at present during the period between about 44,000 and 20,000 years ago (DIRS 169734-BSC 2004, p. 8-97). Based on the information in Figure 2-4, both of these time periods included extensive periods of the intermediate climate and some periods of the glacial climate. Investigators have found paleodischarge paths lined with calcite deposits in areas up to 14 kilometers (8.7 miles) north and northeast of Devils Hole in the area often referred to as Amargosa Flat (or Peters Playa). Figure 2-5 shows a large shaded area designated as Ash Meadows. Amargosa Flat is the area that extends to the right, or east, at the top (or north) of the shaded area. Intensive searches for these deposits have shown that they occur at scattered, isolated locations on the surface that coincide with known or suspected faults. They have not been found at similar elevations elsewhere within the basin or along its margin. It is believed that the upward hydraulic gradient in the lower carbonate aquifer may have been even greater during the Pleistocene than at present, and that the scattered evidence of paleodischarges in the Amargosa Flats area was due to upflow along the faults (DIRS 169734-BSC 2004, p. 8-98).

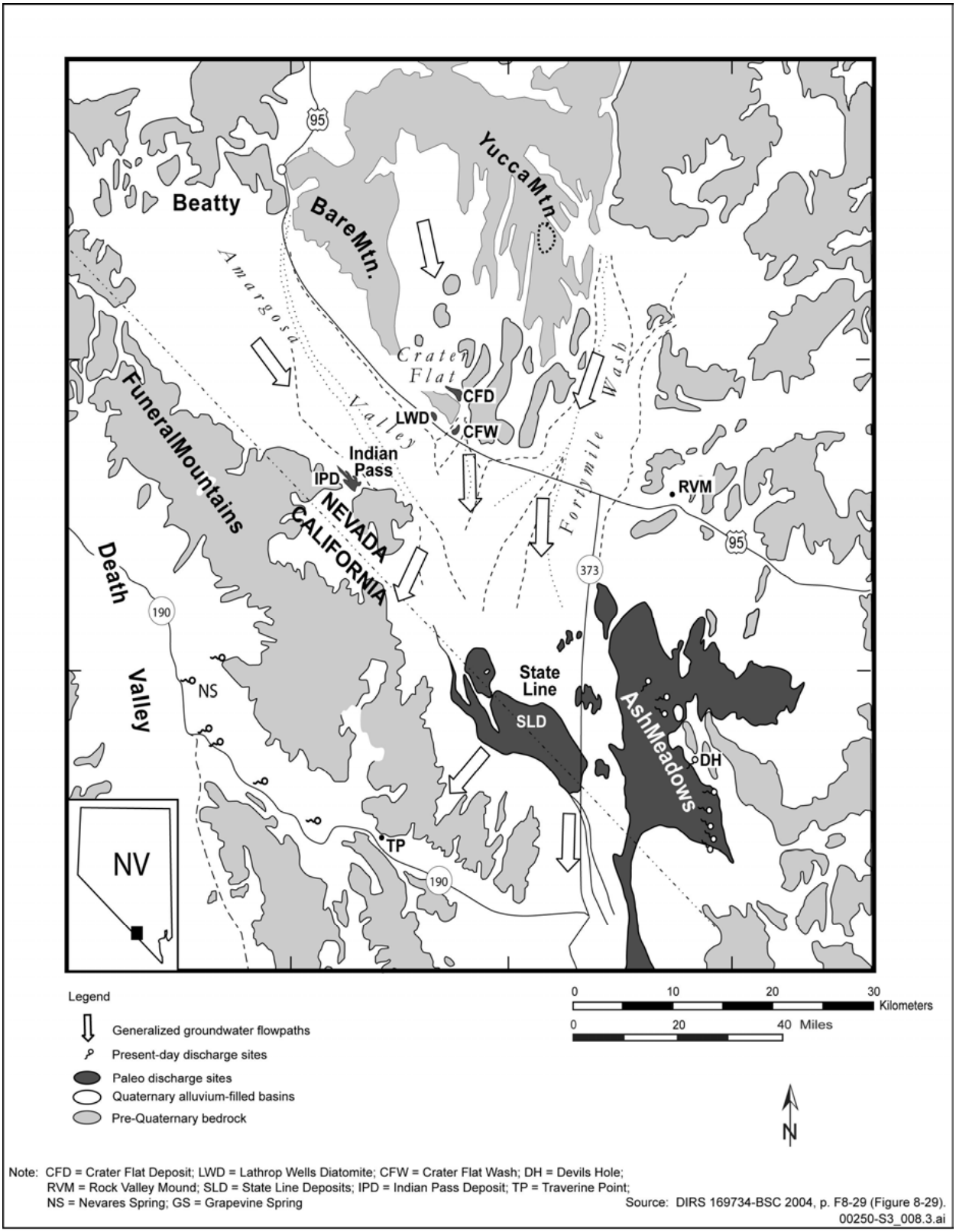


Figure 2-5. Paleodischarge areas in the Yucca Mountain region.

2.2.2.1.2 *Southern Crater Flat Area*

Investigators found deposits from ancient springs on both the north and south side of the unnamed ridge that defines the southern boundary of Crater Flat. This ridge, or band of hills, extends to the southeast from Bare Mountain, almost reaching the hills extending south from Yucca Mountain. On the north side of the ridge, the Crater Flat Deposit occurs at an elevation of about 840 meters (2,760 feet) above present sea level. There are two deposits on the south side of the ridge: The Lathrop Wells Diatomite site occurs at elevations between 790 and 800 meters (2,590 and 2,620 feet) and the Crater Flat Wash deposit occurs at an elevation of about 790 meters.

Evidence of ancient springs at the Crater Flat sites consists of various mineral deposits, casts of insect burrows, and petrified plants. The Lathrop Wells Diatomite site includes a 1- to 2-meter (3- to 7-foot)-thick bed of *diatomite* (a soft, chalk-like sedimentary rock rich in the skeletons of diatoms) that is not present at the other sites (DIRS 169734-BSC 2004, p. 8-98). Efforts to date the spring deposits indicate they formed beginning about 60,000 years ago and continued until about 15,000 years ago. It is estimated that the water table needed to be 17 to 30 meters (56 to 100 feet) higher than at present to support the southern springs and 10 to 70 meters (30 to 230 feet) higher at the Crater Flat site (DIRS 169734-BSC 2004, p. 8-99). The compositions of the spring deposits indicate that water from the volcanic and alluvial aquifers generated them. Possibly, but less likely, the composition of the deposits also suggest that they could have been formed by the lower carbonate aquifer (DIRS 169734-BSC 2004, p. 8-100). Current groundwater temperatures in the area indicate there may be upward contributions from the lower carbonate aquifer, possibly along faults in the local area. Thus, there could have been similar contributions in the past.

2.2.2.1.3 *State Line Deposits*

Ancient spring deposits similar to those at the Crater Flat sites occur along the Nevada-California state line, adjacent to the south end of the Funeral Mountains. The general area starts about where the Amargosa River first enters California, and continues to the southeast to the area where Fortymile Wash joins the riverbed. The present water table is shallow along this reach of the river, which is consistent with it being identified in Section 2.1.1.1.2 as an area with notable evapotranspiration losses. Carbonate-capped terrace deposits indicate that ancient spring discharges occurred as much as 6 meters (20 feet) above the river bottom. Dating of the deposits indicate these high elevation discharges occurred for a span of 30,000 to 50,000 years. Other samples indicate deposit ages as old as 100,000 years and as young as about 10,000 years. These findings are consistent with the belief that the Amargosa River was a major contributor to Lake Manly in Death Valley (Section 2.2.1.2) and appear to show an interplay of surface flow and spring discharge (DIRS 173179-Belcher 2004, p. 158) in a large area where flow from Fortymile Wash joined the Amargosa River.

As with the Crater Flat sites, composition of the State Line deposits indicate water from the volcanic and alluvial aquifers generated them. Possibly, but less likely, the lower carbonate aquifer could have formed the spring deposits (DIRS 169734-BSC 2004, p. 8-100).

2.2.2.1.4 *Indian Pass*

A final location of ancient spring discharge in the vicinity of Yucca Mountain is near the toe of the northeast-facing slope of the Funeral Mountains. This site, designated the Indian Pass deposit, occurs at

an elevation of 780 meters (2,560 feet) above sea level and has deposits similar to those at the Crater Flat sites, including being of the same general age.

2.2.2.1.5 *Other Paleodischarge Locations*

Evidence of other ancient lakes and discharge locations within the Death Valley regional groundwater flow system, some of which are mentioned in Section 2.2.2 above, is not addressed further. These other locations are too far removed from potential groundwater flow paths from Yucca Mountain to be relevant to the discussion. For example, the shallow lakes described in Section 2.2.2 that existed in the Gold Flat, Kawich, and Emigrant basins to the north and northwest of the Nevada Test Site are well away from flow paths from Yucca Mountain. Were those lakes to reform during a future, wetter climate, they would not be affected by any contaminants migrating in groundwater away from Yucca Mountain. Similarly, there are wetland deposits in Pahrump Valley (DIRS 173179-Belcher 2004, p. 158) that suggest the area could have surface water in future climates, but that area would not receive groundwater flow from beneath Yucca Mountain.

2.2.2.2 Ancient Groundwater Flow Paths

Groundwater conditions in the vicinity of Yucca Mountain have been modeled several times under different climate scenarios. A focus of earlier efforts was to determine the potential effects of different climate scenarios on the height of the water table at Yucca Mountain and whether the proposed repository might be threatened (DIRS 169734-BSC 2004, p. 8-103). This concern was addressed in the Yucca Mountain FEIS (DIRS 155970-DOE 2002, pp. 3-59 and 3-60) and the Repository SEIS (DIRS 180751-DOE 2008, pp. 3-44 and 3-45) and will not be addressed in this document. The USGS used the regional flow system model of the time to address different climate scenarios (DIRS 120425-D'Agnese et al. 1999, all), but in this case, the goal was to assess the potential impacts on the flow system. The simulation of interest to the current discussion was based on climatic conditions of approximately 21,000 years ago and was intended to represent cooler and wetter conditions during the late Pleistocene under a full glacial condition. This section addresses specific findings from that simulation.

The USGS modeled the cooler and wetter climate of 21,000 years ago primarily by changing the distribution and rates of groundwater recharge over the model grid (DIRS 120425-D'Agnese et al. 1999, p. 1). Results from the climate-change simulation were evaluated by several means, one of which was the comparison of simulated discharge areas with paleodischarge sites. The model results indicated there would have been sufficient groundwater to maintain paleolake levels in the northern parts of the regional flow system and for Lake Manly in Death Valley, and that groundwater discharges occurred at most of the paleodischarge sites. A few exceptions occurred along the east side of the flow system. For example, in Indian Springs Valley, there is evidence of paleodischarges and wetlands in a large area extending north from the present community of Indian Springs. The model failed to identify discharges in this area except for springs closest to the Spring Mountains near the present-day Indian Springs and Cactus Springs (DIRS 120425-D'Agnese et al. 1999, p. 22). The paleodischarge areas closest to Yucca Mountain, however, were reasonably well duplicated, and the simulation is considered a valid representation of paleoclimatic and paleohydrologic conditions.

In conclusion, the model simulation resulted in a raised water table with a potentiometric surface shaped very similar to that for present conditions (DIRS 120425-D'Agnese et al. 1999, p. 1). This means the groundwater flow paths under the simulated past climate condition were basically the same as for the

present day. In addition, the potentiometric surface configuration also predicted surface discharges that match well with identified paleodischarge sites, providing additional confidence in the results. The locations of the primary recharge areas (the mountains) and the regional sink (Death Valley) are the same as at present, further supporting a conclusion that flow paths were not significantly different.

For these reasons, DOE reached the following conclusions with respect to which paleodischarge sites would be in the flow path from Yucca Mountain:

- Ash Meadows. Devils Hole, the other springs within Ash Meadows, and the area of Amargosa Flat (or Peters Playa) are all east of the current flow paths from Yucca Mountain. As a result, the identified paleodischarge locations within the general area of Ash Meadows would not be potential discharge locations for groundwater from beneath Yucca Mountain. Similar to current conditions, water from the lower carbonate aquifer rising to or near the surface in this area resulted in a higher potentiometric surface, or head, in this area, which affected flow paths from Yucca Mountain by keeping the primary paths to the west, closer to the Amargosa River.

- Southern Crater Flat Area. As with the fossil spring deposits of the Ash Meadows area, the Crater Flat sites are not within the current flow paths from Yucca Mountain, and it appears they were not in the flow path in past times when groundwater levels were higher. The groundwater flow path from beneath Yucca Mountain is to the southeast, then basically beneath Fortymile Wash and southward. At its closest, Fortymile Wash is approximately 10 kilometers (6 miles) to the east of the Crater Flat sites.

- State Line Deposits. The State Line fossil spring deposits are in the area where Amargosa River and Fortymile Wash join. This area is in the flow path of groundwater from beneath Yucca Mountain. Both the river and the wash were likely perennial streams during the last glacial period. The USGS's modeling effort characterized the area bracketed by the confluence of the two streams as a potential wetland area (DIRS 120425-D'Agnese et al. 1999, p. 18). The USGS's simulation also described the southern part of Fortymile Wash as being a gaining stream (DIRS 120425-D'Agnese et al. 1999, p. 22), meaning groundwater contributed to its flow. Based on a figure provided in the USGS's report that shows the distribution of drains and constant head cells in the past climate simulation (DIRS 120425-D'Agnese et al. 1999, p. 23), it appears that under the simulation, the gaining portion of the stream extended as far as about 20 kilometers (12 miles) upstream (to the north) from where Fortymile Wash joins Amargosa River.

- Indian Pass. The fossil spring deposits at Indian Pass are located directly southwest, across the Amargosa Desert from the Crater Flat sites. Being even further west of Fortymile Wash than the Crater Flat sites, the Indian Pass site is not within the groundwater flow path from Yucca Mountain.

As identified in the preceding statements, it appears that of the fossil springs, or paleodischarge sites, identified in the vicinity of Yucca Mountain, only the State Line site would be within the groundwater flow path from beneath Yucca Mountain. As a result, this discharge area, along with the southern reach of Fortymile Wash, would be locations where groundwater contaminants originating in the proposed repository could surface under a future cooler and wetter climate.

2.3 Numerical Modeling of the Regional Groundwater Flow System

2.3.1 PREVIOUS WORK

Groundwater modeling efforts in the Death Valley region began more than 20 years ago and have resulted in a succession of models with increasingly more realistic representations of the groundwater flow system. DOE has supported the development of these models for use at the Nevada Test Site and Yucca Mountain to address the complex water resource issues in the region. This section describes some of the earlier efforts and how they contributed to the most recent flow model, the *Death Valley Regional Ground-Water Flow System, Nevada and California – Hydrogeologic Framework and Transient Ground-Water Flow Model*. The primary source of information for this section is the USGS report of the same title (DIRS 173179-Belcher 2004, all), and the USGS developed many of the models described.

Results from a series of modeling efforts were published from 1982 to 1995. Two models were developed, one in 1982 and one in 1984, to simulate groundwater systems of the Nevada Test Site and Amargosa Desert, respectively. In 1984, another model was constructed to address the Nevada Test Site and vicinity. All of these were two-dimensional models and each had notable shortcomings; common to each was the inability to reproduce adequate simulations of vertical flow components. In 1987, results of a more sophisticated, quasi-three-dimensional model of the Nevada Test Site regional groundwater flow system were published. This 1987 model consisted of two aquifer layers: the uppermost layer represented a shallow aquifer—for example, volcanic rocks or basin-fill deposits—and the lowermost layer represented a deep aquifer composed of carbonate and volcanic rocks. Although this model represented the Nevada Test Site flow system more accurately than the earlier models, analysis of the model indicated that small changes in recharge or discharge rates generally produced substantial changes in the simulated magnitude and direction of groundwater flow (DIRS 173179-Belcher 2004, p. 14).

Results were published from another model in 1995. In this case, the model was a regional-scale numerical model of the carbonate-rock province of the Great Basin. The conceptual model of the groundwater flow system behind this numerical model was one of relatively shallow components where groundwater moved from mountain ranges to basin-fill deposits in adjacent valleys, as well as a deeper component where groundwater moved through the carbonate rocks. This conceptual model of the groundwater flow system is the basis for subsequent numerical models of the Death Valley regional groundwater flow system.

The more recent efforts have consisted of three-dimensional groundwater flow models, which allowed for a better representation of the spatial and process complexities and heterogeneities of the hydrogeologic system. The efforts have incorporated a three-dimensional hydrogeologic framework model into the groundwater flow model. The hydrogeologic framework model is a digital, computer-based description of the geometry and composition of the hydrogeologic units that are internal to the volume encompassed by the groundwater flow model. This framework provides the basis for assigning the hydrologic properties that directly affect groundwater movement in the groundwater flow model. For example, the hydrogeologic framework model (or a specific unit within that model) provides the initial spatial bounds for a permeability parameter assigned to the model and which can later be modified or adjusted in the flow analysis and calibration. Modeling efforts in this group include a 1996 effort by IT Corporation for the Nevada Test Site and centered on the Nevada Test Site, a 1997 effort for the region around Yucca Mountain, and a 2002 effort that merged elements of the other two models (DIRS 173179-Belcher 2004,

p. 15). The remaining portion of this section briefly describes these three modeling efforts. Also described is a specific application of the 1997 model.

The 1996 modeling effort by IT Corporation for the Nevada Test Site was undertaken to estimate hydrologic and *radionuclide attenuation* properties of the rocks through which radionuclides related to nuclear weapons testing might migrate (DIRS 173179-Belcher 2004, p. 15). It included a geologic model with a 2,000-meter (4,920-foot) horizontal grid, with 20 vertical layers of varying thickness, and extending from land surface to 7,600 meters (25,000 feet) below sea level. Twenty hydrogeologic units were modeled. This was integrated into a three-dimensional, *steady-state* flow model. The model domain encompassed 17,700 square kilometers (6,830 square miles) that centered on the Nevada Test Site and extended west to east from Death Valley to the East Pahranagat Range, and north to south from the southern Railroad Valley to the Black Mountains. DOE also used the model for estimating the amount of water moving through the flow system and associated uncertainties, and for supplying boundary conditions for more detailed models of underground testing areas.

The 1997 modeling effort for the Yucca Mountain Project included a geologic model with a 1,500-meter (6,560-foot) horizontal grid, with variable vertical thickness, and extending from land surface to 10,000 meters (32,800 feet) below sea level. Ten hydrogeologic units were modeled. This was integrated into a three-dimension, steady-state flow model. The model domain encompassed 70,000 square kilometers (27,000 square miles) that centered on Yucca Mountain and the Nevada Test Site and extended west to east from Death Valley to the East Pahranagat Range, and north to south from Cactus Flat to the Avawatz Mountains. The three-layer flow model supported analysis of interactions between the relatively shallow, local and subregional flow paths and the deeper, regional flow paths of the lower carbonate aquifer (DIRS 173179-Belcher 2004, p. 15).

The USGS, in cooperation with DOE, subsequently used the 1997 model to assess the potential effects of past and future climates on the regional flow system. This effort involved the simulation of flow system conditions during the full glacial climate of 21,000 years ago, as well as during future conditions under a scenario involving a doubling of atmospheric carbon dioxide (DIRS 120425-D'Agnese et al. 1999, p. 1). Section 2.2.2.2 describes this modeling effort and results.

In 2002, the hydrogeological framework models from the 1996 and 1997 efforts were merged. This resulted in a single, integrated hydrogeologic framework model for use with a steady-state, prepumping flow model. The three-dimensional flow model incorporated a nonlinear least-squares regression technique to estimate aquifer-system parameters. This model was designated the Death Valley regional groundwater flow system prepumping model, and its lateral boundaries were slightly larger than those of the 1997 model. This model provided a reasonable representation of prepumping conditions for the regional flow system and was an improvement over previous models; however, important uncertainties and model errors remained (DIRS 173179-Belcher 2004, p. 17).

The current USGS model of the Death Valley regional groundwater flow system, published in 2004, builds upon these previous efforts.

2.3.2 DEATH VALLEY REGIONAL FLOW SYSTEM MODEL (2004)

In 1998, the USGS began a 5-year project to develop an improved groundwater flow model of the Death Valley regional groundwater flow system. This project was in support of both the Nevada Test Site and

Yucca Mountain Project and was largely funded by DOE. However, because of the model's potential use in dealing with a wide range of regional water resource issues, several other agencies contributed financially to the work, including Nye County in Nevada, Inyo County in California, the National Park Service, the U.S. Fish and Wildlife Service, and the U.S. Air Force (DIRS 173179-Belcher 2004, p. iii). The initial objectives of this effort included development of the steady-state model representing prepumping conditions (see above). The goal of this project was to provide a starting point for the calibration of a transient groundwater flow model (DIRS 173179-Belcher 2004, p. 7). Ultimately, the model was intended to be used for the following (DIRS 173179-Belcher 2004, pp. 7 and 8):

- Providing the boundary conditions for the site-scale models at Yucca Mountain and Corrective Action Units at the Nevada Test Site;
- Evaluating the impacts of natural or human-induced changes in system *flux*;
- Providing a technical basis for decisions on the quantity of water available for development on the Nevada Test Site;
- Determining the potential effects of increased offsite water use on Nevada Test Site water supplies;
- Providing a framework for determining effective groundwater quality monitoring locations; and
- Facilitating the development of a cooperative, regional Death Valley groundwater management district.

The 2004 Death Valley regional groundwater flow system model was constructed with 16 layers and a horizontal grid with cells 1,500 meters (6,560 feet) on a side. The total model domain has 194 rows and 160 columns and is essentially the same as the 2002 prepumping model described in Section 2.3.1. The hydrogeologic framework model component includes the geometries of 27 hydrogeologic units that include (from youngest to oldest) (DIRS 186227-USGS 2006, p. 2):

- Cenozoic basin-fill and playa deposits (making up local aquifers and confining units depending on the characteristics of the deposits);
- Cenozoic volcanic rocks (making up aquifers and confining units depending on their physical properties);
- Cenozoic and Mesozoic intrusive igneous rocks (making up local confining units);
- Mesozoic sedimentary and volcanic rocks (making up aquifers and confining units depending on their physical properties);
- Paleozoic carbonate rocks (main regional aquifer);
- Paleozoic to Late Proterozoic sedimentary rocks (main regional confining unit); and
- Proterozoic igneous and metamorphic rocks (regional confining unit, generally forming the bottom of the flow system).

Investigators tested and calibrated the Death Valley regional groundwater flow system model by performing and repeating simulations with adjusted input parameters until water-level and spring-flow values simulated by the model matched the corresponding measured values. The input parameters adjusted during this process included values for parameters of the hydrogeologic units, and recharge and discharge amounts and locations. The model was first calibrated for steady-state groundwater levels developed for prepumping conditions (that is, for conditions before groundwater pumping began in the region in 1913). The model was then calibrated for transient conditions using values for water level, spring flows, evapotranspiration, and pumping as they changed over time from 1913 to 1998 (DIRS 186227-USGS 2006, p. 3).

Results from the model simulations indicated that modeled groundwater flow matched well with inferred groundwater flow patterns throughout the model domain. Simulated groundwater levels generally matched measured water levels except in areas where the water levels change rapidly over a short distance. Areas with this steep hydraulic gradient condition include Indian Springs, western Yucca Flat, and the southern part of the Bullfrog Hills. Water level declines from the transient simulations generally matched those declines observed in Pahrump Valley, Amargosa Desert, and Penoyer Valley. The model also adequately simulated observed spring flow declines in Pahrump Valley during the last century. Finally, the hydrologic parameters of the hydrogeologic units that define the ability of the unit to transmit and store water, and that were adjusted during the calibration process, ended at values within the range of values measured in the field (DIRS 186227-USGS 2006, p. 5).

Section 2.4 of this Analysis of Postclosure Groundwater Impacts provides an overview of the extensive modeling done to evaluate the potential impacts of the proposed repository. The discussion focuses on the movement of water through the *unsaturated zone* at Yucca Mountain (including through the horizon of the proposed repository), into the saturated zone beneath the repository location, and away from Yucca Mountain in the hydraulically downgradient direction. DOE used site-scale models to simulate water movement in the unsaturated and saturated zones at Yucca Mountain and downgradient past the location of the *accessible environment*, as defined by regulation (Section 2.4.3.1). Because these site-scale models were developed to simulate a much smaller area than the regional models, they could be developed at much finer detail. Evaluations for this Analysis of Postclosure Groundwater Impacts required that output from the site-scale saturated zone flow model be input to the regional model to evaluate potential impacts from the repository to locations beyond the accessible environment. This involved using the site-scale saturated zone model to track a group of simulated particles from beneath the repository to the boundary of the accessible environment. The distribution of particles from this site-scale model simulation was then input to the regional model, and the particle tracking function was again used to develop simulated flowpaths beyond the accessible environment boundary. The site-scale and regional models can support this action, but transition to the coarser level of detail inherent in the regional model has certain limitations.

DOE has high confidence in the site-scale saturated zone flow model for use in evaluating potential repository impacts. The model includes a horizontal grid with cells 250 meters (820 feet) on a side and 67 layers of varying size or depth in the vertical direction. For comparison, the most recent regional model has a 1,500-meter (4,920-foot) grid size and 16 layers (DIRS 186186-SNL 2009, p. 34). One can visualize the effect of the differences in these model construction parameters in terms of the hydrogeologic framework models. The site-scale and regional models can have the same physical information describing the positions of applicable hydrogeologic units. However, in the regional model, the hydraulic conductivity for an entire cell (defined by one grid in the horizontal plane and one model

layer) is represented by a single geometric mean value calculated from whatever hydrogeologic units are within that cell. Therefore, depending on what units are present, some detail can be lost through the averaging process. In the horizontal plane, the 250-meter grid of the site-scale model offers a resolution that is 36 times finer than the regional model (DIRS 185814-DOE 2008, p. 2.3.9-22).

In the evaluations Chapter 3 describes, the regional model was sometimes used in simulations similar to those for which the site-scale model was used. Variation in model results are recognized and expected; these differences are attributed primarily to the coarse scale of the regional model in comparison with the site-scale, but can also be attributed to the overall purposes for which both models were originally constructed. The regional model was constructed to support simulations from which regional conclusions might be drawn. In some cases, evaluations described in Chapter 3 are based on efforts to use the regional model to define characteristics of discrete flow paths within a small portion of the region. These efforts are within the general capabilities of the model, but the results need to be taken in context of the model's intended use, the relative coarseness of the model structure, and uncertainties inherent to the modeling process.

2.4 Modeling of Yucca Mountain Infiltration, Groundwater Movement, and Impacts as Described in the Repository SEIS

This section discusses the basis for the groundwater modeling presented in Chapter 3. The discussion is primarily in terms of the modeling associated with the Repository SEIS but also includes how that effort fits with the regional model the USGS developed. Chapter 3 discusses the specific ways in which the current evaluation used the existing models.

The Repository SEIS described results from the *Total System Performance Assessment Model/Analysis for the License Application* (DIRS 183478-SNL 2008, all), or TSPA-LA, which was used to assess long-term repository performance in terms of a characterization of radiological dose to humans over time. The configuration of the TSPA-LA model provided a framework for the incorporation of information from various *process models* and *abstraction model*s into an integrated representation of the important features, events, and processes that apply to the repository system, including engineered and natural *barriers*. Figure 2-6 provides an overview of the principal model components and submodels that were integrated into the TSPA-LA model.

Process models (large, complex computer models) provided information to the TSPA-LA model and included representations of such features as thermal-hydrologic conditions, degradation characteristics of the *Engineered Barrier System*, and unsaturated and saturated zone flow fields. The process models were based on fundamental laboratory and field data. Abstraction models are generally simpler than the process models, possibly consisting of nothing more than a simple function or table of numbers, but usually representing the results from a much more detailed process model. The TSPA-LA model functioned by handing off data from one subsystem to the next along the primary release path and allowing an assessment of behavior at intermediate points. The integration performed by the TSPA-LA model occurred in a Monte-Carlo simulation-based method to create multiple random combinations of the likely ranges of parameter values for the process models. In this manner, the TSPA-LA model computed

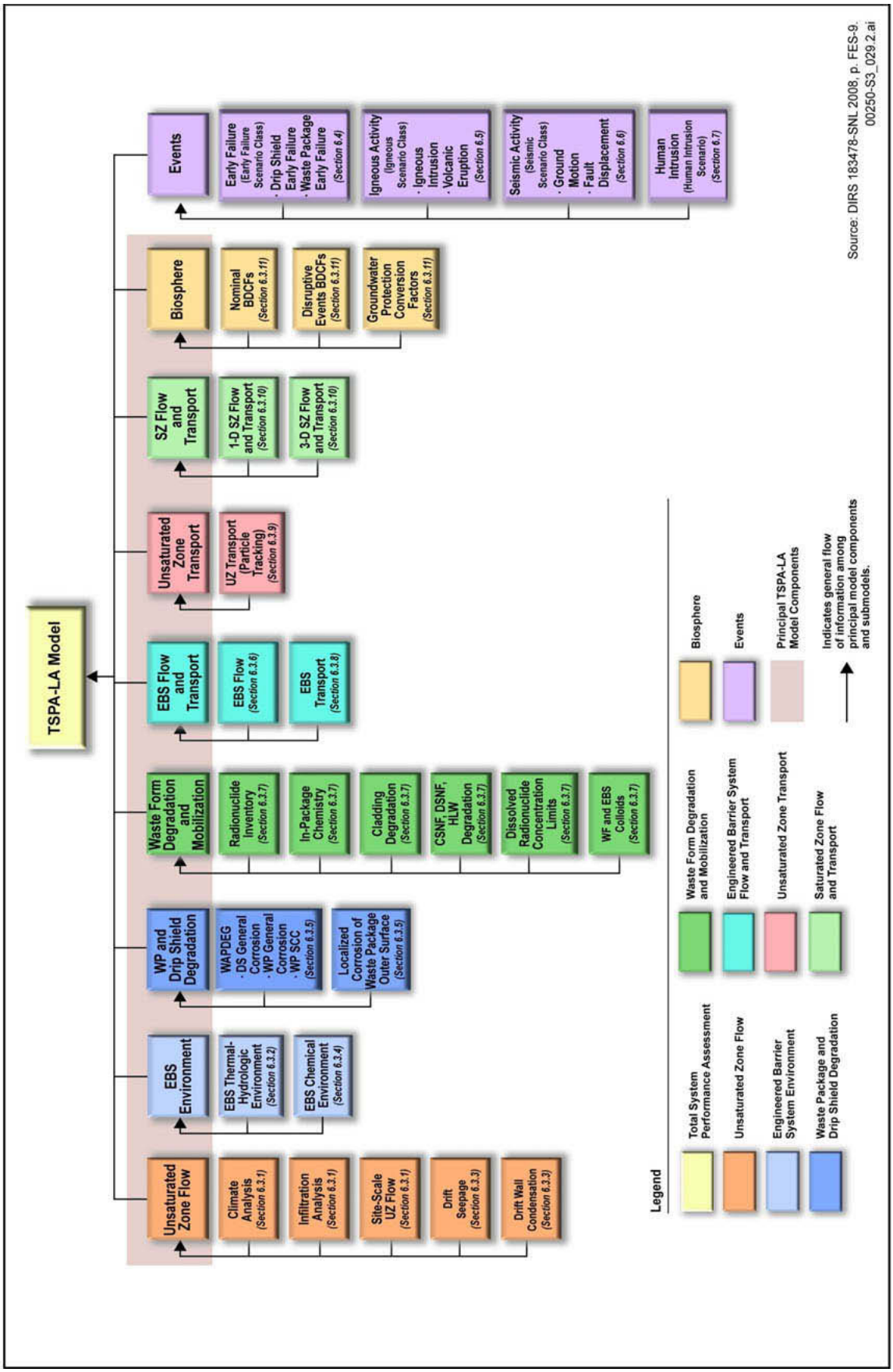


Figure 2-6. TSPA-LA principal model components and submodels.

the probabilistic performance of the entire waste *disposal* system, and the result reflected an appropriate range of process behaviors or parameter values, or both, of the inherently variable Yucca Mountain Repository system (DIRS 183478-SNL 2008, p. ES-7). Performance was measured in terms of radiological dose to the RMEI located at a distance of approximately 18 kilometers (11 miles) south of the repository, which is the predominant direction of groundwater flow (DIRS 180751-DOE 2008, p. F-4). The TSPA-LA model evaluated the following nine major elements of the Yucca Mountain Repository (DIRS 183478-SNL 2008, pp. ES-8 and FES-9):

- Water flow from the ground surface through the unsaturated tuffs above and below the repository horizon, which would include water that dripped into the waste *emplacement drifts*;
- Thermal and chemical environments in the Engineered Barrier System, effects of disruptive events on that system, and perturbations to the surrounding natural system due to waste emplacement;
- The degradation of the engineered components that would contain the *radioactive* wastes;
- The degradation and dissolution of the waste forms and the release of radionuclides from the waste packages;
- The release of radionuclides from the Engineered Barrier System to the unsaturated zone below the repository;
- The migration of these radionuclides through the unsaturated zone below the repository to the saturated zone;
- The migration of these radionuclides from beneath the repository and downgradient through saturated rocks and alluvium to the RMEI;
- Arrival of the radionuclides at the *biosphere* and their potential uptake by humans at the RMEI location, which could lead to a radiation dose consequence; and
- Disruptive events such as igneous activity, *seismicity*, and human intrusion (drilling).

The remainder of this section briefly describes how the TSPA-LA modeled the movement of water through the various model components. This section mentions other elements of the repository system that interacted with the modeling of water, but the focus of the discussion is the water as it infiltrates, through the unsaturated zone, reaches the groundwater, and moves away from Yucca Mountain. Appendix F of the Repository SEIS (DIRS 180751-DOE 2008, all) contains additional summary information on other elements of the repository, as well as on the water. DOE's report on the TSPA-LA (DIRS 183478-SNL 2008, all) provides more detail on the model of the entire repository system.

2.4.1 INFILTRATION AT YUCCA MOUNTAIN AND MOVEMENT THROUGH THE UNSATURATED ZONE

This section discusses how the TSPA-LA model treated infiltration and the movement of infiltrating water through the unsaturated zone.

2.4.1.1 Infiltration

The initial water input into the TSPA-LA model is from the site-scale unsaturated zone flow model, which incorporates infiltration at ground surface above the proposed repository location. This infiltration is the precipitation that is not lost to evapotranspiration, runoff, or change in the amount held in the soil or rock, and makes it into the unsaturated zone flow system. Modeling of infiltration for the TSPA-LA model was much different than that used in the TSPA model as described in the Yucca Mountain FEIS. As the Repository SEIS, Appendix F described (DIRS 180751-DOE 2008, pp. F-7 to F-9), the TSPA-LA model used a new infiltration model to increase confidence in the model's performance. The manner in which climate variation was addressed during the post-10,000-year period was changed significantly to meet requirements proposed by the NRC in changes to Title 10 of the Code of Federal Regulations (CFR) 63.342(c) [Volume 70 of the *Federal Register* (FR) 53313, September 8, 2005].

The TSPA-LA considered infiltration scenarios for three specific climates for the first 10,000 years after *closure*: present day (or interglacial), monsoon, and glacial transition (or intermediate). For each of these climates, there was a set of four infiltration rates that represented 10th-, 30th-, 50th-, and 90th-percentile values, which allowed the model to incorporate infiltration rate uncertainty. In modeling the first 10,000 years, the TSPA-LA used the present-day climate for the period from 0 to 600 years; the monsoon climate for the period from 600 to 2,000 years; and the glacial-transition climate for the period from 2,000 to 10,000 years (DIRS 180751-DOE 2008, p. F-8).

The rate of percolation at the repository horizon for the post-10,000-year period was specified by the proposed changes to 10 CFR 63.342(c)(2) (70 FR 53313, September 8, 2005). The proposed rule directed that DOE represent the effects of climate change after 10,000 years by assigning percolations rates at the repository horizon that vary between 13 and 63 millimeters (0.5 and 2.5 inches) per year. DOE implemented this direction by defining the new, temporally averaged climate in the same terms as it used for the three pre-10,000-year climates.

It should be noted that since the Repository SEIS and license application were submitted, the EPA issued a final rule (73 FR 61256, October 15, 2008) governing the post-10,000-year period. The NRC thereafter issued a final rule (74 FR 10811, March 13, 2009) revising 10 CFR Part 63 to implement the EPA's revision. The final NRC rule revised the deep percolation rate to be used in modeling the post-10,000-year climate slightly upward from that contained in the earlier proposed rule and which was used in the license application. In particular, the NRC's proposed rule permitted DOE to represent future climate change in the performance assessment by sampling constant-in-time deep percolation rates from a log-uniform distribution with a range of 13 to 64 millimeters (0.5 and 2.5 inches) per year and an average arithmetic mean of 32 millimeters (1.3 inches) per year. By way of comparison, the NRC final rule slightly raised the average arithmetic mean for the deep percolation rate to 37 millimeters (1.5 inches) per year, while broadening the range of the lognormal distribution to between 10 and 100 millimeters (0.39 and 3.9 inches) per year.

The radionuclide fluxes used for this Analysis of Postclosure Groundwater Impacts were the mean results obtained from the outputs of the TSPA-LA, which were developed in accordance with the NRC proposed rule. Because the NRC Final Rule increased the average arithmetic mean of the deep percolation rate distribution from 32 to 37 millimeters (1.3 to 1.5 inches) per year, one would expect the mean radionuclide flux at the location of the RMEI to show only minor, if any, increase. This conclusion is reflected in the NRC's responses to comments on the proposed amended rule in the *Federal Register*

notice of the Final Rule (74 FR 10811, March 13, 2009): (from page 10820) "… dry-to-wet transients in performance assessments would have less influence on the mean of the distribution of projected doses than on any single projected dose used to construct the distribution. …Performance assessment models and analyses continue to improve; however, dry-to-wet conditions appear to have a limited effect on the mean dose within the constraints of current performance assessment approaches." Therefore, it is unlikely that this slight change in the distribution of deep percolation values would have any significant effect on the mean radionuclide fluxes used in this analysis.

Table 2-4 shows the average infiltration rates the TSPA-LA model used. It is important to note that the rates in the first four rows of the table are the averages over the entire domain of the site-scale unsaturated zone flow model, a larger area than the footprint of the repository. Corresponding infiltration rates over the smaller area of the repository footprint would be slightly larger. As an example, the table also shows infiltration rates for the post-10,000-year period over the repository footprint. These rates are more easily recognized as those proposed by the NRC. The infiltration rate for the post-10,000-year climate is representative of a temporal average that accounts for all four climate conditions expected to occur in the future. As Table 2-4 shows, the post-10,000-year climate is associated with higher infiltration rates than either present-day or glacial-transition climates, which when combined, would account for about 80 percent of the future climate based on paleoclimatology studies described in Section 2.2.1.2 (Table 2-3).

Table 2-4. Average net infiltration and percolation rates (millimeters per year)[a] for each of the climates considered in the TSPA-LA.

Climate	Percentile			
	10th	30th	50th	90th
Infiltration over the unsaturated zone flow and transport model domain[b]				
Present-day (interglacial)	3.03	7.96	12.28	26.78
Monsoon	6.74	12.89	15.37	73.26
Glacial-transition (intermediate)	11.03	20.45	25.99	46.68
Post-10,000-year	16.89	28.99	34.67	48.84
Infiltration over the repository footprint (for comparison)[c]				
Post-10,000-year	21.29	39.52	51.05	61.03

a. To convert millimeters to inches, multiply by 0.03937.
b. Source: DIRS 180751-DOE 2008, p. F-9.
c. Source: DIRS 184614-SNL 2007, p. 6-19.

2.4.1.2 Unsaturated Zone

The TSPA-LA model incorporated numerous process and abstraction models to represent the events that would, or could take place in the unsaturated zone; that is, the zone at Yucca Mountain lying between the surface and the water table, which would include the repository. The various system elements are interwoven as necessary to depict complete processes and often involve effects from or to water moving through the zone. For example, a model simulates a breach in a *drip shield* and in the underlying *waste package* containment, then incorporates water moving down through the unsaturated zone that could dissolve some of the waste material in the repository and carry that material to the saturated zone. DOE developed several models for the area or zone of the mountain where the repository would be located to represent how contaminants could be released. DOE also developed an unsaturated zone flow model to represent the movement of water in this zone. The unsaturated zone transport model was developed to describe the movement of radionuclides through the natural system below the level of the repository (DIRS 180751-DOE 2008, p. F-18).

The site-scale unsaturated zone flow model of the TSPA-LA was designed to represent the rock mass of Yucca Mountain that would be the pathway of water moving down from the surface, past or through the repository, and to the underlying groundwater. Significant observations from study of the unsaturated zone included these facts (DIRS 180751-DOE 2008, p. F-9);

- Water moves in both fractures and the rock *matrix* (the solid, but porous, portion of the rock), but generally moves faster in fractures;
- In some areas, water movement along faults can also be significant;
- Water can collect in locally saturated zones (perched water); and
- Water can be diverted in lateral directions due to differences in rock properties at rock layer interfaces or the presence of features such as perched water bodies.

The unsaturated zone flow model that was part of the TSPA-LA represented these physical features of the unsaturated zone. A primary objective of the unsaturated zone flow model was to generate values for the percolation flux at the water table, where percolation flux was defined as the total vertical liquid mass flux through both fractures (and faults) and matrix, expressed as millimeters (or inches) per year (DIRS 184614-SNL 2007, p. 6-80). The flow model also generated percolation flux values at different locations or layers of the unsaturated zone; at those locations, the model generated estimates of the amount of water moving through fractures, the matrix, and in faults (DIRS 184614-SNL 2007, p. 6-91 to 6-96). This feature was used to characterize the nature and quantities of water that would reach the footprint of the repository and included the ability to generate frequency distribution plots displaying the average percentage of the repository area subject to a particular percolation rate. The infiltration model described above provided the net infiltration boundary condition to the unsaturated zone model. The unsaturated zone model used temporally constant, but spatially variable, infiltration boundary conditions for each climate state and generated three-dimensional flow fields for each of the four boundary conditions represented by the 10th-, 30th-, 50th-, and 90th-percentile infiltration rates for each climate.

At the proposed repository horizon (or repository level), the unsaturated zone flow model integrated with several other models representing processes that would affect the movement of water and transport of radionuclides in or near the unsaturated zone. Some of these other models are described as follows:

- A thermal hydrology model represented the effects that heat generated by the waste would have on water movement near the emplacement drifts. During an initial period after emplacement of the nuclear materials, water and gas in the heated rock would be driven away from the repository drifts. Over time, the thermal output of the material decreases, the rock returns to its normal temperature, and the water and gas flow back toward the repository (DIRS 180751-DOE 2008, p. F-11).
- A seepage flow model characterized how water would move when it reached drift walls. In many areas, the capillary effect at the drift walls would have a barrier effect and cause water to be diverted around the drift. In other areas, hydrogeologic properties would focus water movement and cause a seep into the drift. As infiltration would increase with changing climates, the number and locations of seeps would tend to increase. DOE based the seepage model on measurements from tests in the Exploratory Studies Facility (DIRS 180751-DOE 2008, p. F-10) and designed the model to include *probability distributions* for the fraction of waste packages that could encounter seepage and the seep

flow rate. The model also accounted for parameter uncertainty and spatial variability, and effects caused by such things as drift degradation and the presence of rock bolts.

- Chemical environment models represented the chemistry of seepage water that would move into the drifts as well as the composition of the gas phase in the drifts. Water and gas compositions would be affected by the heat generated by the emplaced waste. The chemistry of the water and gas, which would evolve over time, would affect the potential for *corrosion* of the waste packages and the mobility of radionuclides released from degraded packages.

- An Engineered Barrier System radionuclide transport abstraction model determined the rate of radionuclide releases from the Engineered Barrier System to the unsaturated zone. This conceptual model consisted of a flow model and a transport model (DIRS 177407-SNL 2007, p. 1-1). Input to the flow model included the seepage flux into the drift and the model defined pathways for water flow in the Engineered Barrier System. As described in the Repository SEIS (DIRS 180751-DOE 2008, pp. F-13 and F-14), this flow model addressed eight pathways by which water could move through the drifts, going around or through the drip shields, waste packages, and inverts to the unsaturated zone below the repository. The transport model considered both advective and diffusive transport of radionuclides from a breached waste package and included colloid-facilitated transport (DIRS 177407-SNL 2007, p. 1-1).

There are a number of other models associated with the repository zone and with the behavior of the components of the associated Engineered Barrier System. These included models to address the degradation of waste packages and drip shields over time, as well as the degradation and mobilization of the waste form within the waste packages.

The final element of this discussion is the unsaturated zone transport model, which DOE used to represent the movement of released contaminants from the repository level down to the water table. This model incorporated the flow fields from the unsaturated zone flow model and considered flow through welded and nonwelded tuff and through fractures and the rock matrix. It also accounted for some regions having zeolitic tuffs, which have low permeability and enhanced radionuclide absorption. The model addressed the transport of dissolved species and of colloids, the small particles that can remain suspended in groundwater for indefinite periods and to which radionuclides could sorb.

As described in the Repository SEIS (DIRS 180751-DOE 2008, pp. F-18 and F-19), the five basic processes that would affect the movement of dissolved or colloidal radionuclides, and which are represented in the unsaturated zone transport model, are described as follows:

1. Water flux and advection. The radionuclides are carried along with the water moving through the unsaturated zone. The total water flux and the amount of water moving relatively fast through fractures are significant factors in this transport process.

2. Matrix diffusion. This is the exchange of solute mass (the dissolved radionuclides) between fluid in the fractures and fluid in the rock matrix. Water movement is generally much slower in the matrix than in the fractures and there is more rock surface available for *sorption*. As a result, for water moving through the rock matrix, diffusion can be an efficient retarding mechanism.

3. Sorption. This is the process by which radionuclides are sorbed onto the rock. The various radionuclides have different retardation characteristics; that is, some are sorbed more readily than others. If there is significant matrix diffusion or flow into the rock matrix from the fractures, then there can be significant retardation in the movement of specific radionuclides.

4. Colloidal Transport. Several specific radionuclides could move as, or sorbed onto, colloidal particles. The transport model addresses this mechanism as well as retardation of colloids at fracture-rock matrix interfaces.

5. Radioactive *decay* and ingrowth. As radionuclides move along flow paths in the unsaturated zone, they would decay, and in some cases the decay would be into other radionuclides of potential concern (ingrowth). The model included decay and ingrowth processes for dissolved and colloidal radionuclides.

The output from the unsaturated zone radionuclide transport model provided the rate and spatial distribution of radionuclide releases, which was then the input to the saturated zone flow and transport model.

2.4.2 GROUNDWATER MOVEMENT IN THE SATURATED ZONE

The TSPA-LA modeled the flow of groundwater and the transport of radionuclides within the saturated zone from beneath Yucca Mountain. As with the movement of water and radionuclides in the unsaturated zone, the saturated zone involved both a flow model and a transport model.

DOE developed the site-scale saturated zone flow model to determine the groundwater flow field at Yucca Mountain. This model was designed to have an optimal size for being able to capture flow fields near Yucca Mountain and to assess groundwater flow at distances beyond (but close to) the RMEI location at 18 kilometers (11 miles) from the repository, while still being small enough to incorporate the necessary structural detail and have reasonable computational efficiency (DIRS 177391-SNL 2007, p. 6-3). Figure 2-7 shows the horizontal boundaries of the site-scale saturated zone flow model incorporated by the TSPA-LA. Also shown in the figure, for reference, are nearby surface features.

The site-scale saturated zone flow model received input from the unsaturated zone flow model (described above). The model incorporated geologic and hydrologic data collected from investigations in the Yucca Mountain area and used a three-dimensional numerical grid to describe flow in the saturated zone. The model included flow in the fractured volcanic rock in the areas near Yucca Mountain and in the alluvium of Amargosa Desert, as well as discrete flow features (for example, faults and high- and low-permeability regions) in the fractured tuff units that would affect transport of radionuclides. The calibrated flow field that the site-scale saturated zone flow model generated formed the basis for the site-scale saturated zone transport model (DIRS 180751-DOE, 2008, p. F-20).

The site-scale saturated zone transport model received input from the unsaturated zone transport model in the form of radionuclide mass fluxes at the water table beneath Yucca Mountain. Output from the model was also in the form of radionuclide mass fluxes, but these were at the location of the RMEI where they provided input to the biosphere model, which the next section addresses further. Simulating advection as the principal transport mechanism, DOE used the model to represent the transport of radionuclides, both

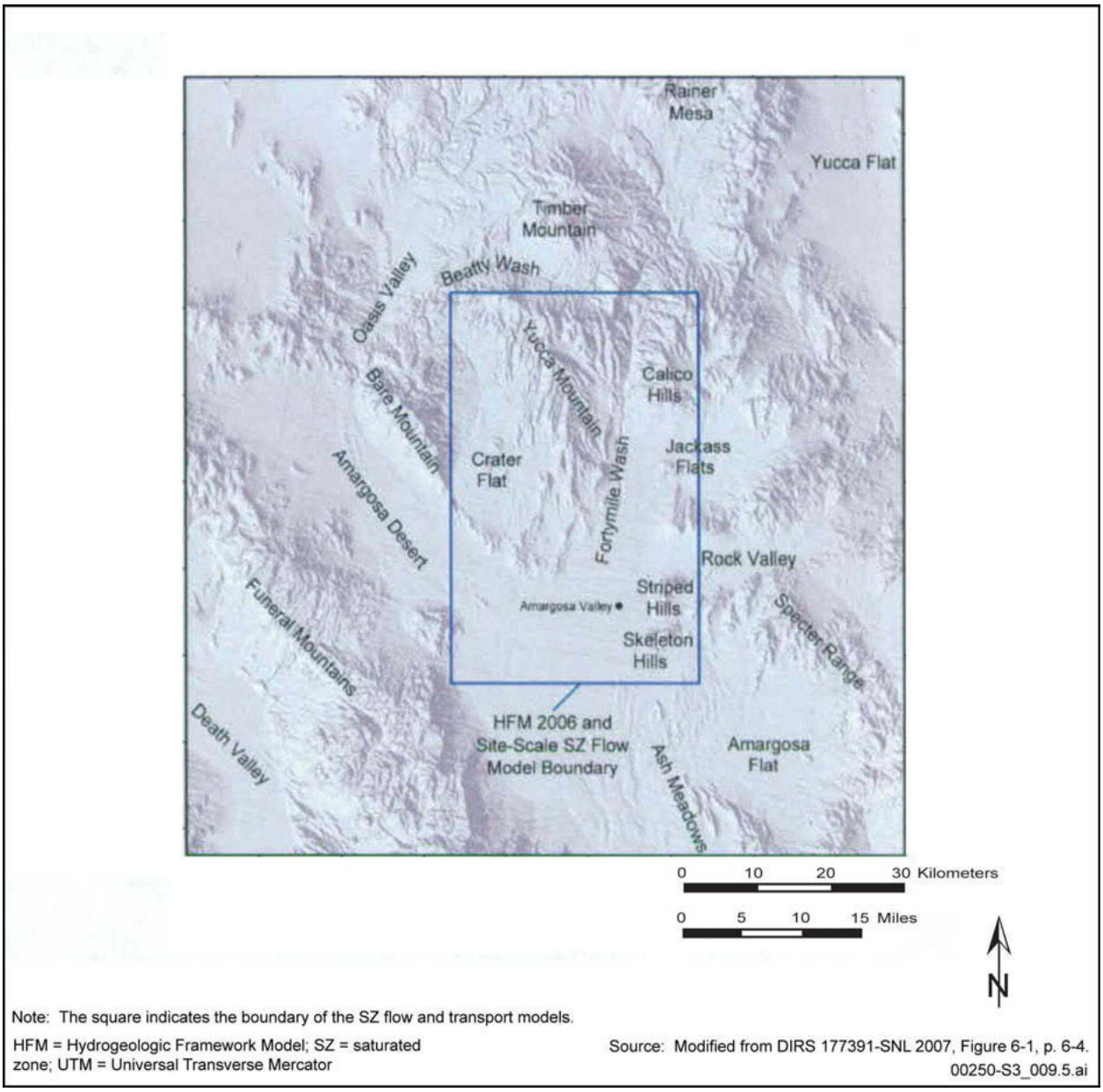


Figure 2-7. Boundaries of the site-scale saturated zone flow model and nearby surface features.

dissolved and sorbed onto colloids, along the groundwater flow path from beneath Yucca Mountain to the southeast, then to the south toward the Amargosa Desert. The model also accounted for the water-rock and water-soil interactions along the flow path. The saturated zone transport model represented transport in the volcanic rock by including flow and advective transport in the fractures and diffusive transport between the fractures and the surrounding rock matrix, where water moves more slowly. Flow at greater distances from Yucca Mountain is primarily through the basin-fill (alluvial) materials, and these were simulated as more uniformly porous materials. A three-dimensional particle-tracking model was the primary transport component of the saturated zone analysis. The particle-tracking model generated a library of breakthrough curves, which determined the timing for radionuclides reaching the accessible environment. During implementation of the TSPA-LA model, output from the unsaturated zone transport model, in the form of radionuclide mass fluxes, was combined with this library of breakthrough curves to

determine the radionuclide mass fluxes at the location of the RMEI where they provided input to the biosphere model, which was developed, as described in Section 2.4.3, to generate estimates of annual radiation exposures, or doses, to the RMEI.

For purposes of the evaluations addressed by this Analysis of Postclosure Groundwater Impacts, it is important to understand that the site-scale saturated zone flow model (and the site-scale transport model) was designed to integrate with the Death Valley regional groundwater flow model, introduced in Section 2.1 above. DOE used the USGS's documentation of that model (DIRS 173179-Belcher 2004, all) as a primary source for describing the regional groundwater flow system. One of the reasons for developing the regional groundwater flow system model was to characterize the groundwater system in the vicinity of the proposed repository at Yucca Mountain and one of the ultimate objectives was to provide target boundary conditions for the site-scale saturated zone model (DIRS 173179-Belcher 2004, p. 7).

Correspondingly, DOE designed the site-scale model to mesh, or nest, within the larger regional model to take advantage of the great amount of regional geologic information. Figure 2-8 shows the domains, or boundaries, of the regional groundwater flow system model and those of the site-scale model inside the larger one. The figure also shows the domains of the site-scale geologic framework model (not discussed in this document) and the unsaturated zone flow model (Section 2.3.1.1).

The vertical scales of the regional groundwater flow system and site-scale models also closely match; both extend from the land surface down to a depth of 4,000 meters (13,000 feet) below sea level and, as applicable, incorporate the same hydrogeologic units (DIRS 177391-SNL 2007, p. 6-29). Examples of ways in which the site-scale flow model incorporated data from the regional groundwater flow system model include the following:

- The regional groundwater flow system model provided the volumetric and mass flow rates through the lateral boundaries of the site-scale model. Specifically, the cell-by-cell fluxes from the regional groundwater flow system model were set as the target values for boundary conditions during calibration of the site-scale model (DIRS 177391-SNL 2007, pp. 6-5 and 6-17).

- The regional groundwater flow system model, as well as other sources, provided the recharge to the site-scale flow model (DIRS 177391-SNL 2007, pp. 6-17 and 6-18).

This discussion of the manner in which the regional groundwater flow system and site-scale models were designed to be integrated and used together is provided as a background for evaluations described in Chapter 3. A primary objective of this Analysis of Postclosure Groundwater Impacts, as stated in the NRC staff Adoption Report, is the evaluation "of the impacts on soils and surface materials from the processes involved in surface discharges of contaminated groundwater." Considering the groundwater flow path from Yucca Mountain, the potential locations of surface discharges are beyond the southern boundary of the site-scale flow model used in the TSPA-LA. To perform this evaluation, the regional groundwater flow system model used output from the site-scale model to develop pathways farther to the south.

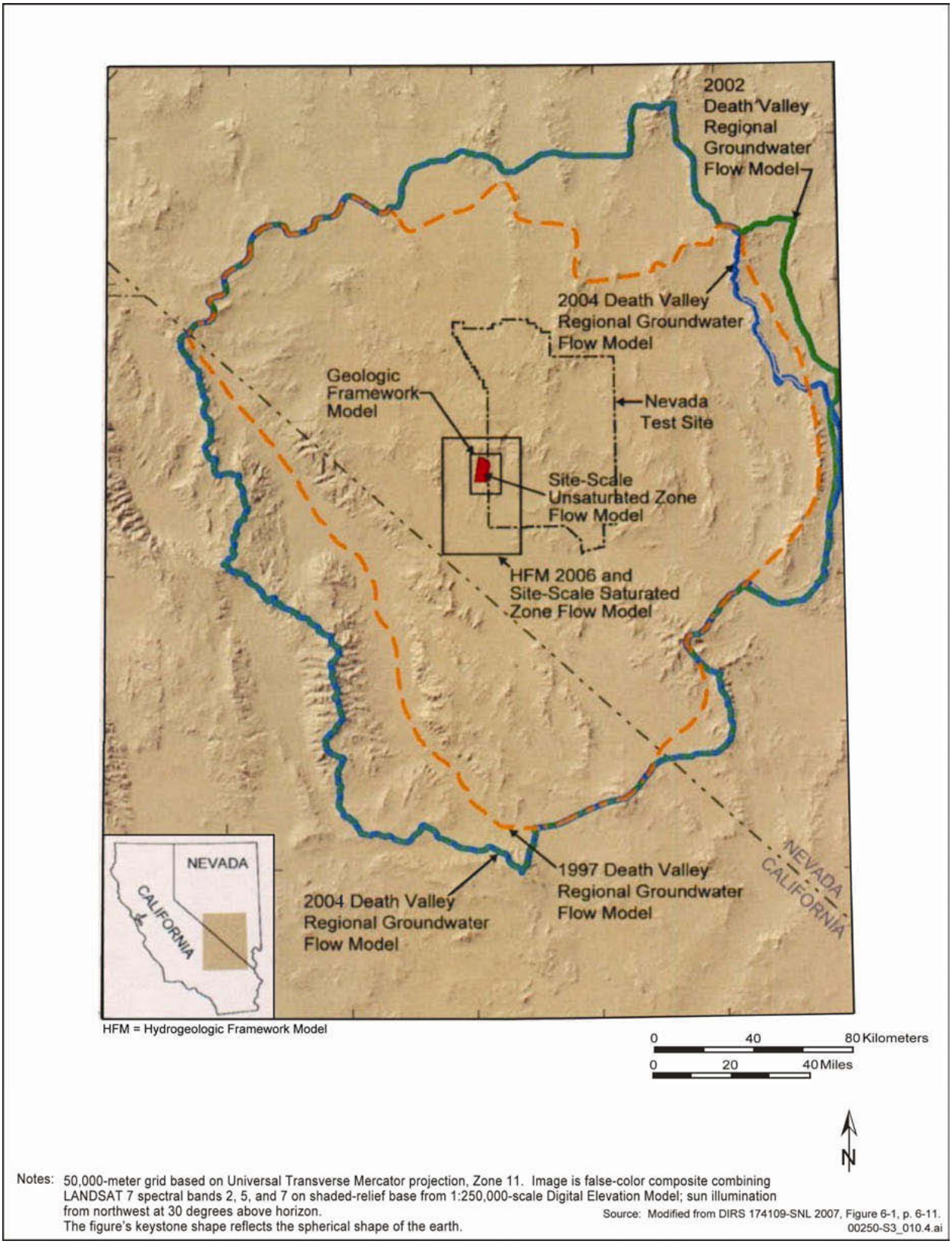


Figure 2-8. Locations of the Death Valley regional groundwater flow system and site-scale saturated zone flow model domains.

2.4.3 GROUNDWATER USE AND EXPOSURES AT THE RMEI LOCATION

DOE used the saturated zone site-scale flow and transport models described in Section 2.4.2 to develop estimates of groundwater flux at the RMEI location and to determine the distribution of travel times for radionuclides released from the repository to reach the RMEI location. This section briefly describes how the TSPA-LA model then derived estimates of radioactive dose to a hypothetical individual at the RMEI location. Key elements of the TSPA-LA methodology included the manner in which the RMEI was defined and the manner in which that hypothetical individual would be exposed to contaminants in the groundwater moving beneath the RMEI location. This section discusses these elements in terms of the regulations developed by the EPA and the NRC to establish defining criteria for the RMEI and DOE's subsequent efforts to define specific exposure mechanisms within the framework set by NRC and EPA. DOE developed the biosphere model as part of the TSPA-LA model to characterize the exposure mechanisms and generate estimates of annual radiation exposures, or doses, to the RMEI. The biosphere model characterizes results of individual exposure mechanisms in terms of *biosphere dose conversion factors*, which are used to calculate doses.

In addition to being integrated with the saturated zone flow and transport models, the biosphere model was integrated with the volcanic eruption model used to simulate a volcanic eruption modeling case. The biosphere model was also used to calculate annual radiation exposures from this scenario, but this Analysis of Postclosure Groundwater Impacts does not address this portion of the model. It should also be noted that the biosphere model was not used to evaluate impacts from potential exposures to chemically toxic materials; rather, DOE used separate analyses to compare concentrations of these materials with available regulatory standards (DIRS 180751-DOE 2008, p. F-22).

2.4.3.1 Regulatory Structure of Exposure Scenario

DOE developed the exposure scenarios used to assess impacts to the RMEI in accordance with regulations that establish specific characteristics for that hypothetical individual. The EPA set public health and environmental standards for the proposed repository at Yucca Mountain in 40 CFR Part 197. The NRC is responsible for implementing the EPA standards and, as part of its role, the NRC issued corresponding, implementing regulations in 10 CFR Part 63. The primary requirements that define the RMEI are the following criteria [from 10 CFR 63.312(a)-(e)]:

a) Lives in the accessible environment at a location above the highest concentration of radionuclides in the plume of contamination [where the accessible environment is defined as any point outside the controlled area and the definition of controlled area includes locations no further south than 36° 40' 13.6661" North latitude, in the predominant direction of groundwater flow (10 CFR 63.302)];

b) Has a diet and living style representative of people currently living in Amargosa Valley;

c) Uses well water with average concentrations of radionuclides based on an annual water demand of 3,000 acre-feet;

d) Drinks 2 liters of water per day from the above well; and

e) Is an adult with metabolic and physiological considerations consistent with present knowledge.

With respect to item b above, both the EPA regulations and the implementing NRC regulations require that DOE determine the current diets and living styles based upon surveys of the people residing in the town of Amargosa Valley [40 CFR 21(b) and 10 CFR 63.312(b)]. DOE met this requirement by collecting dietary and lifestyle data in a 1997 survey that included adults living in Amargosa Valley. Of the 900 adults estimated to live in Amargosa Valley at the time of the survey, data from 187 respondents were included in the evaluations. The evaluations also incorporated data from the 2000 Census along with regional and national information on behavioral patterns, food intake, and potential exposure parameters (DIRS 172827-BSC 2005, pp. 4-1 to 4-9). DOE documented the results of the evaluations in *Characteristics of the Receptor for the Biosphere Model* (DIRS 172827-BSC 2005, all) and included estimates of activity distributions (for example, percent of time away, active outdoors, and asleep), consumption of locally produced food, and proportions of the representative population in various occupation categories. Parameters developed through this effort provided input to the biosphere model.

The EPA's public health and environmental standards for the repository establish a two-tiered compliance standard: one tier for the first 10,000 years after disposal and the other tier for the period from 10,000 to 1,000,000 years [40 CFR 197.20(a)]. The 1 million years after disposal is termed the period of *geologic stability*. The characteristics of the RMEI remain the same for both compliance periods. The EPA regulations specify that DOE may not assume that future geologic, hydrologic, and climate conditions will be the same as they are at present, but that "DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge to technology" during the period of geologic stability (40 CFR 197.15). Holding societal and biosphere conditions constant during the entire 1-million-year performance period was a result of recommendations from the National Academy of Sciences to use biosphere assumptions that reflect current technologies and living patterns because of the unlimited possible future states of society. As described in the preamble to EPA's final rule of June 13, 2001 (66 FR 32074), "we *(EPA)* believe there may be an essentially unlimited number of predictions that could be made about future human societies, with an unlimited number of potential impacts on the significance of future risk and dose effects. Regulatory decision making involving many speculative scenarios for future societies and impacts would become extraordinarily difficult without any demonstrable improvement in public health and safety and should be avoided as much as possible."

2.4.3.2 Biosphere Dose Conversion Factors

Continuing to address the groundwater flow path as it was represented in the TSPA-LA model, DOE used the site-scale saturated zone flow and transport models to characterize movement of the simulated contamination plume to a point where the groundwater was accessible to inhabitants of the area. At the RMEI location, this would involve the use of one or more wells, and considering the diet and lifestyles of the residents of the town of Amargosa Valley, human exposures would result from using the contaminated groundwater for domestic and agricultural purposes. DOE developed the biosphere model, as described previously, to support calculation of estimated annual radiation doses to the RMEI from the use and consumption of this pumped groundwater.

Once radionuclides in the groundwater are brought to the surface, they would move through various environmental components of the biosphere and could result in dose to the RMEI through three exposure pathways: inhalation, ingestion, and external exposure. DOE addressed and modeled each of these exposure pathways using the diet, lifestyle, and other characteristics established for the hypothetical RMEI. The five environmental components, or submodels, considered in the groundwater exposure case of the biosphere model were soil, air, plant, animal, and fish (DIRS 183478-SNL 2008, pp. 6.3.11-3 and

6.3.11-4). The environmental transport processes explicitly included in the biosphere model are as follows (DIRS 183478-SNL 2008, pp. 6.3.11-4 and 6.3.11-5):

- Radionuclide accumulation in surface soil layers as a result of continuous long-term cultivation using contaminated water;
- Resuspension of contaminated soil;
- Radionuclide deposition on crop surfaces by dry processes (resuspension of contaminated soil and subsequent adhesion of soil particles onto vegetation surfaces);
- Radionuclide deposition on crop surfaces by interception of contaminated irrigation water;
- Removal of surface contamination by weathering processes;
- Translocation and retention of contaminants from the deposition site to the edible tissues of vegetation;
- Radionuclide uptake from soil by plants through the roots;
- Release of radionuclides in gaseous phases, radon-222 and carbon dioxide-14, from the soil into the air with subsequent inhalation;
- Photosynthesis by crops of carbon dioxide-14 from the atmosphere;
- Radionuclide intake from animals through consumption of contaminated feed, water, and soil, followed by transfer to animal products;
- Radionuclide transfer from water to air through use of evaporative coolers (a type of air conditioner); and
- Radionuclide transfer from water to fish.

The interrelationships among the identified transport pathways, environmental components (or media), and exposure pathways can be conceptualized, as shown in Figure 2-9.

DOE developed the biosphere model to generate a catalog of biosphere dose conversion factors. These conversion factors were generated in terms of dose per year to the RMEI per unit of *radioactivity* in a volume of groundwater (that is, concentration of radioactivity in the groundwater). In this manner, the TSPA-LA could generate an annual dose by applying the applicable biosphere dose conversion factors to the concentration of radionuclides estimated for the groundwater. Because the radionuclides have different radiological characteristics (they emit different types and levels of energy), the conversion factors are unique to a specific radionuclide, and the corresponding groundwater concentration to which they are applied also has to be radionuclide specific. For the groundwater scenario, the biosphere model developed conversion factors for 30 different radionuclides plus several decay products either considered separately or with their parent radionuclides (DIRS 177399-SNL 2007, pp. 6-13, 6-68 and 6-69).

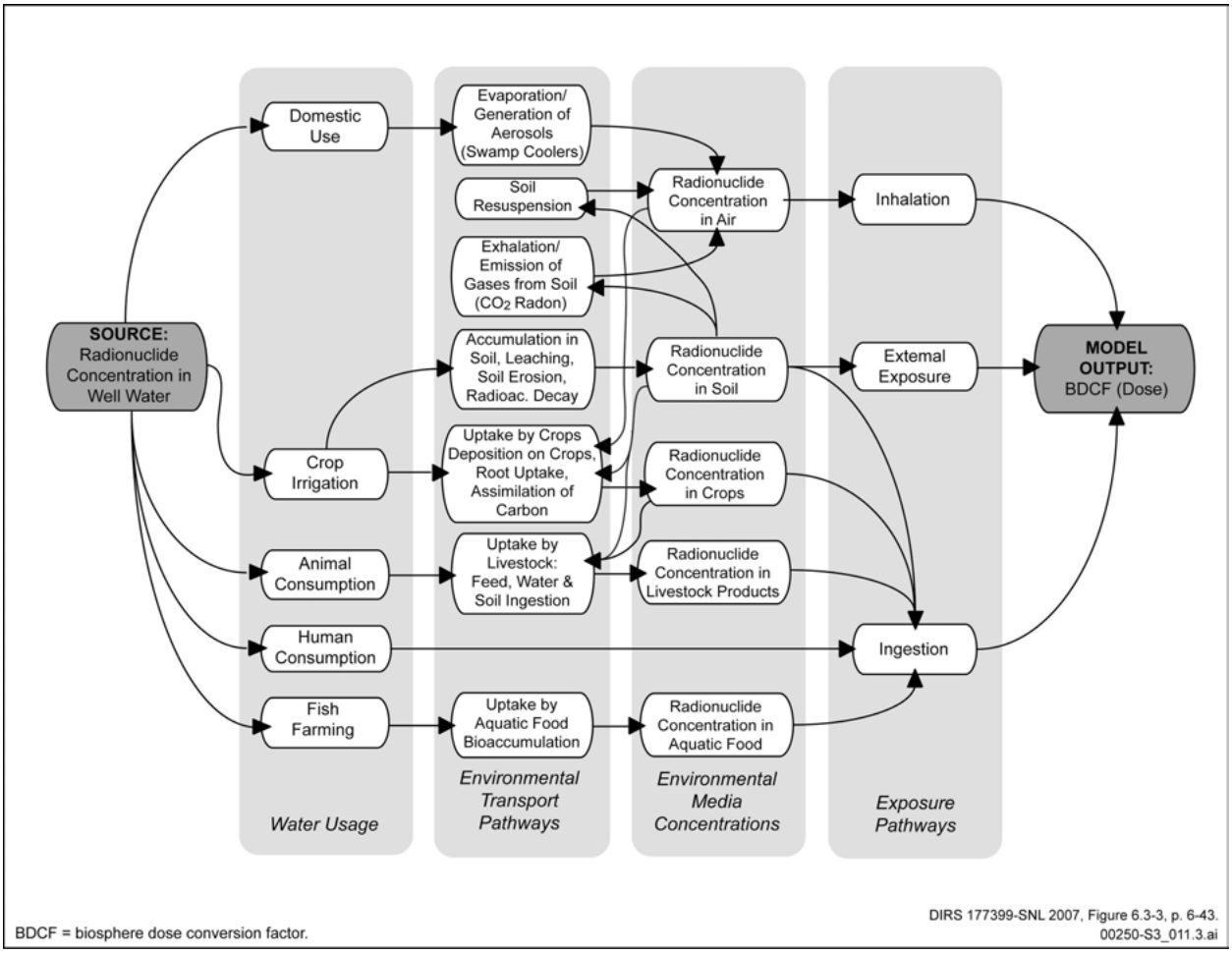


Figure 2-9. Conceptual representation of the biosphere model for the groundwater exposure scenario.

Table 2-5 provides an example of the exposure pathway contributions to an all-pathway biosphere dose conversion factor for one radionuclide, plutonium-239. The all-pathway biosphere dose conversion factor is the sum of the factors for the three exposure pathways: external, inhalation, and ingestion. The table describes the various parameters that contribute to each of the potential exposure pathways. As applicable, a pathway biosphere dose conversion factor is the sum of the contributing factors. The contributing dose conversion factors are additive because they each have a linear relationship with the radionuclide concentration in the groundwater. Not shown in the table is any indication of the numerous submodels developed to support each of the contributing groups and subgroups. The submodels incorporate a wide range of diet and lifestyle characteristics of the residents as well as exposure and dose relationships.

Development of the biosphere model included the calculation of biosphere dose conversion factors for different climates. As might be expected, groundwater use and resulting exposures vary with climate changes. For example, a wetter climate requires less irrigation and thus a lower concentration of radionuclides in fields due to use of less irrigation water. However, the biosphere dose conversion factors for the different climates ultimately were not used for the TSPA-LA. Because the present-day climate is characterized as the driest of any of the anticipated climates, it had the highest biosphere dose conversion factors. DOE used the present-day biosphere dose conversion factors for all of the climate scenarios to be conservative and to simplify the calculations.

Table 2-5. Summary of the elements contributing to an example (in this case for plutonium-239) all-pathway biosphere dose conversion factor.

Exposure pathway	Dose contributing parameters		Example dose factors for one radionuclide – Pu-239 [in (mrem/yr)/(pCi/L)][a,b]	
	Group	Subgroup	Contributor	Total
External				2.40×10^{-5}
	Environmental-specific exposure time (hours/day)	Active outdoors (0.45)		
		Inactive outdoors (1.45)		
		Active indoors (9.45)		
		Asleep indoors (8.30)		
		Away (4.35)		
Inhalation				1.95
	Inhalation dose, soil particles		1.31	
	Inhalation dose, evaporative cooler		6.37×10^{-1}	
Ingestion				7.85×10^{-1}
	Ingestion dose for water		6.78×10^{-1}	
	Ingestion dose for crops	Leafy vegetables	1.91×10^{-2}	
		Other vegetables	3.81×10^{-3}	
		Fruit	1.22×10^{-2}	
		Grain	1.54×10^{-3}	
	Ingestion dose for animal products	Meat	6.74×10^{-5}	
		Milk	2.57×10^{-6}	
		Poultry	1.01×10^{-5}	
		Eggs	1.80×10^{-4}	
	Ingestion dose for fish		3.64×10^{-2}	
	Ingestion dose for soil		3.26×10^{-2}	
All pathway dose conversion factor ($BDCF_{Pu-239}$)				2.73

Source: DIRS 177399-SNL 2007, pp. 6-261 to 6-264, Table 6.10-1.

a. The biosphere dose conversion factors shown here are in terms of dose in millirem per year per a unit groundwater concentration of pico-curries per liter. The biosphere model presents these values in terms of dose in sieverts per year (Sv/yr) per unit groundwater concentration of becquerels per cubic meter (Bq/m^3). The conversion was made by multiplying the (Sv/yr) per (Bq/m^3) units by 3.70×10^6.

b. The biosphere dose conversion factor values shown here were derived through a deterministic calculation to check the biosphere model. Actual output from the model (values used in calculation of dose impacts) is the result of stochastic calculations done to generate uncertainties associated with the ranges of values that could fit the various model parameters. For example, the mean all-pathway $BDCF_{Pu-239}$ from the model is $(3.54 \pm 1.25) \times 10^0$ (DIRS 177399-SNL 2007, p. 6-284) compared with the value at the bottom of the table. The plus or minus value (±1.25) represents the standard deviation of the values generated by the biosphere model.

BDCF = biosphere dose conversion factor.
mrem/yr = millirem per year.
pCi/L = picocuries per liter.

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3. ENVIRONMENTAL IMPACTS OF POSTCLOSURE REPOSITORY PERFORMANCE

This chapter describes assessments and analysis of potential environmental impacts resulting from postclosure *repository* performance and its effect on the *groundwater* environment described in Chapter 2. The assessments focus on the effects of long-term transport of radiological and nonradiological contaminants. The analysis estimates flow and accumulation of contaminants throughout the *affected environment* for the *postclosure* period. Environmental impacts resulting from surface *discharges* of contaminated water (including impacts to groundwater quality), health and safety, and *biota* are assessed.

The *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F-S1; DIRS 180751-DOE 2008, all) (Repository SEIS) analyzed the transport of *radionuclides* from the repository to the *Regulatory Compliance Point* south of the repository where a hypothetical *reasonably maximally exposed individual* (RMEI) used water from a hypothetical well. The Repository SEIS reported results of an assessment of the radiologic doses to the RMEI. That assessment was guided by U.S. Environmental Protection Agency (EPA) and U. S. Nuclear Regulatory Commission (NRC) regulations. Chapter 2, Section 2.4 of this document details the nature of the Repository SEIS radiological analysis. The Repository SEIS also assessed the release of *nonradiological contaminants*, transport to the Regulatory Compliance Point (the location of the RMEI), and impacts. The Repository SEIS analysis provided a qualitative evaluation of radiological and nonradiological impacts that might occur beyond the Regulatory Compliance Point.

REGULATORY COMPLIANCE POINT

This point is defined as the location over the highest concentration of contaminants in the plume as required by the U.S. Nuclear Regulatory Commission at 10 CFR 63.312(a). The TSPA-LA calculates radiologic dose to a reasonably maximally exposed individual located at a point on the Nevada Test Site boundary (36°40'13.66661" North Latitude) that is approximately 18 kilometers south of the repository. In this Analysis of Postclosure Groundwater Impacts, this location is referred to as the Regulatory Compliance Point.

The NRC staff identified a need for a more extensive description of the affected environment, assessment of the transport of *contaminants* throughout the affected environment beyond the Regulatory Compliance Point, and assessment of associated impacts (see Chapter 1).

CONTAMINANTS

This Postclosure Groundwater SEIS discusses two types of contaminants: radiological contaminants (also referred to as radionuclides) and nonradiological contaminants (such as toxic metals with a nonradiological toxicity). When the word "contaminants" is used by itself, then the reference is to both types of contaminants.

The work described in this chapter responds to the NRC staff by performing the following analyses:

- Trace the release and movement of contaminants from the repository into the *aquifer* system up to and beyond the Regulatory Compliance Point, including releases at natural discharge sites. Assess the cumulative amounts entering and leaving the aquifer system and the accumulation within the system; and

- Assess the impacts resulting from the release, movement, and accumulation of contaminants throughout the region.

The analyses discussed in this chapter followed these steps:

- Used a regional groundwater flow model to define the potential paths contaminants could take after exiting the repository, transporting to the Regulatory Compliance Point, and beyond into the region. This modeling also identified natural discharge points (DIRS 173179-Belcher et al. 2004, all; DIRS 177391-SNL 2007, all);

- Performed transport analyses of radionuclides starting with the release of radionuclides from the Regulatory Compliance Point as previously analyzed using the *Total System Performance Assessment Model/Analysis for the License Application* (DIRS 183478-SNL 2008, all; TSPA-LA) (see Chapter 2, Section 2.4);

- Performed the transport analyses of nonradiologic contaminants starting with the release of the contaminants at the *unsaturated zone-saturated zone* interface. DOE estimated release at the unsaturated zone-saturated zone interface using an extension of the bounding release calculations performed in the Repository SEIS (DIRS 180751-DOE 2008, Appendix F, Section F.4);

- Analyzed transport of contaminants along the flow paths developed from the *Death Valley regional groundwater flow model* to natural discharge or pumped withdrawal points;

- Analyzed doses and associated health effects from radiological contaminants;

- Analyzed human health impacts from nonradiologic contaminants at points where contaminants interact with the *biosphere* (that is, natural discharge and pumped withdrawal points);

- Analyzed soil concentrations of contaminants at natural discharge and pumped withdrawal sites; and

- Evaluated *processes* that could occur at the natural discharge sites.

3.1 Analytical Framework for the Analysis of Postclosure Groundwater Impacts

This section describes the development of an analytical framework for this Analysis of Postclosure Groundwater Impacts. DOE developed this framework based on variables or assumptions regarding the future in the region and results of the regional flow modeling.

3.1.1 CONSIDERATION OF UNCERTAINTIES ABOUT THE FUTURE

The analyses of postclosure groundwater impacts include the following assumptions:

- The current population and its distribution will continue for the period of *geologic stability* [1 million years, as prescribed by Title 40 of the Code of Federal Regulations (CFR), Part 197], and

- The current range of human activities will continue for the period of geologic stability.

The analyses use these two assumptions based on guidance in the EPA regulations (at 40 CFR 197.15) regarding avoidance of speculation about future populations and human activities. As described in the preamble to EPA's final rule of June 13, 2001 [Volume 66 of the *Federal Register* (FR) 32074], avoiding

such speculation is recommended because the future is unknown and the analyses would be open to limitless possibilities. Consistent with the amended EPA regulations at 40 CFR Part 197 (73 FR 61256) and the amended NRC regulations at 10 CFR Part 63 (74 FR 10811), which incorporate the National Academy of Sciences guidance for the period of geologic stability, this Analysis of Postclosure Groundwater Impacts analyzes a 1-million-year postclosure period.

The other primary variables considered are:

- Future climate conditions, and
- Future groundwater withdrawals (pumping).

3.1.1.1 Future Climate Conditions

In its *U.S. Nuclear Regulatory Commission Staff's Adoption Determination Report for the U.S. Department of Energy's Environmental Impact Statements for the Proposed Geologic Repository at Yucca Mountain* (NRC staff's Adoption Report), the NRC staff specifically mentioned that the requested analyses should be performed for the present and a future, wetter climate (DIRS 186113-NRC 2008, p. 3-12). Therefore, DOE analyzed two separate climate conditions: the present climate and a future, wetter climate. The wetter climate DOE considered for this Analysis of Postclosure Groundwater Impacts is the same as the post-10,000-year climate used in the TSPA-LA. Chapter 2, Section 2.2 of this analysis, has a detailed discussion of past climates and their influence on regional *geohydrology*. The intent of the approach in this analysis is to bound the possibilities by offering results for a continued present day climate and a future, wetter climate.

In this Analysis of Postclosure Groundwater Impacts, DOE conducted the analysis with the climate constant for the entire 1-million-year postclosure period. The analysis was repeated for the present climate and the future, wetter climate. This analysis uses radionuclide *fluxes* derived from previous TSPA-LA model runs as input (for example the radionuclide fluxes at the Regulatory Compliance Point). When the TSPA-LA model produced these fluxes, it was run with four climate changes occurring during the 1-million-year period. The climate changes in the TSPA-LA are primarily drivers to the *infiltration* into the repository rather than regional transport. Reprogramming and rerunning the TSPA-LA twice with a fixed climate for 1-million years solely to match each of the climate assumptions in this document would be unnecessary for the following reasons: (1) it would input conservative results for the present climate scenario and (2) it would input essentially the same results for the wetter climate (the TSPA-LA maintained the present climate for only 600 years and then the climate became progressively wetter). This Analysis of Postclosure Groundwater Impacts used the TSPA-LA results as input to both the present and future, wetter climates for the regional analysis.

3.1.1.2 Future Groundwater Pumping

Groundwater pumping can lead to changes in the *hydraulic gradient*s and therefore alter the direction and rate of groundwater flow in the region. As is shown below, groundwater modeling demonstrates that different flow paths result from different *pumping scenarios*. This Analysis of Postclosure Groundwater Impacts used the TSPA-LA model to develop characteristics of the contaminant plume at the Regulatory Compliance Point. To evaluate the results of a range of pumping scenarios, DOE extended flow and transport simulations to areas physically beyond those addressed in the TSPA-LA model. DOE used

output from the TSPA-LA model as input to the Death Valley regional groundwater flow system model to develop contaminant flow paths beyond the Regulatory Compliance Point.

Both the site-scale saturated zone flow model and the Death Valley regional groundwater flow system model include particle-tracking capabilities. This allowed a simulation of adding particles to track where they would go as they moved with the groundwater (that is, assuming there is no *adsorption*, filtering, *decay*, or other mechanisms that would prohibit the particles from moving with the water). As Chapter 2 of this document explains, the site-scale saturated zone flow model only extends to the Amargosa Farms area (see Figure 2-8). The Death Valley regional groundwater flow system model extends farther south to encompass the entire Death Valley flow region. Therefore, the particle-tracking effort required the application of both models. DOE began with particle locations obtained from the site-scale saturated zone flow model as input to the Death Valley regional groundwater flow system model at the Regulatory Compliance Point. DOE then used the particle-tracking capabilities of the regional model to determine where those particles would move in the regional flow system. DOE repeated this process for two pumping scenarios to determine how the flow paths would change under differing conditions imposed on the model. The *no-pumping scenario* simulated conditions of the regional flow system before any significant groundwater pumping had started (or the equilibrium conditions if all pumping were to cease). The pumping scenario simulated *steady-state* conditions with 2003 groundwater pumping locations and rates reported by the U.S. Geological Survey (USGS; DIRS 185968-Moreo and Justet 2008, all) (see Chapter 2, Section 2.1.1.1.2 for a discussion of the choice of pumping rates). In the modeling, most of the pumping was at the Amargosa Farms area, which represents the majority of all the pumping in the region.

Under the no-pumping scenario (Figure 3-1), the model shows the particles initially traveling to the south from the Regulatory Compliance Point. Then essentially all of the particles flow to the west to exit the groundwater flow system at the *floor of Death Valley* in the Furnace Creek area on or near the saltpan at Middle Basin. There is a small particle trace that continues to the south to Alkali Flat. This track represents only 2 particles out of the total 8,024 particles. There is also a minor particle track near the west end of the main particle track extending farther south into Death Valley toward Badwater Basin. This track also represents 2 particles out of the 8,024.

Under the pumping scenario (Figure 3-2), no particles go farther than the central portion of the Amargosa Desert. The model indicates that the groundwater pumping in the Amargosa Farms area draws in all the particles.

The endpoints of the groundwater flow pathways in Figures 3-1 and 3-2 represent the range of locations where contaminants could be released from the proposed repository under present climate conditions. Under future, wetter climates, these flow paths would still be followed because studies have shown that the same paths are followed under wetter climates (DIRS 185814-DOE 2008, Section 2.3.9). However, as Chapter 2, Section 2.2.2 of this document describes, higher groundwater levels under wetter and cooler conditions could result in groundwater discharge locations closer to the boundary of the *accessible environment* than would occur under present-day conditions (see Section 3.2.1.8 for an analysis of this situation).

These particle-tracker results illustrate that an analytical framework that includes pumping and no-pumping scenarios would capture the range of potential impacts at both the groundwater pumping and natural discharge locations. The analysis therefore focused on the floor of Death Valley in the Furnace

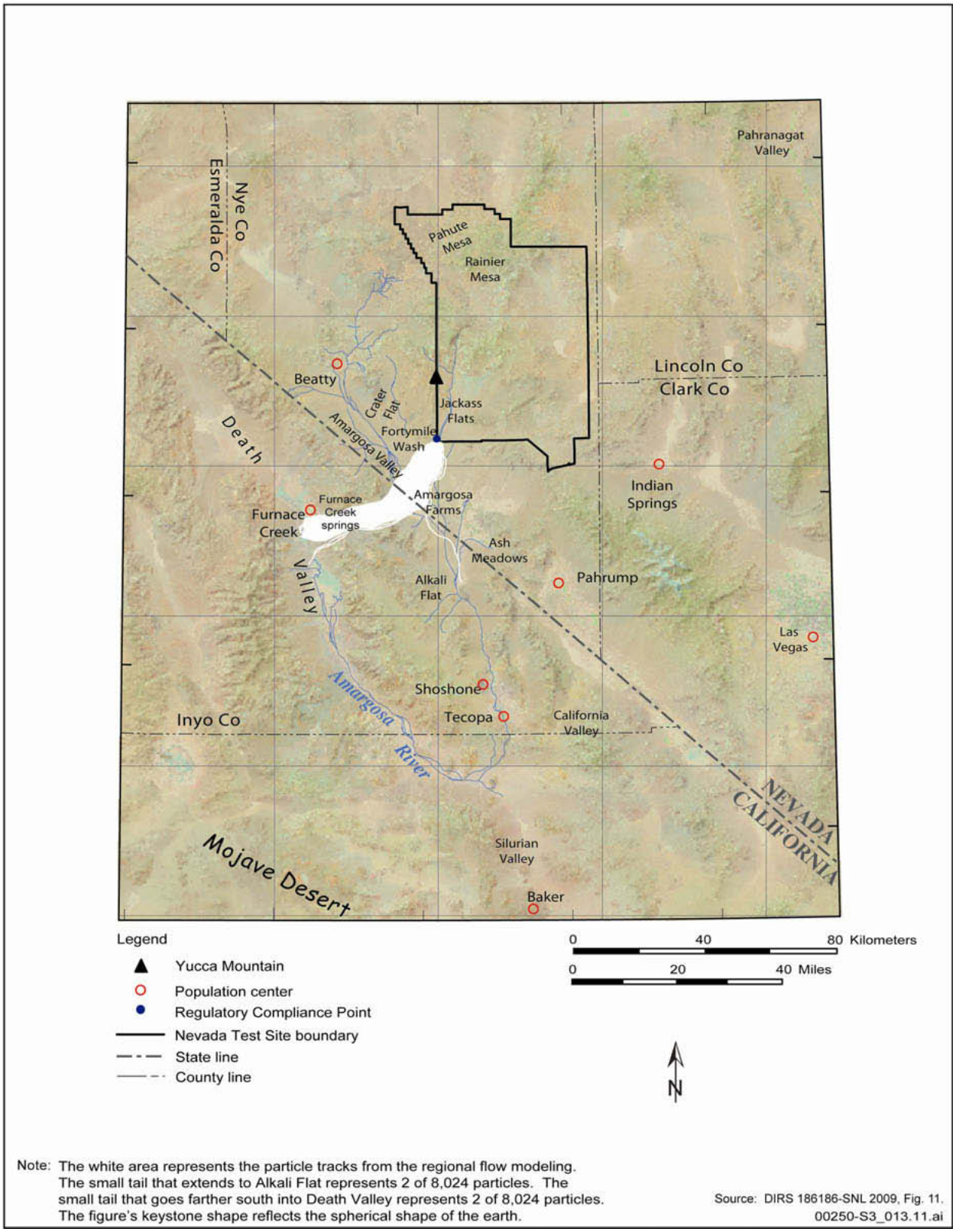
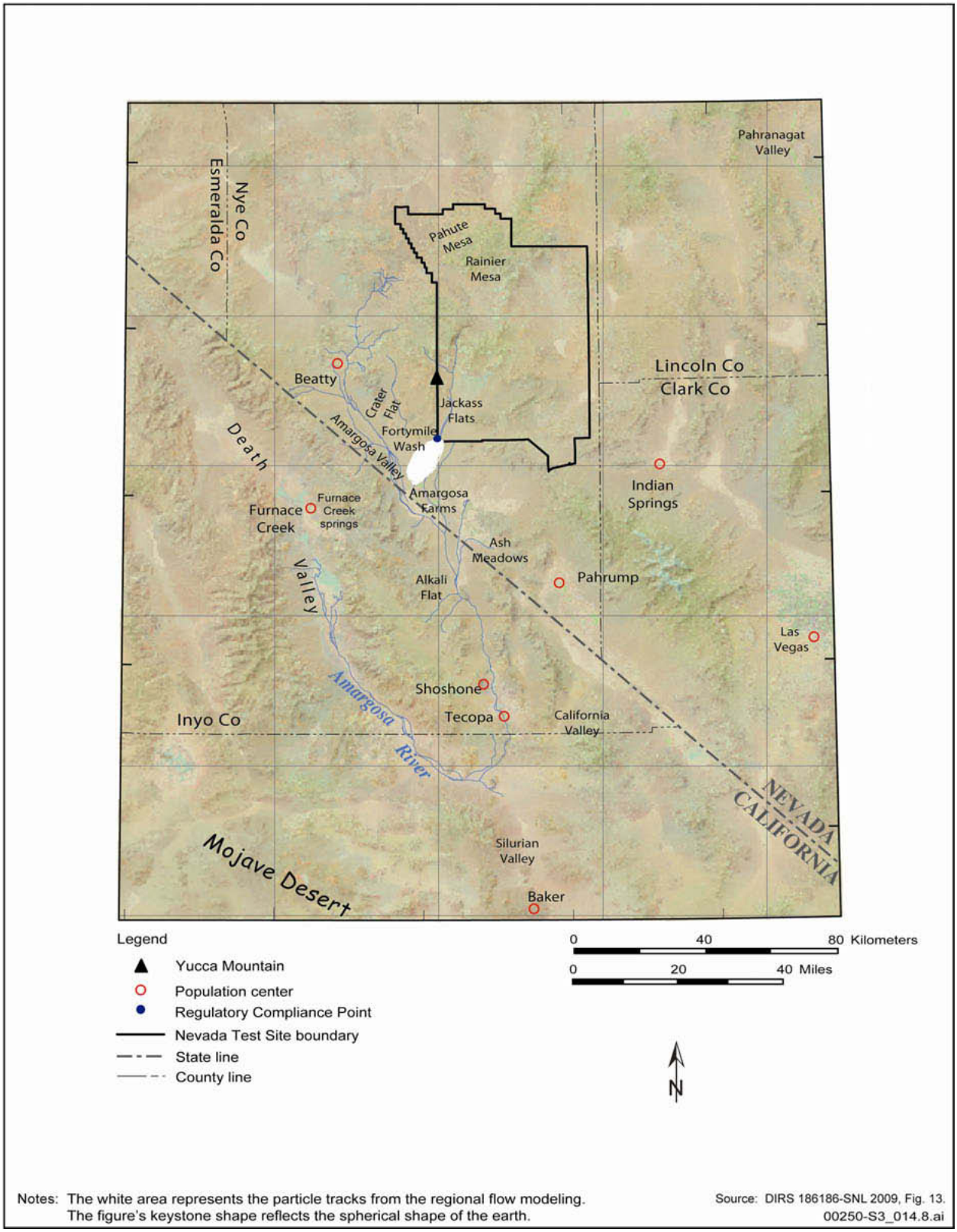


Figure 3-1. Groundwater flow paths for the no-pumping scenario.



Notes: The white area represents the particle tracks from the regional flow modeling. The figure's keystone shape reflects the spherical shape of the earth.

Source: DIRS 186186-SNL 2009, Fig. 13. 00250-S3_014.8.ai

Figure 3-2. Groundwater flow paths for the pumping scenario.

Creek area and Amargosa Farms area. Although the regional flow model predicts that natural discharge would exit the flow system through *evapotranspiration* from the alluvium on the floor of Death Valley at Middle Basin, DOE cannot preclude the possibility that contaminants could mix with carbonate waters and discharge at the springs in the Furnace Creek area. To evaluate the consequences of this possibility, DOE analyzed two scenarios for the discharge of contaminants in Death Valley: (1) that all discharge of contaminants would occur via evapotranspiration at the floor of Death Valley and (2) that all discharge of contaminants would occur at the springs in the Furnace Creek area. In addition, because the particle track analysis indicates that some particles could flow to Alkali Flat, DOE also assessed the possibility of discharges at that location.

Note that in the no-pumping scenario, natural discharges in Death Valley (Furnace Creek springs area and Middle Basin) and Alkali Flat are the only sources of potential exposure considered because DOE assumes groundwater pumping in Amargosa Desert would not occur in this scenario. Conversely, in the pumping scenario, use of groundwater in the Amargosa Farms area is the only source of potential exposure considered because particle-tracker results indicate that no particles would bypass the Amargosa Farms area. Although it is likely that future events would be a combination of these two scenarios, the analysis of the two extremes ensures this Analysis of Postclosure Groundwater Impacts does not underestimate the impacts at these locations.

3.1.2 FINAL SELECTION OF ANALYTICAL FRAMEWORK

The inputs required for the analysis of radiological contaminants involved outputs from the TSPA-LA model. In the Repository SEIS, DOE used the TSPA-LA model to analyze four scenario classes. For this Analysis of Postclosure Groundwater Impacts, the summation of fluxes from the Repository SEIS combined case were used as the input. The combined scenario case included the following scenario classes:

- The Nominal Scenario Class: undisturbed case where normal degradation processes, such as *corrosion* of *waste packages*, proceed over time and result in releases;
- Early Failure Scenario Class: failure of *drip shields* or waste packages caused by manufacturing defects;
- Igneous Scenario Class: events and processes initiated by eruption through the repository or intrusion of igneous material into the repository; and
- Seismic Scenario Class: events and processes initiated by ground motion or fault displacement.

DOE used the radiological release results from this combined case as input for this Analysis of Postclosure Groundwater Impacts.

The estimated waste package failures in the combined scenario were used to develop the release rates for the nonradiological contaminants, which were then used as input to the transport analysis for those contaminants (see Section 3.2.1.3).

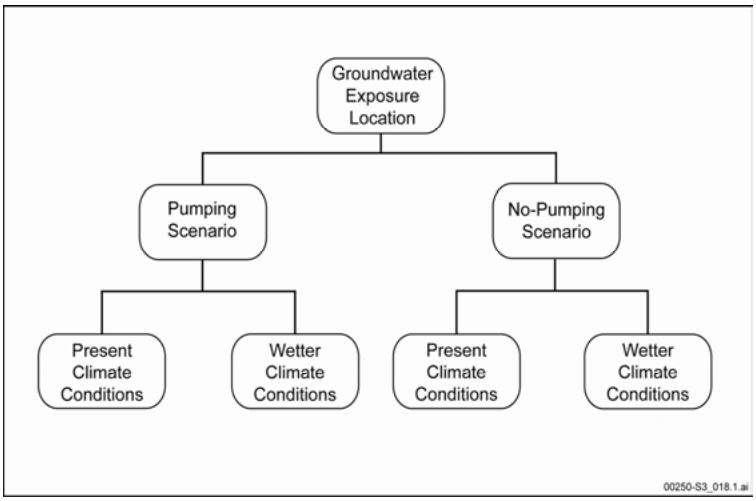


Figure 3-3. Analytical framework for each potential groundwater exposure location.

Considering the treatment of uncertainties discussed in the previous section and the potential exposure pathways, Figure 3-3 illustrates the analytical framework for analysis of all of the contaminants.

There would be no contaminants at the natural discharge locations for the pumping scenario and no contaminants at the Amargosa Farms area (the site of the predominant groundwater withdrawals under the pumping scenario) under the no-pumping scenario.

The list of analytical constructs that provide the expected range of potential impacts is:

- Path to the Amargosa Farms area, pumping, present climate
- Path to the Amargosa Farms area, pumping, wetter climate
- Path to the Furnace Creek springs area, no-pumping, present climate
- Path to the Furnace Creek springs area, no-pumping, wetter climate
- Path to the *Death Valley floor* (Middle Basin), no-pumping, present climate
- Path to the Death Valley floor (Middle Basin), no-pumping, wetter climate.

Note that full results were not developed for Alkali Flat; Section 3.3.1 below includes a discussion for purposes of comparing the results for Middle Basin.

As mentioned above, DOE analyzed this framework for a 1-million-year postclosure period (Section 3.3). Section 3.3 also provides results for a 10,000-year period to allow comparison with results provided in the Repository SEIS for 10,000 years after *closure* at the Regulatory Compliance Point.

3.2 Analysis Methods

This section discusses the methods used in the analysis, the flow of data between the various types of models, and some of the inherent conservatisms in the approach.

3.2.1 DESCRIPTION OF METHODS

This section summarizes the methods used in this Analysis of Postclosure Groundwater Impacts long-term performance analysis. Appendix B has more detailed descriptions of the conceptual and numerical models. Figure 3-4 diagrams the interrelationships of the models/techniques used in the analysis. Section 3.1.1.2 discusses how DOE used the Death Valley regional groundwater flow system model to identify and quantify flow paths. The following sections discuss the remainder of the elements in Figure 3-4.

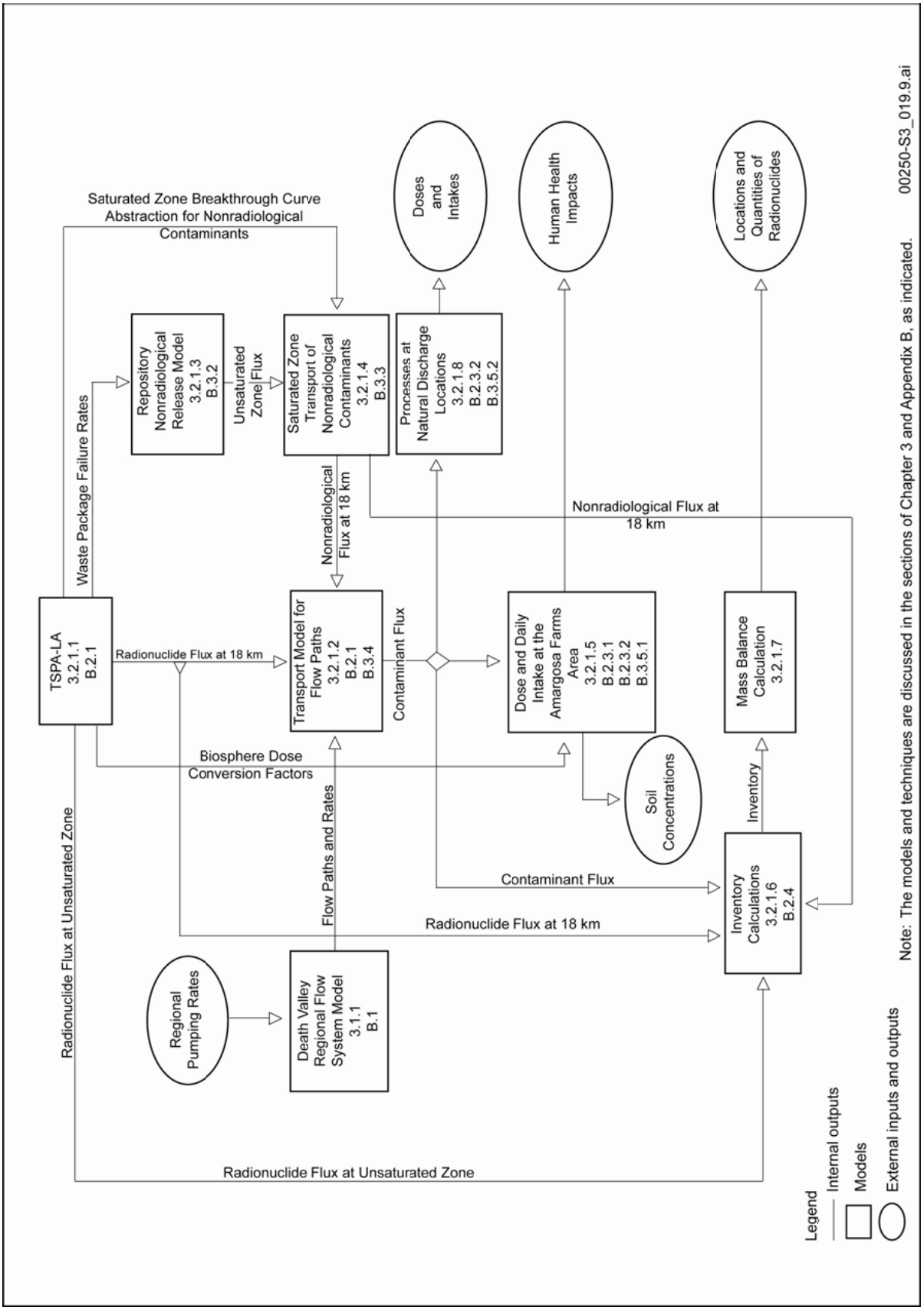


Figure 3-4. Diagram of the interrelationships of the models/techniques used in this Analysis of Postclosure Groundwater Impacts.

3.2.1.1 TSPA-LA

Chapter 2, Section 2.4 provides a summary of the TSPA-LA, its objectives, and how DOE applied it to the Repository SEIS. The analysis of postclosure groundwater impacts used five types of output from the TSPA-LA, as follows:

1. Radionuclide flux at the unsaturated zone-saturated zone interface,
2. Radionuclide flux at the 18-kilometer Regulatory Compliance Point,
3. Saturated zone breakthrough curves,
4. Waste package failure rates for the combined case, and
5. *Biosphere dose conversion factors*.

The primary type of outputs used from the TSPA-LA were the sets of mass release rates (fluxes) at the unsaturated zone-saturated zone interface under the repository and at the saturated zone at the Regulatory Compliance Point. The fluxes at the Regulatory Compliance Point were the primary input to the radionuclide transport modeling in the region beyond the Regulatory Compliance Point. The other outputs relate to uses by other analysis components (from Figure 3-4) and are discussed below with those components.

3.2.1.2 Transport Model for Flow Paths

The transport model used a one-dimensional pipe model with *longitudinal dispersion* (mixing) and equilibrium adsorption of dissolved contaminants on surfaces of a porous solid contained within the pipe. DOE assumes the pipe contains the entire plume (that is, all of the mass flux) moving in a certain direction. This pipe concept is appropriate for modeling the transport along the paths because there would be little horizontal or vertical mixing (dispersivity) in the aquifer and along the flow paths (DIRS 184806-SNL 2008, p. 4-13). This model took the contaminant flux at the Regulatory Compliance Point as input and generated the flux at the output of the pipe. For radionuclides, the TSPA-LA output provided the input flux. For this deterministic analysis, all cases used the *mean value* outputs from TSPA-LA. For nonradiological contaminants, DOE developed the input flux from the saturated zone transport model for nonradiological contaminants described below in Section 3.2.1.4.

3.2.1.3 Repository Nonradiological Release Model

Since the TSPA-LA model did not analyze the release of the nonradiological contaminants molybdenum, nickel, and vanadium, DOE developed a means for estimating the releases of these metals at the unsaturated zone-saturated zone interface (see Appendix B for a more detailed discussion on the choice of nonradiological contaminants for this analysis). DOE used a modified version of the bounding release analysis of these contaminants from the Repository SEIS (DIRS 180751-DOE 2008, Appendix F, Section F.4). Such an analysis was not needed for uranium, as uranium results are available directly from the TSPA-LA results by summing all uranium isotopes. The Repository SEIS analysis of nonradiological contaminants was for 10,000 years (before a significant number of packages would be expected to fail) and therefore did not consider potential releases of nonradiological contaminants from the inside of waste packages. Using package failure rates from the TSPA-LA model output enabled DOE to extend the release analysis to 1 million years and account for materials inside the packages. The output of the nonradiological contaminant release model was the mass flux of the nonradiological contaminants at the

unsaturated zone-saturated zone interface, which became the input to the saturated zone transport model for nonradiological contaminants molybdenum, nickel, and vanadium.

3.2.1.4 Saturated Zone Transport of Nonradiological Contaminants

This model used breakthrough curves developed by running the TSPA-LA site-scale saturated zone transport model for species with transport properties equal to those of molybdenum, nickel, and vanadium to estimate the transport of nonradiological materials to the Regulatory Compliance Point. The fluxes developed as output were then the input to the transport model described above in Section 3.2.1.3, which then produced the fluxes of nonradiological contaminants at the potential exposure locations.

3.2.1.5 Dose and Daily Intake at Amargosa Farms

The radiological dose and nonradiological daily intake calculations used the fluxes at the Amargosa Farms area as input and generated human health impacts and soil concentrations. If water was to be pumped at high rates from a large number of widely distributed wells (unlike the limited water use from a single or a small number of hypothetical wells at the RMEI location), the contaminants distributed over the irrigated fields would tend to percolate back into the groundwater system where they could be recaptured by the wells. DOE developed well water concentrations of contaminants using a special case of the *Irrigation Recycle Model* (DIRS 182130-SNL 2007, p. 7-1). The special-case version of the *Irrigation Recycle Model* is one in which there is no decay or *sorption* of the contaminants. This provides a very conservative result because it does not include holdup of contaminants and decay of radionuclides in the soil column after they have infiltrated back into the aquifer. The special-case model generates water concentration as a function of input mass flux, pumping rate, and two fractions: (1) the fraction of contaminants recycled (not lost outside of the irrigation system) and (2) the fraction of contaminants recaptured by the wells. DOE conservatively assumed the recapture fraction to be 1 (meaning that all of the contaminants would be recaptured by the well). DOE developed the recycle fraction from consideration of usage of the pumped water (irrigation versus other uses) and consideration of diversion of some contaminants from being reintroduced into the soil. The value developed for the recycle fraction was 0.86, as further detailed in Appendix B, Section B.2.3.1.

The biosphere dose conversion factors for the TSPA-LA were developed based upon the characteristics of agricultural production in Amargosa Valley and the behaviors and lifestyle of the residents of that area. Thus, as appropriate, DOE calculated doses at the Amargosa Farms area using those biosphere dose conversion factors (see Chapter 2, Section 2.4.3.2). DOE also calculated daily intakes of nonradiological contaminants for a 70-kilogram person, drinking 2 liters of water per day (see Section 3.3.2 for more details).

3.2.1.6 Inventory Calculations

The mass flux of contaminants resulted in an inventory at each location analyzed in the transport analysis. This inventory was a decay- and growth-adjusted measure of the total amount of material arriving at the specific location as a function of time. DOE calculated the inventory for a contaminant from the flux by integrating the flux as a function of time as modified for radionuclides by decay of each radionuclide and growth equations for the radionuclide chains. This decay/growth-adjusted time integral of the flux-time curve is a quantitative measurement of the cumulative release of material adjusted for decay and growth at a specific location at specific times during the 1-million-year period.

3.2.1.7 Mass Balance Calculation

DOE developed *mass balances* for contaminants using the inventories. For example, the amount of a radionuclide in the saturated zone path between the Regulatory Compliance Point and the Amargosa Farms area is the difference between the inventory released beyond that point and the inventory accumulated at the Amargosa Farms area. The mass balances provide an overall accounting of where contaminants have been transported and where they have accumulated.

3.2.1.8 Processes at Natural Discharge Locations

As identified in Section 3.1.1.2 under the no-pumping scenario, the regional flow model predicts that natural discharge would exit the flow system through evapotranspiration from the alluvium on the floor of Death Valley at Middle Basin. As previously mentioned, DOE cannot preclude the possibility that contaminants could mix with carbonate waters and discharge at the springs in the Furnace Creek area. Therefore, DOE analyzed both potential natural discharge locations.

3.2.1.8.1 *Furnace Creek Springs Area*

To calculate the annual dose resulting from the use of potentially contaminated water discharged from springs in the Furnace Creek area, DOE used the biosphere dose conversion factors developed for the TSPA-LA. Because there is no large-scale irrigation of agricultural fields in that area, the irrigation recycle model was not used to calculate radionuclide concentrations in the soil. The *receptors* considered for this analysis include full-time residents in the Furnace Creek area, such as local members of the Timbisha Shoshone Tribe and employees of the National Park Service. Those persons would receive external exposure from contaminants deposited in soil from spring flows or use of spring water for landscaping, and from inhalation and inadvertent ingestion of contaminated soil particles. They also could be exposed by drinking spring water or using that water in evaporative coolers in their residences and offices. The biosphere dose conversion factors developed for the TSPA-LA, and used in this analysis, include these pathways and were developed based on exposure rates for full-time residents of the Amargosa Farms area. Because there is little agricultural production or other local production of foodstuffs in the Furnace Creek area, DOE did not include food ingestion pathways in the Furnace Creek springs analysis. This resulted in reductions of the biosphere dose conversion factors by 40 to 60 percent for the radionuclides that are the principal contributors to dose. Because the biosphere dose conversion factors were developed based on year-round exposure to soil and groundwater by residents, the calculated dose substantially overestimates the risk to visitors to Death Valley National Park or other non-residents in the area (see details in Appendix B, Section B.2.3.2.1).

3.2.1.8.2 *Middle Basin and Alkali Flat*

The Middle Basin at the Death Valley floor near the springs at Furnace Creek is a playa. The Franklin Lake Playa is a major feature at Alkali Flat.

Playas have been classified as wet playas and dry playas (DIRS 186240-Reynolds et al. 2007, p. 1811). Wet playas are characterized as having groundwater less than 5 meters below the surface. Middle Basin and Franklin Lake Playa currently are wet playas. In a wet playa, capillary action brings water to the surface, resulting in evaporation from the shallow groundwater. This action produces a soft surface of *evaporite* minerals that are typically rich in minerals such as calcium carbonate, hydrated calcium sulfate, sodium chloride (common salt), and sodium sulfate. The deposits originate from the total-dissolved-

solids in the groundwater and are found in the capillary fringe area and on the surface. Often the deposits are described as "fluffy" with large pore space and low density (DIRS 186240-Reynolds et al. 2007, p. 1812). As the evaporite mineral crystals form, they displace the rock-derived *clastic* minerals, expanding the sediments upward (DIRS 186240-Reynolds et al. 2007, p. 1812). Sometimes a more compact, but still *friable*, material forms, which contains a lower fraction of evaporites. These deposits are associated with lower rates of evaporation or lower salinity in the groundwater.

At times, durable, wind-resistant crusts of evaporite minerals can form a protective layer about 1 centimeter thick on top of unconsolidated and dry, fine-grained sediment that might be as much as 10 centimeters thick. Breaking this crust can release material that is easily carried by the wind (DIRS 186240-Reynolds et al. 2007, p. 1823). It has been observed that changes occur in evaporite sediments due to wind deflation, rainfall events, and water table fluctuations (DIRS 186240-Reynolds et al. 2007, p. 1816). Thus, the deposits may take on many forms; some very susceptible to resuspension and some not.

If radiological and nonradiological contaminants from a repository at Yucca Mountain were transported to Middle Basin, they would occur as trace amounts in the dissolved solids. As the surface evaporite minerals form, trace contaminants (such as radionuclides or other nonradiological contaminants) would also precipitate. There is no mechanism for preferential precipitation, so the ratio of trace contaminants to evaporites is reflective of the ratio or concentration of trace contaminants to concentration of all dissolved minerals in the groundwater that is evaporating. Based on this principle, DOE estimated the concentration of contaminants in the evaporite minerals (see Appendix B, Section B.2.3.2.2). DOE assumed that the surface materials would be made up entirely of these evaporite mineral deposits. This is a conservative assumption because rock-based clastic soils would make up some of the material and thus reduce the effective concentration of contaminants. Doses and intakes would be proportional to this concentration.

An additional potential natural discharge location under the future, wetter climate was identified in Chapter 2, Figure 2-5. The potential impacts at this location are discussed qualitatively in Section 3.3.5.

3.2.1.8.3 *Doses and Intakes at Wet Playas*

Estimates of doses and intakes at the floor of Death Valley (Middle Basin) were based on the scenario that the wet playa condition continues to exist for the entire analysis period. Occasional dust storms, rain storms, and runoff may alter the evaporite deposits, causing erosion, silt coverage, compaction, and consolidation. Some of these alterations would cause increased concentration of resuspended particulates in the air, while others, such as compaction and consolidation, would reduce air emissions. A relatively high annual average concentration of resuspended particles, associated with conducting activities outdoors while not significantly disturbing soil, was used in the analysis to account for these processes. Occasional flooding of the playa would reduce, if not eliminate, exposure to contaminants in the deposits. Any standing water or runoff water would be extremely brackish and non-potable; therefore, ingestion of this water would be unlikely and was not included. Most municipalities define potable water as having less than 250 milligrams per liter total-dissolved-solids. Brackish water is considered to have 500 to 3,000 milligrams per liter total-dissolved-solids, and saline water is classified as greater than 30,000 milligrams per liter total-dissolved-solids. At the Franklin Lake Playa (Alkali Flat), stagnant water has total-dissolved-solids of 70,000 to 80,000 milligrams per liter and drainage paths have water with total-dissolved-solids of 6,000 to 20,000 milligrams per liter (DIRS 186240-Reynolds et al. 2007, p. 1814).

Inhalation exposure may be eliminated during the wetter climate if the playa was covered by standing water.

The receptor that was considered for the Furnace Creek springs area [a full-time resident of Death Valley (see Section 3.2.1.8.1)], was also considered in the analysis of health impacts at Middle Basin from the deposition of contaminated evaporites on the soil surface. Three potential exposure pathways (external exposure to evaporite minerals, inhalation of resuspended evaporites, and ingestion of evaporites) were evaluated in the analysis. Ingestion of water, and other uses of contaminated water, was not included because it is more likely that residents would continue to rely upon water obtained from nearby, existing springs and wells than from any mineral-laden seeps or other standing water that may occur in the valley bottom. As described in Section 3.2.1.8.1, DOE included the exposure pathways of ingesting water from springs and using that water for other purposes (for example, evaporative cooling) in the calculation of impacts in the Furnace Creek springs area.

To calculate external exposure and inhalation exposure of contaminated evaporites, DOE assumed that the receptor would always be outdoors, where contaminants would be present, and that they would be engaged in activities that would not significantly resuspend soil. It was also assumed that all particulates inhaled and inadvertently ingested would be contaminated evaporites. Thus, the analysis very conservatively estimates exposure because it does not account for time spent indoors, where concentrations of resuspended particles would be lower and the receptor would be shielded from some radiation, or time spent away from the area of potential surface contamination. Because there are no residences and few other permanent facilities (such as parking lots, overlooks, and nature paths for tourists visiting Death Valley National Park) on or immediately adjacent to the saltpan at Middle Basin, it is likely that residents would spend substantially less time in areas directly contaminated by evapotranspiration of groundwater. In addition, contaminated evaporites would only be a portion of the total amount of particulates inhaled or inadvertently ingested, which is not discounted in the exposure estimates (see details in Appendix B, Section B.2.3.2.2).

The mass concentration of contaminants in the soil at the discharge site on the floor of Death Valley would not increase over time due to accumulation because contaminants would continue to precipitate along with the same or similar mass of other dissolved solids. Evaporite minerals deposited on the surface of wet playas in this region often are deflated, or eroded, by wind (Reynolds et al. 2007, pp. 1815 through 1820). Similarly, over time, contaminants and the evaporite minerals would be removed from the playa surface by *eolian processes* and dispersed over a large area within and surrounding Death Valley. The mass concentration of contaminants at those sites would be less than that on the floor of Death Valley (at Middle Basin) because the contaminants and associated evaporites would be mixed with uncontaminated, rock-based clastic soils and uncontaminated evaporites blown or washed in from other locations. Thus, even after many years of dispersal, the dose or intake at locations surrounding the playa where contaminants may be redeposited would be less than that estimated for Middle Basin on the floor of Death Valley.

3.2.2 CONSERVATISMS IN THE APPROACH

As mentioned previously, DOE selected the analytical framework developed for this Analysis of Postclosure Groundwater Impacts to provide the range of potential impacts at the groundwater exposure locations while considering the various uncertainties discussed in Section 3.1.1. Therefore, the following conservatisms were inherent in the analytical framework.

1. DOE developed an analytical framework based on a scenario that a relatively high rate of pumping would continue for 1 million years, regardless of climate or other factors. The long-term pumping would result in collection and recycling of all contaminants in one limited area. This scenario is very conservative for the estimates of potential impacts in the Amargosa Farms area.

2. *Glacial* climate conditions generally occur periodically in 10,000- to 100,000-year cycles (see Section 2.2.1.2.4). For example, very wet conditions are postulated to have occurred during the Illinoian glacial stage of about 140,000 to 170,000 years ago, and a full glacial wet condition is evidenced around 21,000 years ago (DIRS 120425-D'Agnese et al.1999, p. 4). These glacial conditions are characterized by significantly cooler and wetter climate conditions. Periodic glacial climate conditions would result in high *recharge* rates at the recharge areas and cause a general rise in the water table. The result would be increased discharge of surface water at locations where contaminants are released, which could dilute and disperse many of the contaminants over a very large area such that accumulation at natural discharge points would be unlikely over 1 million years.

3. DOE used present day discharge flow rates at natural discharge locations because there is no sure way to predict these flow rates when there is no pumping. Actual discharge rates presently observed were used at the Middle Basin (in this case evapotranspiration), the springs at Furnace Creek, and Alkali Flat (also an evapotranspiration site). Currently, there is regional pumping so these rates will not match what might be expected if there were no pumping. Thus, the flow rates are likely underestimated for the no-pumping scenario. While higher flows tend to move contaminants to the location faster, the *attenuating* effect of delay is not nearly as important in the calculation of the concentrations of radionuclides and other contaminants as dilution (especially for radionuclides with long half-lives, stable metals, and contaminants with low or zero *partition coefficients*). The results below show that higher flow rates at the natural discharge locations during the wetter climate result in lower doses even though more contaminants arrive earlier. Therefore, use of present day flow rates likely resulted in overestimation of doses at the natural discharge locations.

The techniques DOE used in this analysis were suitable for characterizing the regional releases and impacts identified by NRC staff. In such an approach, some specific details need not be included. For example, the interaction of contaminants with the solids (rocks and soils) through which the water flows is a very complex set of processes. The TSPA-LA model accounted for a wide variety of processes with a large body of research and computational complexity. The modeling with the Death Valley regional groundwater flow model accounted for heterogeneities in the flow system, and this was reflected in the transport analysis. Many other simplifications were used. Whenever simplifications were used, DOE applied them in a conservative manner to avoid underestimation of impacts. For example, when comprehensive knowledge of complexities of transport were not know, DOE selected partition coefficients with low values compared with literature values (especially for the nonradiological contaminants).

For this Analysis of Postclosure Groundwater Impacts, DOE used a fairly large time step in the flux-versus-time curves. To ensure conservatism, discrete steps were taken in such a way so that the stepped curve was generally higher and occurred sooner than the continuous flux curve being represented. This approach maximizes both the flux (during a period of rising flux) and the cumulative release.

The release rates for the nonradiological contaminants from the repository are conservative because DOE assumed that all surfaces are constantly corroding and in constant contact with water flowing through the

repository. This is different from the seepage models in the TSPA-LA model, which estimate intermittent drips at various locations in the repository. The nonradiological contaminants release rate model also does not consider that all of the *Alloy 22* (the major source of molybdenum) is initially under drip shields, protected from infiltrating water.

The estimate of doses and intakes at Middle Basin on the Death Valley floor included the following conservatisms:

- In the estimate of concentration of contaminants in the solids, DOE used a low level of total-dissolved-solids found in local groundwater. Higher values of total-dissolved-solids would reduce the estimated concentration and therefore dose and intakes.

- In the calculation of exposure from inhalation of airborne particulates:

  - DOE assumed that all resuspended particulates that the receptor breathes in are evaporite minerals. Inclusion of rock-based clastic soils would reduce the estimated concentration and therefore doses and intakes;

  - DOE used the maximum value for the concentration of resuspended particles for the environment considered in the analysis;

  - DOE assumed that the receptor would inhale air containing the estimated concentration of contaminants for the entire year; and

  - The single value of breathing rate used ignores the fact that people spend 8 or so hours asleep when their breathing rate would drop by at least half the assumed value.

- For ingestion of contaminated soil:

  - DOE assumed that all material that is inadvertently ingested consists of evaporite minerals, and

  - The daily ingestion rate is relatively high at 100 milligram per day (for example, the EPA recommends 50 milligrams per day for adults and 100 milligrams per day for children (DIRS 152549-EPA 1997, Table 4-23).

- For external exposure to radionuclides in soil:

  - DOE used dose coefficients developed for soil contaminated to an infinite depth, although most evaporites would be on or near the soil surface. Dose coefficients for a lesser depth would be lower and would reduce the estimate of dose; and

  - DOE assumed that the receptor would be outdoors and exposed to contaminated evaporites year-round.

The above detailed summary shows that the analysis DOE carried out is, overall, very conservative so as not to underestimate impacts from the scenarios analyzed.

3.3 Results

This section describes the results of release and accumulation analyses. Section 3.1 describes the framework for the analysis and Section 3.2 describes the analytical method. Appendix B contains more details of the technical approach and the results.

3.3.1 RADIOLOGICAL CONTAMINANTS

DOE estimated dose as a function of time for the 1-million-year postclosure period. Table 3-1 summarizes the estimated peak annual doses during this time for the radiological contaminants. This table also gives the *probability* of a *latent cancer fatality* associated with these individual doses. As recommended by the Interagency Steering Committee on Radiation Standards, this Analysis of Postclosure Groundwater Impacts uses a conversion factor of 0.0006 probability of latent cancer fatality per rem of dose, for members of the public, to estimate the health effects of radiologic doses (DIRS 174559-Lawrence 2002, p. 2).

Table 3-1. Peak annual dose and probability of latent cancer fatalities for six exposure scenarios.

	Peak annual dose (millirem per year)		Probability of latent cancer fatality	
Scenario	10,000 years after closure	1,000,000 years after closure	10,000 years after closure	1,000,000 years after closure
Amargosa Farms area, pumping, present climate	2.1×10^{-1}	1.1	1.2×10^{-7}	6.7×10^{-7}
Amargosa Farms area, pumping, wetter climate	2.5×10^{-1}	1.3	1.5×10^{-7}	8.0×10^{-7}
Middle Basin, no-pumping, present climate	0.0	1.6×10^{-1}	0.0	9.5×10^{-8}
Middle Basin, no-pumping, wetter climate	1.5×10^{-2}	4.2×10^{-2}	8.9×10^{-9}	2.5×10^{-8}
Furnace Creek springs area, no-pumping, present climate	0.0	3.4×10^{-1}	0.0	2.1×10^{-7}
Furnace Creek springs area, no-pumping, wetter climate	2.3×10^{-2}	8.9×10^{-2}	1.4×10^{-8}	5.4×10^{-8}

As a point of comparison, the mean peak annual dose for 10,000 years after closure reported in the Repository SEIS for the RMEI at the Regulatory Compliance Point was 2.4×10^{-1} millirem per year, and the mean peak annual dose during 1 million years after closure was 2.0 millirem per year (DIRS 180751-DOE 2008, p. 5-27). Note that the Repository SEIS results during the 10,000-year dose were for a dry climate for the first 600 years and a progressively wetter climate for the remaining 9,400 years. The wetter climate result in this Analysis of Postclosure Groundwater Impacts at the Amargosa Farms area would tend to be somewhat higher because the wetter climate was imposed for the entire period. Also, the doses estimated at the Amargosa Farms area were based on recycling of contaminants back into the groundwater. A calculation of recycling for the RMEI location showed an 11-percent increase in dose when recycling was applied (DIRS 182130-SNL 2007, all). All of the doses in Table 3-1 are less than or about equal to the doses the TSPA-LA presented for the Regulatory Compliance Point. For further comparison, the regulations require that the mean RMEI annual dose be less than 15 millirem per year for the first 10,000 years and the mean RMEI peak annual dose be less than 100 millirem per year for 1 million years (10 CFR Part 63).

Figures 3-5 to 3-8 present the estimate of doses over time at the Amargosa Farms area, the Furnace Creek springs area, and the floor of Death Valley. Appendix B provides plots of dose contributions by individual radionuclides. The long-term risk to area residents and visitors to the *Death Valley region* from groundwater contamination would be very low based on the annual dose calculations presented above.

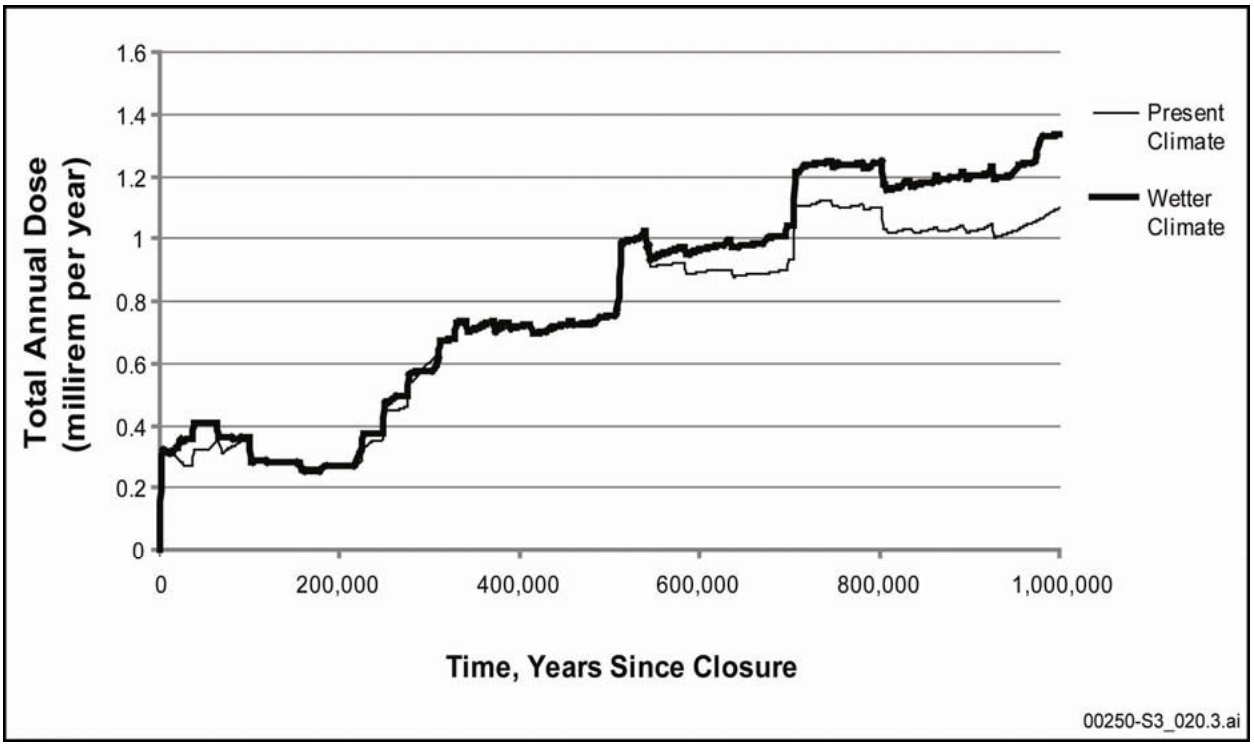


Figure 3-5. Total annual dose at the Amargosa Farms area.

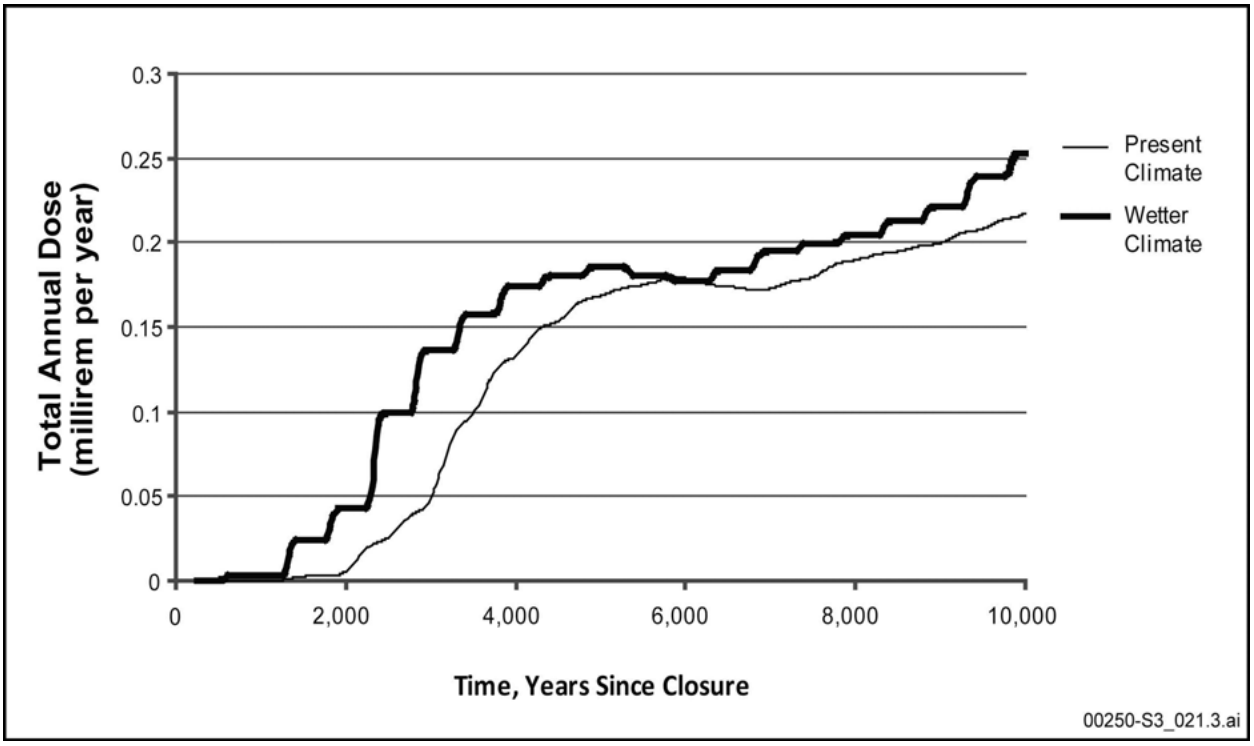


Figure 3-6. Total annual dose at the Amargosa Farms area for the first 10,000 years.

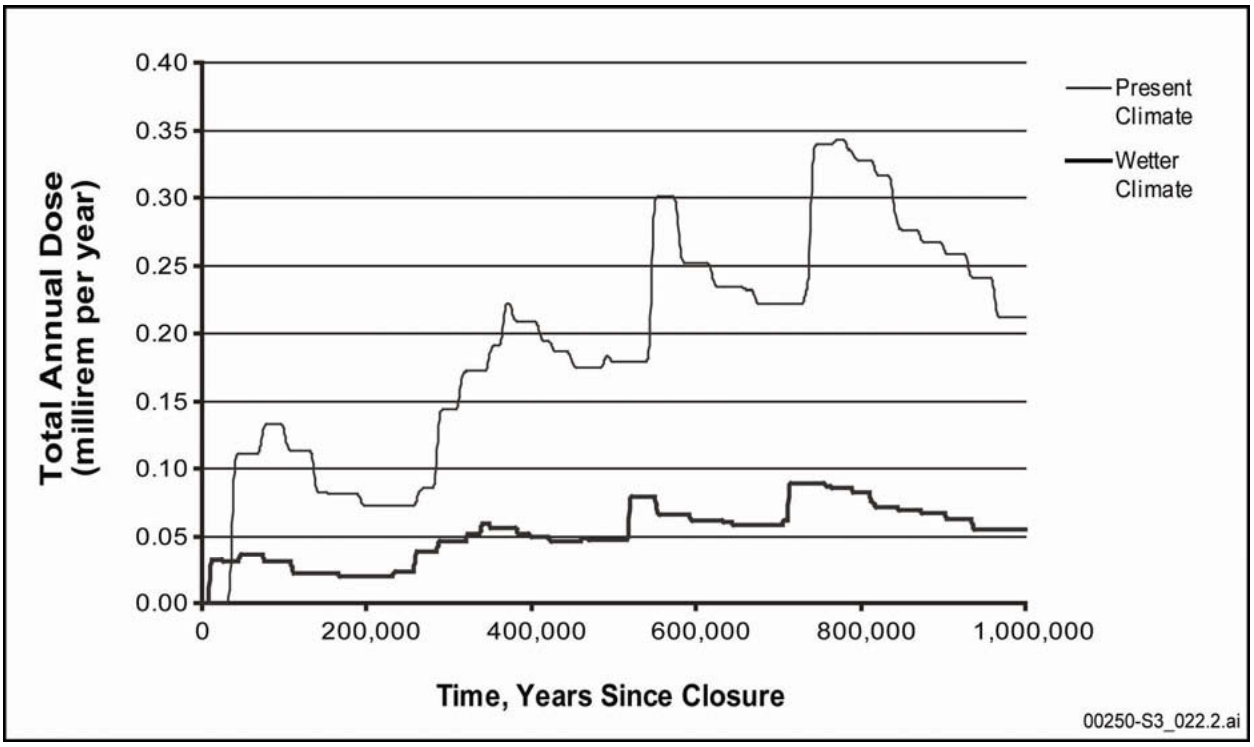


Figure 3-7. Total annual dose at the Furnace Creek springs area.

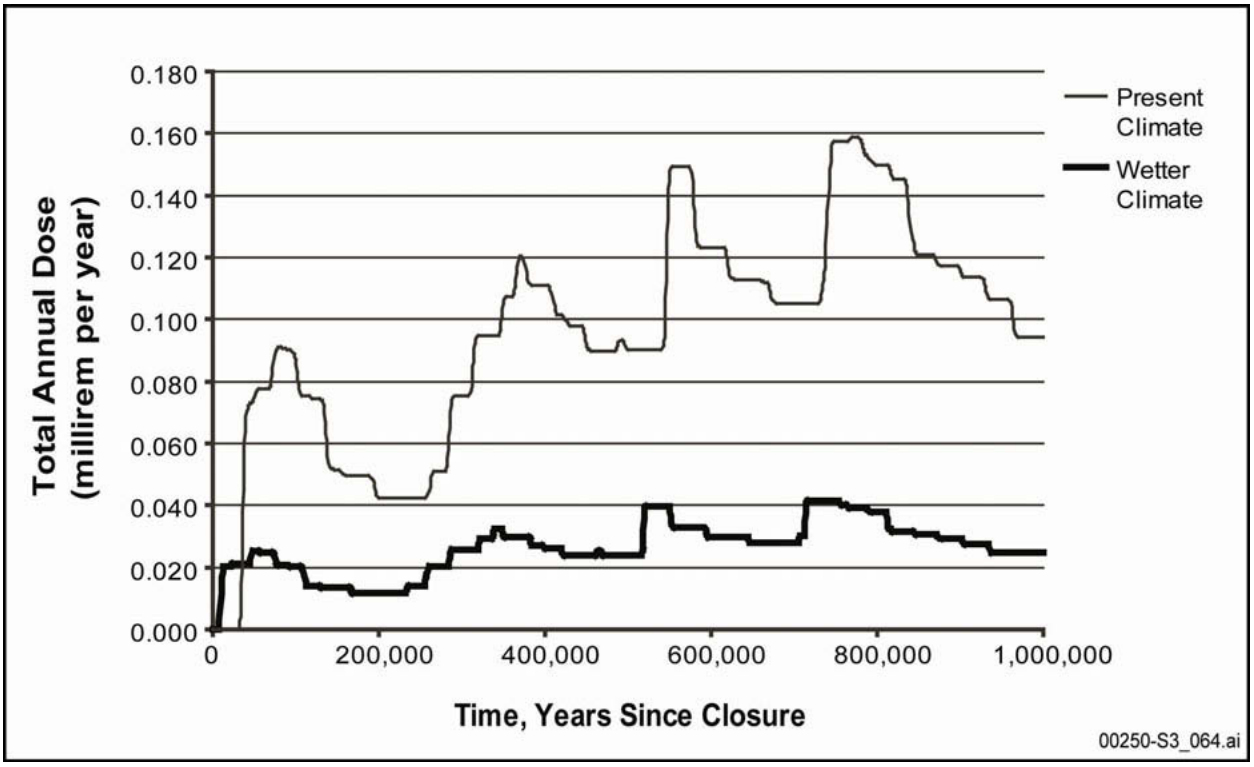


Figure 3-8. Total annual dose at the Middle Basin.

Because the human health consequences are so low, DOE would not expect any harm to flora or fauna. Dose rates to plants and animals are expected to result in radiation absorption levels much less than 100 millirad per day. A rad is a unit of radiation absorption by any object, living tissue or otherwise. In people, rads are converted to rem (roentgen-equivalent-man). For radiation such as gamma or x-rays, one rad equals one rem in a person. For flora and fauna, a radiation unit for humans (rem) would be inappropriate, so radiation absorption is expressed in rad or millirad. The International Atomic Energy Agency concluded that chronic radiation absorption of less than 100 millirad per day is unlikely to cause measurable detrimental effects in populations of the more radiosensitive species in terrestrial ecosystems (DIRS 103277-IAEA 1992, p. 53). While not directly comparable, the fact that annual radiation doses at exposure locations evaluated in this Analysis of Postclosure Groundwater Impacts are all less than 2 millirem (0.002 rem), it can be concluded that radiation effects to flora and fauna would be several orders of magnitude below 100 millirad.

WHY ARE THE DOSE PLOTS SO JAGGED?

Anyone used to viewing plots of dose histories from the TSPA-LA might wonder why the dose histories in this Analysis of Postclosure Groundwater Impacts appear so jagged. There are two basic reasons:

1. The TSPA-LA model resulted in similar abrupt changes in dose histories per time step, but those changes were less apparent because of the use in TSPA-LA reports of logarithmic-scaled plots that depicted changes over long time periods. The results of the TSPA-LA model used as input to the modeling for this document have similar abrupt changes per time step, but those changes are more evident in this analysis because a linear, rather than logarithmic, scale is used for the total dose plots. Logarithmic scales are used to present results that vary by several orders of magnitude.

2. The coarser (that is, longer) time step used in the analyses for this document resulted in curves having a jagged appearance. This longer time step was appropriate for the purposes of these analyses. Using a shorter time step would have resulted in smoother curves, but would not have changed any of the results or conclusions of the analyses.

For the present climate condition, radionuclides that have no adsorption to slow down their travel dominate dose at the Amargosa Farms area; that is, iodine-129 and technetium-99. During the wetter climate condition, some slower-moving radionuclides, such as plutonium-242, contribute significantly to the total dose (at least for a limited time). In the Furnace Creek springs area plot (Figure 3-7), the wetter-climate dose is higher than the drier-climate dose for about the first 30,000 years. This is a good demonstration of the relative effects of delay and dilution. The wetter climate doses are reduced by more dilution from the higher flow rates so that they are generally lower than the dry climate. However, the increased flow of groundwater during the wetter climate causes radionuclides to arrive earlier.

There is also a degree of uncertainty for the actual percentage of flow that could divert to Alkali Flat as opposed to the floor of Death Valley. If all of the flow were to divert to Alkali Flat, then the dose could be as much as twice that calculated for the floor of Death Valley. Franklin Lake Playa at Alkali Flat is also a wet playa and the radionuclide flux would be estimated to be about the same as Middle Basin if all the flow were diverted to Alkali Flat. The analytical difference is that the evapotranspiration rate at Franklin Lake Playa is about half of that at Middle Basin and dose is inversely proportional to evapotranspiration rate. This estimated result applies a very conservative assumption, in that if all of the contaminants were to divert to Alkali Flat, the evapotranspiration rate at that location would not increase

from its current measured value. It would be very likely that any diversion of contaminants would be the result of increased groundwater flow in the direction of Alkali Flat and that there would be increases in the evapotranspiration rate at the playa. Since these parameters are not known, DOE made this conservative, qualitative estimate.

3.3.2 NONRADIOLOGICAL CONTAMINANTS

The nonradiological contaminants considered include molybdenum, nickel, vanadium, and uranium. Uranium is included in both radiological and nonradiological contaminants because uranium has a notable toxicity as a heavy metal. The uranium concentrations are a sum of the uranium isotopes from the radionuclide calculations. DOE assessed human health impacts of the nonradiological materials by comparing daily intakes with EPA's *Oral Reference Dose* standard (DIRS 148228-EPA 1999, all; DIRS 148229-EPA 1999, all; DIRS 103705-EPA 1997, all; DIRS 102173 EPA-1994, all). For exposure locations involving ingestion of potentially contaminated water (that is, the Amargosa Farms and Furnace Creek springs areas), DOE calculated the daily intake for a 70-kilogram person drinking 2 liters of water daily. For exposures at the Death Valley floor, the daily intakes are due to dust ingestion and inhalation in milligrams per day for a 70-kilogram person. Table 3-2 summarizes the estimated daily intakes of the nonradiological contaminants. The bottom row of the table shows EPA's Oral Reference Doses.

ORAL REFERENCE DOSE

The Oral Reference Dose is based on the assumption that thresholds exist for certain toxic effects such as cellular necrosis. It is expressed in units of milligrams per kilograms per day. In general, the Oral Reference Dose is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Table 3-2. Peak daily intakes of the nonradiological contaminants.

Scenario	Peak daily intakes (mg/kg body wt.-day) of metals during 1 million years after closure			
	Molybdenum	Nickel	Vanadium	Uranium
Amargosa Farms area, pumping, present climate[a]	3.00×10^{-3}	1.37×10^{-2}	6.04×10^{-6}	3.47×10^{-6}
Amargosa Farms area, pumping, wetter climate[a]	3.00×10^{-3}	1.37×10^{-2}	6.04×10^{-6}	3.84×10^{-6}
Middle Basin, no-pumping, present climate[b]	6.80×10^{-4}	0.0	0.0	0.0
Middle Basin, no-pumping, wetter climate[b]	1.74×10^{-4}	0.0	0.0	0.0
Furnace Creek springs area, no-pumping, present climate[a]	2.99×10^{-3}	0.0	0.0	0.0
Furnace Creek springs area, no-pumping, wetter climate[a]	7.67×10^{-4}	0.0	0.0	0.0
Oral Reference Dose (mg/kg body-wt/day)	5.00×10^{-3}	2.00×10^{-2}	7.00×10^{-3}	3.00×10^{-3}

Sources: DIRS 148228-EPA 1999, all; DIRS 148229-EPA 1999, all; DIRS 103705-EPA 1997, all; DIRS 102173-EPA 1994, all.
a. Based on a 70-kilogram person drinking 2 liters of water per day.
b. Based on a 70-kilogram person ingesting and inhaling a given amount of contaminant per day (milligrams).
mg/kg body-wt/day = milligram per kilogram body-weight per day.

All intakes are below the Oral Reference Dose. Note that there are a number of zeros in the table. The zero values signify when a contaminant is estimated to not reach the discharge area during the 1-million years.

Figures 3-9 and 3-10 present detailed plots of the daily intakes of nonradiological contaminants for the Amargosa Farms area location.

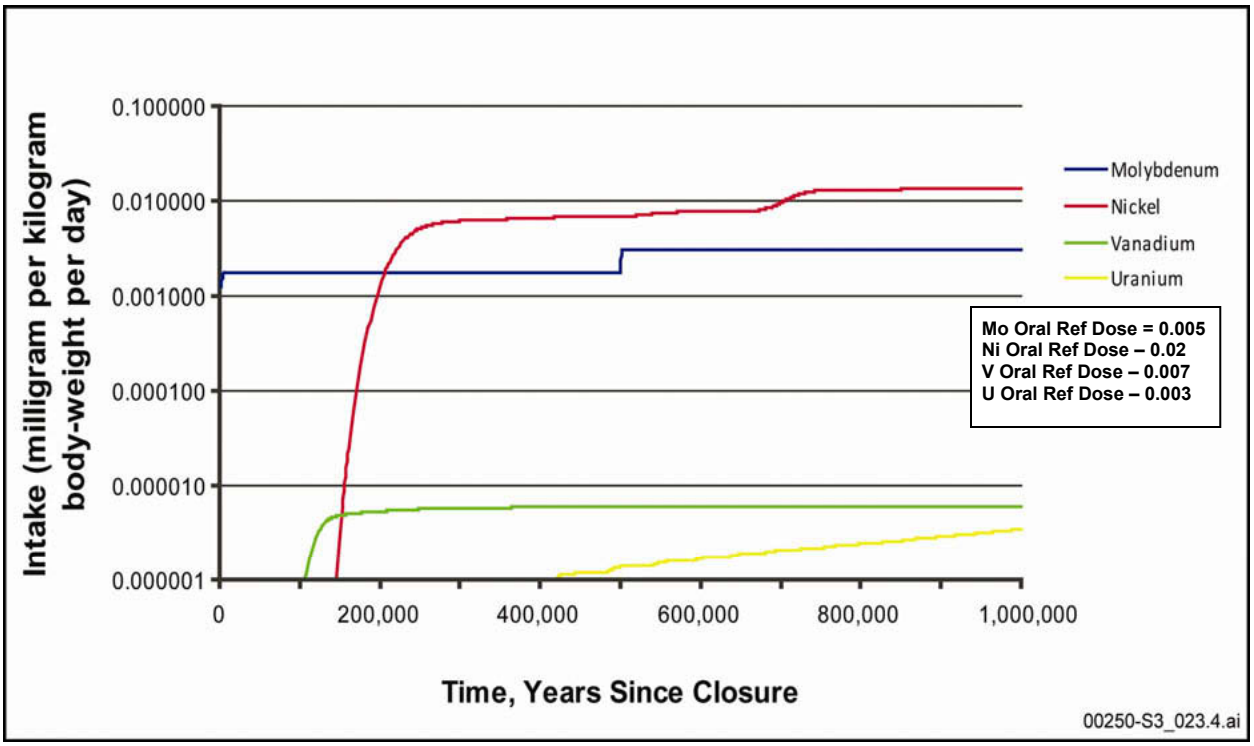


Figure 3-9. Daily intakes of nonradiological contaminants at the Amargosa Farms area, present climate.

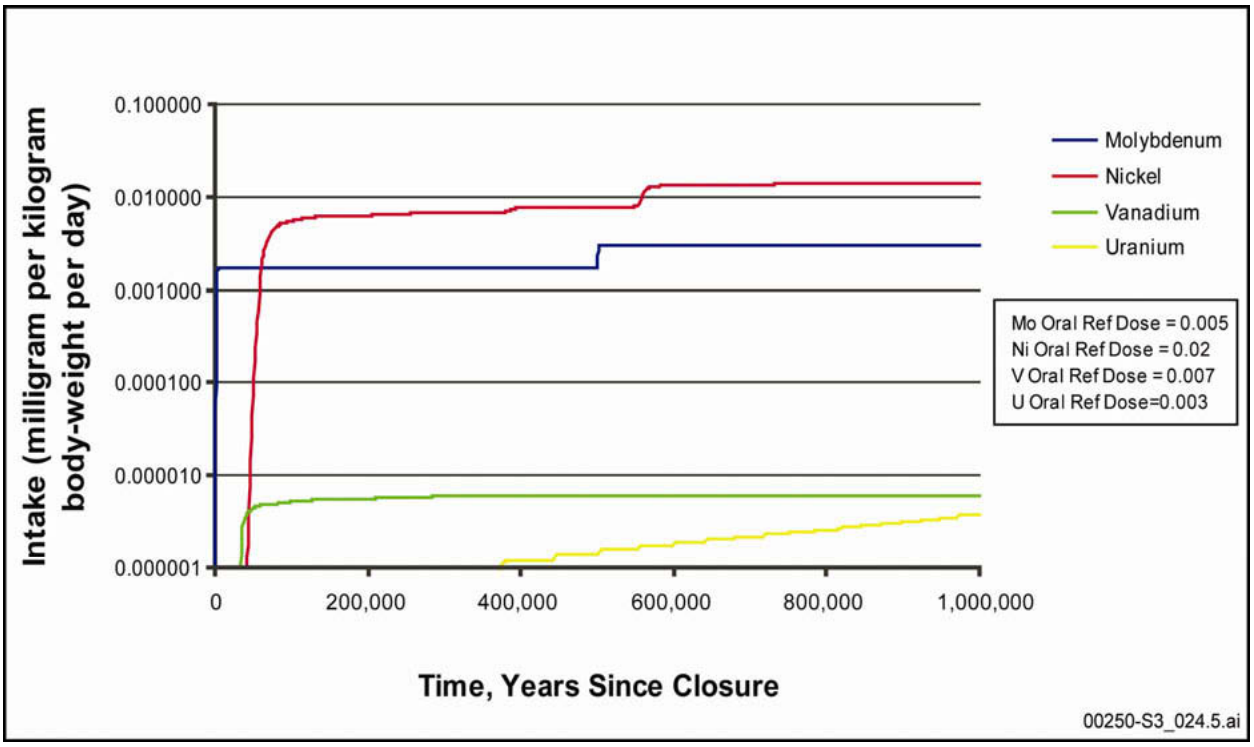


Figure 3-10. Daily intakes of nonradiological contaminants at the Amargosa Farms area, wetter climate.

Figures 3-11 and 3-12 show estimated daily intakes of molybdenum at the Furnace Creek springs area. Molybdenum is the only nonradiological contaminant that would reach the Death Valley natural discharge locations during the 1-million-year period. Figure 3-13 shows the estimated daily intakes of molybdenum at the Death Valley floor (Middle Basin).

Just as with the radionuclides, if all of the contaminants were to divert to Alkali Flat, then intakes would be approximately double those of the Death Valley floor. As explained in Section 3.3.1, this approximation is made using very conservative assumptions.

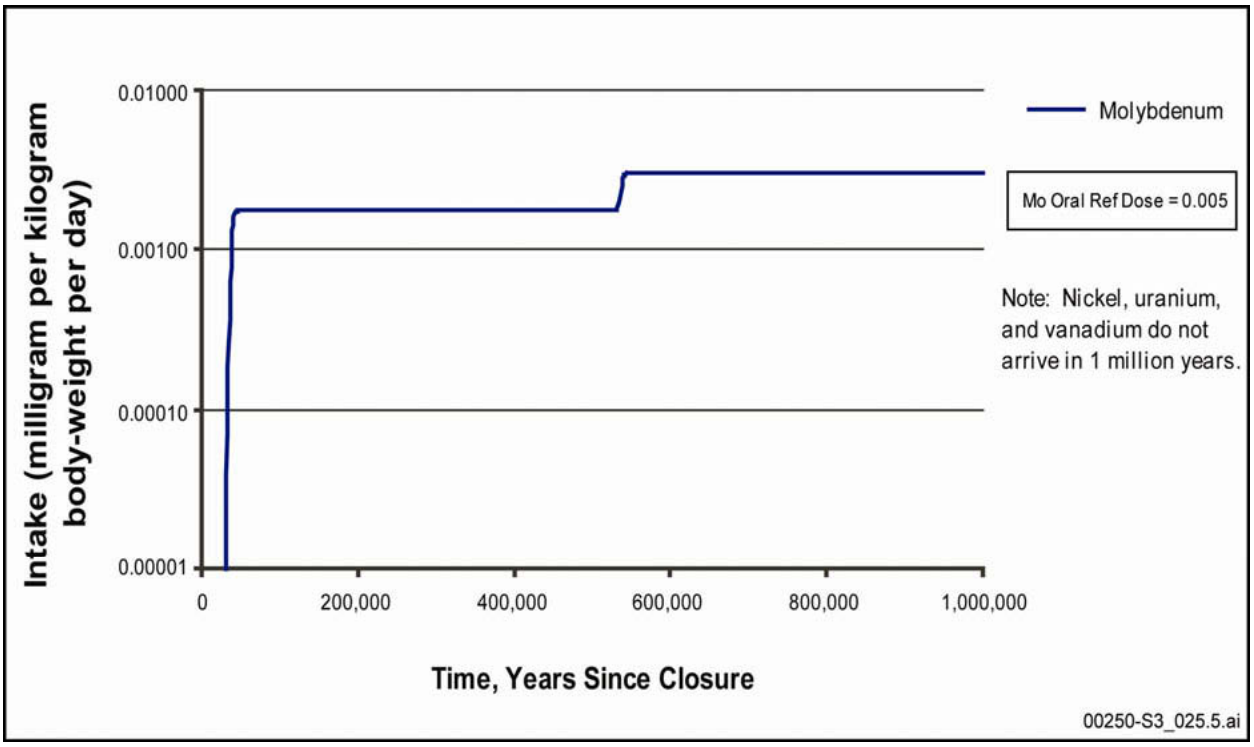


Figure 3-11. Molybdenum daily intake at the Furnace Creek springs area, no-pumping, present climate.

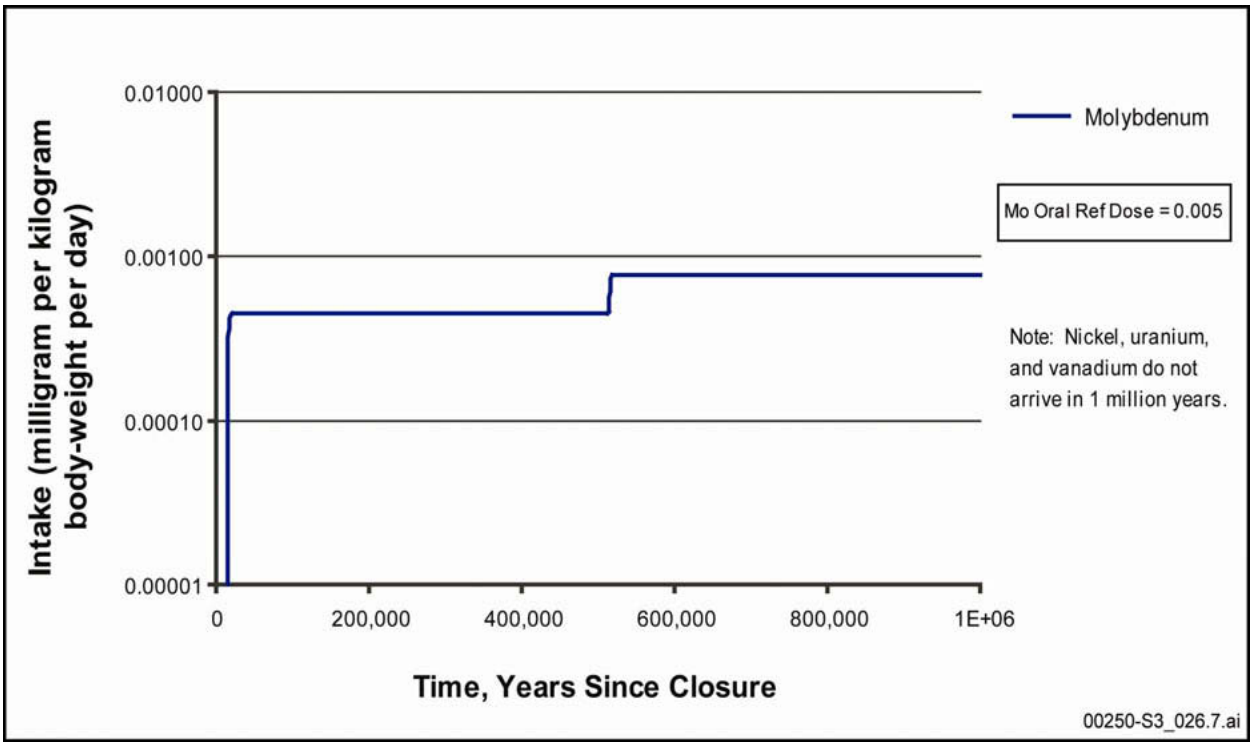


Figure 3-12. Molybdenum daily intake at the Furnace Creek springs area, no-pumping, wetter climate.

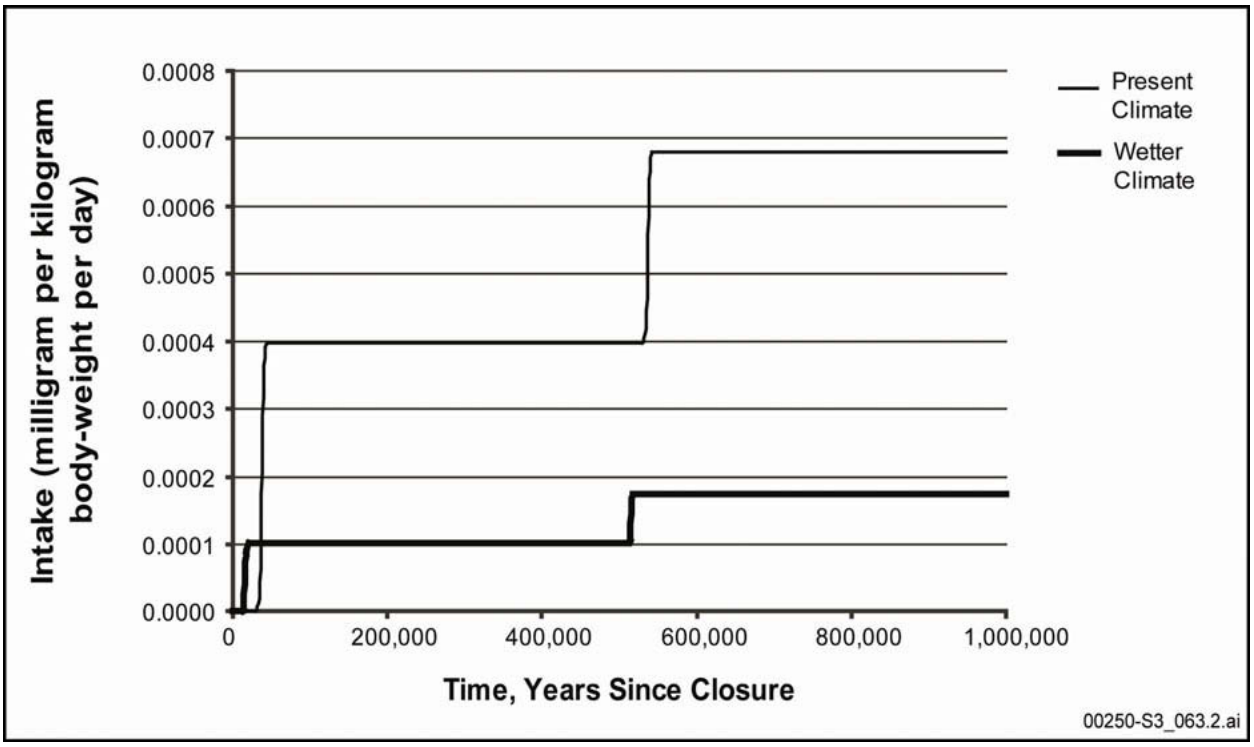


Figure 3-13. Molybdenum daily intake at Middle Basin, no-pumping.

3.3.3 MASS BALANCES

DOE used the fluxes of contaminants to develop inventories at the Amargosa Farms area, Furnace Creek springs, and Middle Basin on the floor of Death Valley. These inventories represent the decay- and growth-adjusted cumulative release. DOE then used the cumulative releases to develop an overall mass balance for individual contaminants. Appendix B provides detailed mass balances.

3.3.4 SOIL CONCENTRATIONS

Under the pumping scenario, the analysis includes the irrigation of fields with potentially contaminated groundwater. As irrigation water containing contaminants dispenses over the fields, contaminants would infiltrate the soil, and water would seep into the soil and also evaporate. Some contaminants (especially those with strong bonding to the soil; that is, high adsorption or high partition coefficients) would remain in a surface layer. DOE estimated soil concentrations as part of the transport and dose calculations. Soil concentrations at the Amargosa Farms area are reported in Appendix B, Section B.4.3. Different processes drive soil concentrations at the natural discharge points; Section 3.2.1.8 discusses these processes. Soil concentrations at Middle Basin are reported in Appendix B, Section B.4.4.

3.3.5 ADDITIONAL POTENTIAL DISCHARGE LOCATIONS

In addition to Furnace Creek springs, the Death Valley floor, and Alkali Flat, contaminants might also discharge at the area of the State Line Deposits during the wetter climate (Chapter 2, Figure 2-5). As described in Section 2.2.2.2, USGS' 1999 groundwater model simulations of the past wetter (full-glacial) climate depict groundwater discharges associated with the State Line Deposits extending northward along the path of Fortymile Wash (DIRS 120425-D'Agnese et. al. 1999, pp. 22 and 23). The report on DOE's Irrigation Recycling Model considered the USGS' 1999 simulations of past and future wetter climates and

identified one of these simulated discharge points as being located on the flow path from the repository and a few kilometers north of the Amargosa Farms area (DIRS 182130-SNL 2007, page 6-47 and Figure 5.1-1). The USGS identified this area as a discharging area during a future climate similar to the wetter climate analyzed in this Analysis of Postclosure Groundwater Impacts. It is not clear what discharge rate might occur at this site, but it is reasonable to assume that it might be approximately 2,000 acre-feet per year during a wetter climate (estimates show Furnace Creek springs' discharge to be over 2,300 acre-feet in the present climate). If some portion of the contaminant plume were to flow to this discharge area, then the dose and intake estimates could be somewhere between those estimated for the Amargosa Farms area (pumped with recycle) and those for the Regulatory Compliance Point with a water supply of 3,000 acre-feet per year. This diversion would somewhat reduce the doses and intakes at Death Valley if there were no pumping. If there were full pumping, the water from the discharge site could contain concentrations of contaminants less than those at Regulatory Compliance Point but somewhat higher than those at the Amargosa Farms area. If the site were a spring, then the discharging water would flow down Fortymile Wash and the Amargosa River in a generally southerly direction. Assuming this surface water might be used for farming, the doses resulting from its use could be somewhere between those estimated for the Amargosa Farms area and those estimated in the Repository SEIS for the Regulatory Compliance Point. The existence of this additional natural discharge site and possible presence of surface water could lead to less pumping, which could result in less groundwater flow, and therefore contaminants, toward the Amargosa Farms area and therefore more flow, and contaminants, toward natural discharge points. Reduced pumping falls within the framework analyzed previously and would result in decreasing doses at the Amargosa Farms area while increasing doses at natural discharge points to levels somewhere in between those reported in Table 3-1 for full pumping at the Amargosa Farms area and those for no pumping at the natural discharge sites in Death Valley.

DOE believes the groundwater levels predicted for past and future wetter climates in the USGS 1999 report may be overestimated based on physical evidence of ancient groundwater elevations beneath Yucca Mountain (Repository SEIS, Section 3.1.4.2.2, page 3-44). However, the information was used in the Irrigation Recycling Report to evaluate conservatively high estimates of groundwater elevation (representing a worse-case in the effects of recycling contaminants back to groundwater from irrigation). Likewise, these high groundwater elevations are qualitatively analyzed here to evaluate a potential future, wetter climate groundwater discharge location closer to the repository site where contaminant concentrations could be higher than those presented for Amargosa Farms. Realistically, potential groundwater discharge locations would be more likely to occur within the primary area of the State Line Deposits, located to the south of Amargosa Farms. This location would experience lower contaminant concentrations than were evaluated for Amargosa Farms and thus, impacts in this area would be expected to be less than those presented for the Amargosa Farms area.

3.4 Cumulative Impacts

The Repository SEIS analyzed the potential environmental impacts of the reasonably foreseeable action of disposing of Inventory Modules 1 and 2 beyond that of the *Proposed Action* (70,000 *metric tons of heavy metal*) (DIRS 180751-DOE 2008, Section 8.3.1). These inventory modules represent the total projected amount of *spent nuclear fuel* and *high-level radioactive waste* (Module 1) and the additional inventory of other *radioactive* materials such as Greater-Than-Class C low-level radioactive wastes (Module 2). The Repository SEIS developed scale factors for how the addition of Modules 1 and 2 to the proposed repository inventory would affect the dose and nonradiological impacts at the Regulatory

Compliance Point. DOE found that impacts of the modules would increase linearly relative to the increased number of waste packages. Because the regional impacts reported in this Analysis of Postclosure Groundwater Impacts depended directly on the fluxes at the Regulatory Compliance Point, it is reasonable to assume that the cumulative impacts of the inventory modules on the regional radiological impacts would also increase by the linear relationship identified in the Repository SEIS. The scale factors for the nonradiological contaminants molybdenum, nickel, and vanadium would be likewise. Because the estimated 1-million-year regional impacts at the various exposure locations Section 3.3 evaluated are all less than the dose estimates the Repository SEIS presented for the Regulatory Compliance Point, the estimated doses at these locations would also be less than the estimated doses presented in the Repository SEIS for the inventory modules. Likewise, the intakes of toxic metals would be less than or about equal to those presented in the Repository SEIS.

The Repository SEIS also evaluated the cumulative impact from Nevada Test Site activities, primarily as a result of past underground weapons testing (DIRS 180751-DOE 2008, p. 8-36). After evaluation, the estimated total potential cumulative impact (Yucca Mountain impact plus Nevada Test Site impact) would be 0.24 millirem per year to the RMEI for the 1-million-year period. It would be reasonable to expect that the same effect applies to the regional dose impacts in this Analysis of Postclosure Groundwater Impacts and would therefore contribute an insignificant amount to the 1-million-year dose.

3.5 American Indian Concerns

The analyses of potential impacts to cultural resources from construction, operation and monitoring, and eventual closure of a repository that were included in the Yucca Mountain FEIS (DIRS 155970-DOE 2002, Section 4.1.5.2) and Repository SEIS (DIRS 180751-DOE 2008, Section 4.1.5.1) focused on resources within and near the land withdrawal area. Those analyses were based in part on a Native American Interaction Program conducted by the DOE since the late 1980s to obtain input and perspectives from American Indian tribes. In addition, consultation between DOE and the tribes, including the Timbisha Shoshone Tribe, has occurred at tribal locations over the years. During preparation of the Yucca Mountain FEIS, DOE interacted with American Indian tribes on a range of topics to assess their viewpoints and perspectives. DOE supported the American Indian Writers Subgroup of the Consolidated Group of Tribes and Organizations in its preparation of American Indian Perspectives on the *Yucca Mountain Site Characterization Project and the Repository Environmental Impact Statement* (DIRS 102043-AIWS 1998, all) and discussed that document in the above environmental impact statements.

Neither the Yucca Mountain FEIS nor Repository SEIS included a specific analysis of potential effects of a change in groundwater quality on the use of springs and associated cultural resources in the Furnace Creek area or elsewhere in the Yucca Mountain region. This is because DOE concluded that groundwater flowing under Yucca Mountain likely would discharge at Alkali Flat (DIRS 180751-DOE 2008, Section 5.4) and that concentrations of radionuclides and associated health effects at downgradient locations would be no greater than those estimated in the Repository SEIS for the Regulatory Compliance Point (DIRS 180751-DOE 2008, Section 5.1.1.4 and Appendix F). This Analysis of Postclosure Groundwater Impacts describes the possibility that groundwater that flows under Yucca Mountain could discharge via evapotranspiration at the floor of Death Valley or at springs in the Furnace Creek area of Death Valley (Section 3.1.1.2); therefore, DOE has further considered potential impacts to cultural resources and American Indian concerns.

Members of the Timbisha Shoshone Tribe reside on a 314-acre parcel of trust land located in the Furnace Creek area of Death Valley. The tribe has federally appropriated rights to 92 acre-feet per year of surface and groundwater in the area (16 U.S.C. 410aaa). The springs in the Furnace Creek area, including the Furnace Creek, Texas, Travertine, and Salt springs, are of traditional and cultural importance to members of the Timbisha Shoshone Tribe, and the purity of water in those springs is important to Tribal spiritual beliefs, culture, and heritage. Members of the Tribe have stated that even small amounts of contaminants would be disrespectful to the springs and to the earth (DIRS 186231-NRC 2009, pp. 28 to 30).

To evaluate changes in groundwater quality during the postclosure period, and potential impacts to American Indians and other residents of Death Valley, DOE estimated annual doses of radiological contaminants and daily intakes of nonradiological contaminants that would result from the use of the springs in the Furnace Creek area. As described in Section 3.3.1, if all radionuclides were to discharge at the springs in the Furnace Creek area, the estimated peak annual doses during the 1-million-year period after *repository closure* would be 0.34 millirem for the present climate and 0.09 millirem for the wetter climate. The corresponding probabilities of a latent cancer fatality are less than 1 chance in 1 million (Table 3-1). Those dose estimates include contributions from the most likely pathways by which residents of Death Valley would be exposed to radionuclides discharged from the springs, including external exposure, ingestion and inhalation of soil, ingestion of water, and use of evaporative coolers (a type of air conditioner). Ingestion of locally produced foodstuffs was not included because there is limited production of food products in Death Valley National Park.

Even if the Department had assumed that fruits, vegetables, and animal products were locally produced using the spring water, following agricultural practices and consumed at rates similar to those of the residents of Amargosa Valley (where locally produced foodstuffs are readily available), the estimated peak annual doses during the 1-million-year period would only increase to 0.61 millirem for the present climate and 0.19 millirem for the wetter climate. These dose estimates account for the potential dose to Death Valley residents that may periodically consume locally produced garden products irrigated with spring water or native plants and animals living at the springs. These estimates also account for external exposure to mineral deposits in the immediate vicinity of the springs and native plant or animal material obtained from the springs and used to construct crafts or other products. This is because DOE based the biosphere dose conversion factors used to calculate the external exposure rates on the assumption that receptors would be exposed year-round and throughout the local environment to soil contaminated by the use of groundwater for irrigation. In Death Valley, people would be exposed to contaminated soil only when they would be within or near the limited areas with flowing or standing water around and downstream of the springs, and where groundwater would be used for gardens and residential landscaping. Thus, the model assumed that the period of external exposure to contaminated soil would exceed the period of exposure to products made with contaminated plant and animal materials. The concentration of radionuclides in those products also would likely be less than in soil contaminated by irrigation because the soil is where most of the radionuclides in the biosphere would remain, and because only a portion of the contaminants in the groundwater would be taken up by plants and animals, especially for those radionuclides that build up in the soil (DIRS 183041-SNL 2008, Section 3.3.03.01.0A).

If all of the radiological contaminants were to discharge at Middle Basin at the floor of Death Valley, which is near trust land of the Timbisha Shoshone Tribe, the peak total annual doses to a person living year-round outdoors on the playa during the 1-million-year period after repository closure would be 0.16 millirem per year for the present climate and 0.04 millirem per year for the wetter climate.

The only nonradiological contaminant that would reach Death Valley in an appreciable concentration by 1 million years is molybdenum. The estimated intake for molybdenum at that location is below the Oral Reference Dose (Section 3.3.2).

In the Yucca Mountain FEIS and Repository SEIS, DOE conducted an analysis of environmental justice as required by Executive Order 12898, "Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations." This Executive Order directs agencies to identify and consider disproportionately high and adverse human health, social, economic, or environmental effects of their actions on minority and low-income communities and American Indian tribes and provide opportunities for community input to the process, which includes input on potential effects and mitigation measures. See Section 4.1.13 of the Repository SEIS for an explanation of the requirements of that Executive Order and the methods the Department used to analyze environmental justice. In the Yucca Mountain FEIS and Repository EIS, DOE concluded that there would be no high or adverse impacts on members of the public, including minority and low-income communities or American Indian tribes.

In this Analysis of Postclosure Groundwater Impacts, DOE has identified no high and adverse potential impacts to members of the general public associated with exposure to contaminants that may occur in groundwater following closure of a repository at Yucca Mountain. Further, DOE has not identified subsections of the population, including minority or low-income populations, that would receive disproportionate impacts. Likewise, DOE has identified no unique exposure pathways that would expose minority or low-income populations to disproportionately high and adverse impacts. The Department acknowledges the sensitivities and cultural practices of the Timbisha Shoshone Tribe concerning the use and purity of springs in the Funeral Creek area; however, the analysis included in this Analysis of Postclosure Groundwater Impacts demonstrates that the potential concentrations of contaminants in those springs would be so low that there would be virtually no potential health effects associated with the use of those springs. Thus, this document supports the Department's previous conclusion that no disproportionately high and adverse impacts would result from the proposed repository.

3.6 Summary

DOE's Analysis of Postclosure Groundwater Impacts indicates that while radionuclides would distribute into one or more of several locations and could discharge from springs, the estimated human health consequences would be minimal and would be below the 1-million-year peak annual doses reported in the Repository SEIS assessments for the Regulatory Compliance Point. The analysis also indicates that the human health consequences of the nonradiological contaminants would be below established guidelines. Based on the low human health effects, no impacts to flora or fauna would be expected.

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186186	SNL 2009	SNL (Sandia National Laboratories) 2009. *Inputs to Jason Associates Corporation in Support of the Postclosure Repository Supplemental Environmental Impact Statement (SEIS-3).* LSA-AR-037. Las Vegas, Nevada: Sandia National Laboratories.

A. COMMENTS RECEIVED ON OCTOBER 24, 2008 NOTICE OF INTENT TO PREPARE THE POSTCLOSURE GROUNDWATER SEIS

A.1 Purpose

This appendix presents the comments received in response to the U.S. Department of Energy (DOE or Department) Notice of Intent, "Supplement to the Environmental Impact Statements for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, NV" (73 FR 63463, October 24, 2008). Although this Analysis of Postclosure Groundwater Impacts is not a supplemental EIS, the Department has elected to include the comments and responses for the benefit of the U.S. Nuclear Regulatory Commission (NRC).

A.2 Summary

DOE received four comment letters from the following entities. The scanned images of the letters are included at the end of this appendix.

- Inyo County Planning Director, County of Inyo, California. Requested expansion and/or refinement of the scope of the supplement as defined by the NRC staff. Specifically, the County requested that DOE evaluate perceived flaws in the model used to analyze long term performance, impacts from continued regional groundwater pumping, and impacts to endangered species in springs in Death Valley, as well as address cleanup and remediation measures.

- White Pine County Nuclear Waste Project Office, Nevada. Requested an expansion of the scope of the supplement to include additional analysis of the potential impacts of a volcanic eruption, specifically addressing how the release of volcanic tephra and radioactive gases might impact human health and the environment in areas downwind of Yucca Mountain, including White Pine County.

- Board of Commissions, Lincoln County, Nevada. Requested an expansion of the scope of the supplement to include additional analysis of the potential impacts of a volcanic eruption, specifically addressing how the release of volcanic tephra and radioactive gases might impact human health and the environment in areas downwind of Yucca Mountain, including Lincoln County.

- Joe Kennedy, Timbisha Shoshone Tribe. Requested that the supplement include analyses of several topics related to groundwater flow, potential transport of nuclear waste, and possible effects in Death Valley National Monument.

A.3 Comments and DOE's Responses

The following subsections present the comment letters received and DOE's responses regarding the comments in each letter.

A.3.1 INYO COUNTY

Inyo County comments pose five topics for consideration, as quoted below:

1. The SEIS should address the flaws in the Total System Performance Assessment model

2. The SEIS should describe of [sic] the full extent of the lower carbonate aquifer, particularly those parts that could become contaminated and how water (and potential contaminants) can leave the flow system

3. Impacts to the lower carbonate aquifer from regional groundwater pumping

4. Impact to Endangered Species that utilize the springs in Death Valley

5. Clean up and remediation measures.

Items 1, 2, and 3 are somewhat interrelated, in that they deal with the pumping scenarios the *Total System Performance Assessment Model/Analysis for the License Application* (DIRS 183478-SNL 2008, all; TSPA-LA) model evaluated, the effects pumping could have on characteristics of the lower carbonate aquifer, and the fate of contaminants should they reach the lower carbonate aquifer. As a result, items 1, 2, and 3 are addressed in the first section below. The second and third sections address impacts to endangered species (item 4 above) and remediation measures (item 5), respectively.

A.3.1.1 Comments on the Total System Performance Assessment and the Lower Carbonate Aquifer

The following summaries are DOE responses to the Inyo County comments. Additional detail and support for these responses can be found in the referenced documents.

Comment #1 Summary

Inyo County asserts that DOE's TSPA-LA model is flawed because the saturated zone flow model "neglects the fact that there is groundwater development in the region, especially in the Amargosa Valley." Inyo County's comment continues, "the drawdown, including the predicted future drawdown that will result from a continuation of current pumping in the region, must be included in the new SEIS's analysis of groundwater flow for the site."

Response to Comment #1

The Repository SEIS used the TSPA DOE prepared for its application to the NRC for a license for construction authorization and is referred to as the TSPA-LA. Inyo County is incorrect in asserting that groundwater pumping was not considered in the TSPA-LA evaluations. Both the groundwater flow models used in the TSPA-LA [that is, the site-scale saturated zone flow model (DIRS 177391-SNL 2007, all) and the Death Valley regional groundwater flow system model (DIRS 173179-Belcher 2004, all)] were calibrated to groundwater elevations that resulted from historical regional pumping from 1913 to 1998, so the effects of that pumping is inherent in the application of those models. The County is correct, however, in its assertion that the TSPA-LA evaluation did not consider how groundwater levels might change in the future as a result of continued pumping. The TSPA-LA's use of steady-state conditions for the future evaluation was appropriate and reasonable for two primary reasons:

1. United States court decisions, including that of the U.S. Supreme Court (DIRS 148102-Cappaert et al. v. United States et al. 1976, all), protect the water level in Devils Hole at a specific elevation. Currently, water in the pool at Devils Hole is less than 1 foot above the court-mandated level. DOE has prepared regional flow model simulations that project the protected water level could be reached by the time the repository opened, assuming the continuation of current pumping conditions (DIRS

186186-SNL 2009, p. 25). This leads DOE to conclude that (1) current levels of pumping in the Amargosa Desert are not likely to continue at their current rate into the foreseeable future and (2) the groundwater levels simulated in the TSPA-LA model are a reasonable representation of where groundwater levels will remain based on court decisions.

2. The TSPA-LA modeling effort was required to address not just a hundred or a thousand years into the future, but hundreds of thousands of years into the future. There simply is no reasonable basis for projecting what groundwater pumping conditions will exist during that period of time. Fossil records and paleoclimatology studies of the Earth's rotational changes suggest there will be significant climate changes over that period, but there are no comparable records to support projections for human activity. As identified above, there is currently a societal set point for groundwater conditions, and DOE contends it is more reasonable to extend that point of reference into the future than any of the limitless number of other scenarios that could be envisioned.

Even though DOE believes it is speculative to predict future pumping rates in the Amargosa Desert over long periods of time, DOE's evaluation in this Analysis of Postclosure Groundwater Impacts (Chapter 3 and Appendix B) includes a scenario of continued pumping (for 1 million years) to provide a reasonable range of potential impacts at natural discharge locations as well as locations of groundwater pumping.

Comment #2 Summary

Inyo County commented that DOE needs to describe the full extent of the lower carbonate aquifer, just as the NRC requested a full description of the volcanic and alluvial aquifers, and that DOE needs to identify how contaminants could reach the lower carbonate aquifer and where they would go. The County asked if the RMEI location should be moved should contamination reach the lower carbonate aquifer.

Response to Comment #2

DOE, Nye County, and Inyo County have each drilled a well into the lower carbonate aquifer along the general groundwater flow path from Yucca Mountain (see Sections 2.1.1.1.1 and 2.1.1.1.2 of this Analysis of Postclosure Groundwater Impacts). An upward hydraulic gradient exists in the lower carbonate aquifer compared with the overlying aquifers in each of these wells. DOE has not identified any reasonable scenario under which contaminants could reach the lower carbonate aquifer at or near Yucca Mountain. Based on additional model simulations (DIRS 186186-SNL 2009, all), DOE is confident that the upward hydraulic gradient will persist in the future (see Comment #3 and Response below) and that the thick intervening layers of low permeability strata will be present for the foreseeable future. As a result, any contaminants entering the groundwater below the repository will remain well above the lower carbonate aquifer at or near Yucca Mountain. As an example of the evaluations that support this position, NRC posed a question on how the site-scale saturated zone flow model reproduced the vertical hydraulic gradient between the lower carbonate aquifer and the overlying aquifers. In response, DOE extracted information from the model (DIRS 186215-Williams 2009, all) and generated Figure A-1 by comparing simulated head values in the lower carbonate aquifer with those of the water table. The figure also shows a cross section of simulated particle paths originating beneath the proposed repository at Yucca Mountain.

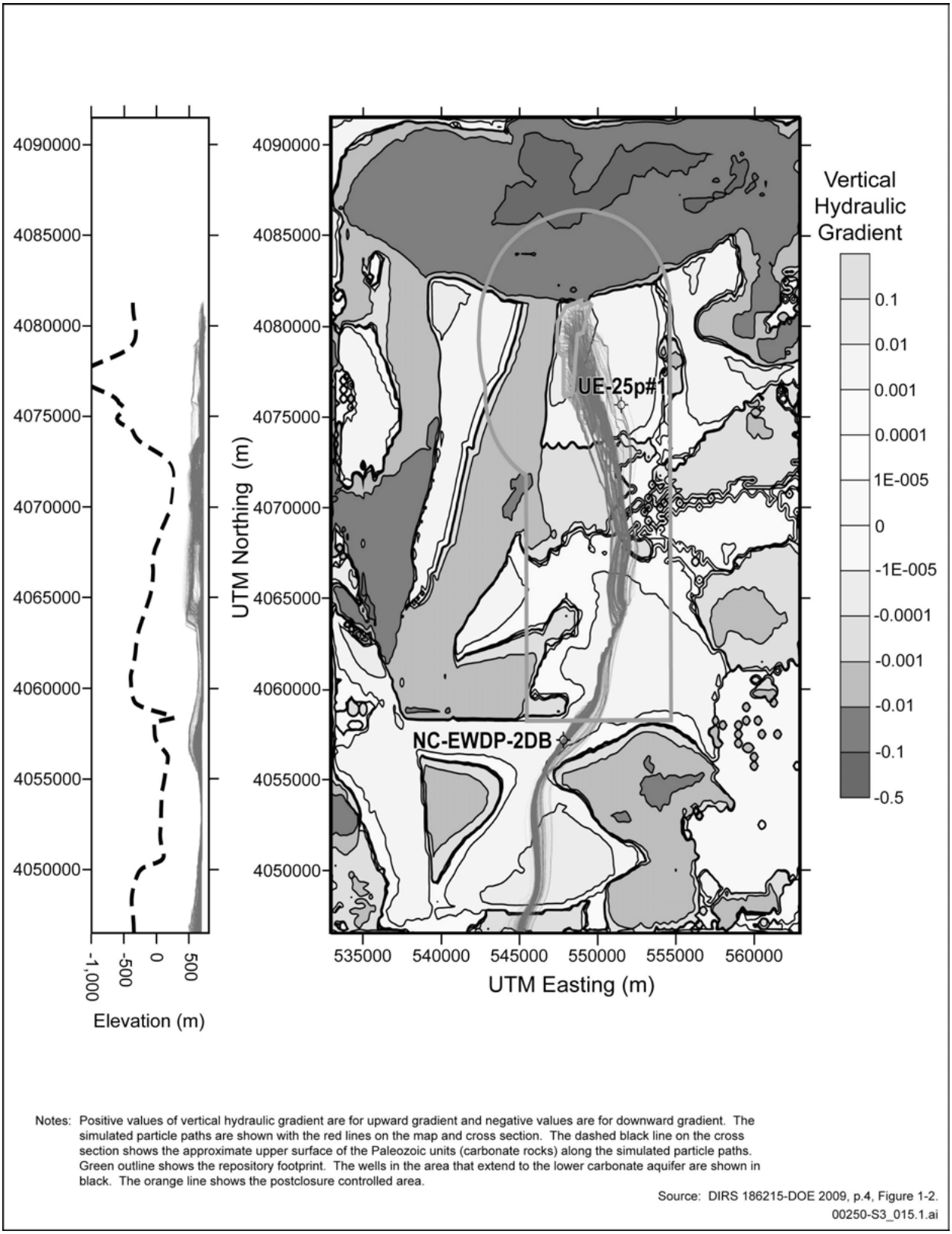

Figure A-1. Map of vertical hydraulic gradient between the water table and the top of the lower carbonate aquifer and cross section of simulated particle paths.

The model simulates an upward hydraulic gradient in the areas of the two wells (that is, UE-25p#1 and NC-EWDP-2DB shown in the figure) into the carbonate aquifer, as well as for much, but not all, of the area in between the two wells. The site-scale model also predicts a zone of slight downward gradient to the south of the repository site. This is attributed to a section of higher, thrusted carbonate rock with high permeability. The cross-section portion of the figure shows some downward movement of the simulated particles in this area, but it is relatively minor and in no areas does the model show particles entering the lower carbonate aquifer. As the figure shows, the model predicts the particles going no deeper than about 300 to 400 meters (1,000 to 1,300 feet) below the water table within its domain, and in many places along the flow path, the vertical spread is noticeably less.

For this Analysis of Postclosure Groundwater Impacts, DOE has evaluated a specific pathway by which contaminants could reach the lower carbonate aquifer (see Chapter 3), but this is in areas well south of the repository and the RMEI location (and to the southwest of the area shown in Figure A-1). The pathway evaluated is via fractures in the carbonate rock in the southern Funeral Mountains, and the evaluated areas of impact are the springs in the Furnace Creek area and the floor of Death Valley beyond. This is not consistent with the scenario envisioned in the Inyo County comments (with contaminants reaching the lower carbonate aquifer directly below the repository), but is a potential flow path identified in the Yucca Mountain FEIS and Repository SEIS.

Since the pathway through the Funeral Mountains is outside the site-scale saturated zone model domain, it was evaluated through use of the Death Valley regional groundwater flow system model. In the area between the RMEI location and the Funeral Mountains, the regional model predicts slightly different behavior for particles moving along the flow path from Yucca Mountain. The regional model simulation shows a small portion of the particles (9 to 10 percent) moving low enough in the Amargosa Desert to reach and enter the lower carbonate aquifer. These particles quickly come back out of the lower carbonate aquifer and resume on the path toward the Funeral Mountains (DIRS 186186-SNL 2009, Section 4.3). The regional model also predicts that the upward hydraulic gradient in the lower carbonate aquifer is not continuous along the flow path from Yucca Mountain, but in areas where the models overlap, locations where the upward gradient is lost are not the same as the site-scale model predicted. These differences between the site-scale model and the regional model may be attributed to the coarser grid of the regional model and to fundamental differences between the models (for example, numerical implementation, geologic interpretation, and vertical resolution). In any case, the differences had no significant effect on the impact evaluations presented in this analysis.

With respect to the possible need to move the RMEI location, this location is set by U.S. Environmental Protection Agency (EPA) and NRC regulations as the point in the accessible environment above the highest groundwater concentration. There is nothing in the results presented in Chapter 3 of this Analysis of Postclosure Groundwater Impacts that indicate higher groundwater concentrations would exist at locations other than what the TSPA-LA and Repository SEIS evaluated.

Comment #3 Summary

Inyo County commented that DOE relies on the upward hydraulic gradient in the lower carbonate aquifer to prevent radionuclide migration to that aquifer and, as a result, must evaluate the effects of regional pumping on the upward hydraulic gradient.

Response to Comment #3

DOE does not agree that it relies on the upward hydraulic gradient to prevent radionuclide migration, but this gradient is an element of the natural environment that affects how groundwater moves, just as there are other elements of the physical setting that affect groundwater movement. As noted previously, the thick sequence of low permeability strata that sits atop the lower carbonate aquifer at Yucca Mountain (DIRS 155970-DOE 2002, p. 3-52) is another of the natural features of significance.

With respect to the other portion of Inyo County's comment, DOE has evaluated the effects of regional pumping on the upward hydraulic gradient of the lower carbonate aquifer (DIRS 186186-SNL 2009, Section 4.1). As noted in the preceding discussion and shown in Figure A-1, models of the groundwater flow system do not predict this upward gradient to be continuous over the complete groundwater pathway from Yucca Mountain to the floor of Death Valley. This is true of the site-scale saturated zone flow model (Figure A-1) (DIRS 186215-Williams 2009, all) and the Death Valley regional groundwater flow system model (DIRS 186186-SNL 2009, Section 4.1). Furthermore, long-term model simulations of current and proposed groundwater pumping rates predict no significant decrease in the magnitude of the upward hydraulic gradient between the lower carbonate aquifer and overlying aquifers along flow paths from Yucca Mountain. To the contrary, the model simulations predict that should heavy pumping continue from the shallow aquifers (in conflict with the potential discussed above regarding the water levels at Devils Hole), this pumping would result in an increase in the upward vertical gradient of the lower carbonate aquifer in the Amargosa Desert (DIRS 186186-SNL 2009, p. 27). DOE's evaluation of the effects of regional pumping on the upward hydraulic gradient included use of the regional model to simulate transient groundwater conditions using 2003 pumping rates for an additional 500 years. The simulation results after 500 years of pumping indicated a drop of about 5 meters in the carbonate aquifer at Yucca Mountain. This is consistent with the Inyo County finding of a drop of 10 meters after a 1,000-year simulation with the regional model using 1998 pumping rates. DOE's simulation results also show that the upward hydraulic gradient would be maintained after 500 years of additional pumping and that the magnitude of the upward hydraulic gradient would be within about 3 percent of the magnitude predicted for steady-state conditions with no pumping (DIRS 186186-SNL 2009, Section 4.1).

DOE ran the 500-year transient simulation described above, using 2003 groundwater pumping rates, a second time with an additional 10,600 acre-feet (13.1 million cubic meters) of annual groundwater withdrawal from the lower carbonate and alluvial aquifers east of the Nevada Test Site, as the Southern Nevada Water Authority proposes (DIRS 186186-SNL 2009, p. 9). The specific well locations and pumping rates used in the simulations for the additional pumping were based on a Southern Nevada Water Authority May 17, 2005 application to the Nevada State Engineer's Office and a subsequent ruling on June 15, 2006 by the Nevada State Engineer (DIRS 186217-Ricci 2006, all). Another finding from these simulations was that the additional pumping the Southern Nevada Water Authority proposed had little additional impact on water levels in areas of the flow paths from Yucca Mountain; that is, compared with the effects on water levels in those areas without the additional pumping (DIRS 186186-SNL 2009, all).

A.3.1.2 Comments on Impacts to Endangered Species

Comment #4 Summary

Inyo County's fourth comment states there is no discussion about how radionuclide migration from the repository could affect the health and well being of endangered species that rely on the springs in Death

Valley and on the Devils Hole pupfish, which resides in the Devils Hole spring. These springs are fed from the lower carbonate aquifer.

Response to Comment #4

The only federally listed threatened or endangered aquatic species living within or near the potential path of water flowing beneath Yucca Mountain are the Devils Hole pupfish and other listed species in the Ash Meadows area. The Repository SEIS (DIRS 180751-DOE 2008, pp. 3-31 and 3-33) described the general flow path of groundwater from beneath Yucca Mountain, including Devils Hole and the Ash Meadows area. Specifically, as groundwater in the Alkali Flat – Furnace Creek groundwater basin moves south beneath the Amargosa Desert, groundwater from the Ash Meadows area joins it. The lower carbonate aquifer feeds a line of springs, which marks a portion of the boundary between the Alkali Flat – Furnace Creek basin and the Ash Meadows basin. These springs support habitat in the Ash Meadows National Wildlife Refuge. Devils Hole, a groundwater-filled cave in a fault zone, is on the eastern side of the refuge. In the Ash Meadows area, there is a relatively sharp decrease in groundwater head, or elevation, from east to west, so it is clear that groundwater from the Ash Meadows area and Devils Hole moves into the Alkali Flat – Furnace Creek basin rather than the opposite direction.

DOE does not expect any impacts to the Devils Hole pupfish or other species in the Ash Meadows area because under all analyzed conditions (that is, pumping, no-pumping, present climate, and wetter climate), no contamination would move into the Ash Meadows area due to potentiometric head differentials. Chapter 2 of this Analysis of Postclosure Groundwater Impacts further describes the groundwater flow system in the area of Devils Hole and the Ash Meadows area.

The estimated concentrations of radionuclides at the natural discharge sites in the region, and associated human health consequences, are so low that DOE would not expect any harm to other flora and fauna, including rare or protected aquatic and terrestrial species living within or near the discharge sites.

A.3.1.3 Comments on Mitigation Measures

Comment #5 Summary

Inyo County's fifth comment regards mitigation measures; specifically, the Yucca Mountain FEIS and Repository SEIS did not address remediation of specific impacts to groundwater in Inyo County.

Response to Comment #5

The comment infers that DOE has deferred its obligations to analyze the appropriate mitigation and remediation measures. The Repository SEIS Comment-Response Document [DIRS 180751-DOE 2008, Volume III, Comment 1.7.4 (2365)] responded to a comment of this nature, as quoted below:

> "During the active, preclosure phases of the project, DOE would be required by NRC regulations (10 CFR 63.161) to develop and be prepared to implement an emergency plan to cope with radiological accidents that may occur at the repository operations area. After sealing the repository, DOE would conduct postclosure monitoring to continue to ensure acceptable performance. DOE studies and models of postclosure performance, as described in Chapter 5 and Appendix F, indicate that impacts under even the most severe scenarios would be represented by low quantities and slow increases of radionuclides in the groundwater pathway. DOE's postclosure monitoring would provide early detection

> of any unusual conditions in the groundwater. As a consequence, there would be ample time to plan corrective measures to protect the public."

Nonetheless, the Analysis of Postclosure Groundwater Impacts indicates that while radionuclides will distribute into several locations and possibly discharge from springs, the estimated human health consequences would be minimal and well below the Repository SEIS assessments over the 1-million-year period. Therefore, there is no need to consider specific mitigation. In the event that unanticipated impacts occur, the postclosure monitoring program would detect such an occurrence and mitigation and remediation measures could be developed as appropriate in accordance with the processes described in Chapter 9 of the Repository SEIS.

A.3.2 WHITE PINE COUNTY

Comment Summary

White Pine County recommended that a Postclosure Groundwater SEIS include estimates of the public health and environmental consequences of contaminated ash from a volcanic eruption and the consequences of the transport of radionuclides in volcanic gases at locations downwind of the repository site, including White Pine County. The County also recommended that a SEIS include a discussion of various measures for mitigating the public health and environmental consequences of a volcanic eruption through the Yucca Mountain Repository.

Response

DOE considered the volcanic events in the Repository SEIS (DIRS 180751-DOE 2008, pp. 3-21 and 3-22), as quoted below.

> "In 1995 and 1996, a panel of 10 recognized experts from federal agencies, national laboratories, and universities evaluated the potential for disruption of the repository by a volcanic intrusion, also known as a dike. The result of that effort was an estimate of the average probability of 1 chance in 7,000 that a volcanic dike could intersect or disrupt the repository during the first 10,000 years after repository-closure. As the Yucca Mountain FEIS reported, DOE increased this probability to 1 chance in 6,300 to account for a slightly larger repository footprint than the expert panel considered (DIRS 155970-DOE 2002, p. 3-27). The likelihood of an intersection increases by small amounts if the footprint size increases because the larger area presents a larger "target" for the dike to intersect, should an event occur. Since DOE completed the Yucca Mountain FEIS, the size and shape of the repository footprint has changed slightly, and so has the probability of a dike intersection. DOE based the new calculation on the work in 1995 and 1996 by the panel of experts. The estimated probability of a dike intrusion is now 1 chance in 5,900 during the first 10,000 years, with 5th- and 95th-percentile values of 1 chance in 133,000 and 1 in 1,800, respectively (DIRS 169989-BSC 2004, pp. 7-1 and 7-2, and Table 7-1)."

Presented in terms of annual frequency, the estimated value of the mean annual frequency of a volcanic dike intersecting the repository footprint is 1.7×10^{-8}. The 5th and 95th percentiles of the uncertainty distribution are 7.4×10^{-10} and 5.5×10^{-8}, respectively (DIRS 185814-DOE 2008, p. 2.3.11-22).

The probability that such a volcanic eruption would result in radionuclides entrained in tephra and that such a volcanic eruption would release radionuclides via atmospheric transport in volcanic gases is even lower than estimated by the above distribution because two additional conditional probabilities must also be considered: (1) the conditional probability that a conduit would form within the repository footprint, and (2) the conditional probability that the conduit intersects waste packages. The combined conditional probability that a conduit forms within the repository footprint and intersects waste packages is about 0.083 (DIRS 185814-DOE 2008, Section 2.3.11.4.2.1). Consideration of these conditional probabilities reduces by more than an order of magnitude the estimated probability that a volcanic eruption would occur at the Yucca Mountain site that would result in the release of radiologically contaminated tephra.

DOE provides the following guidance for the consideration of low-probability events in *National Environmental Policy Act* (NEPA) documents:

- Consider scenarios with frequencies of 10^{-6} to 10^{-7} per year if the consequences may be very large.
- Scenarios with frequencies less than 10^{-7} per year will rarely need examination.
- Report the probability of the accident occurring during the lifetime of the Proposed Action.

DOE guidance on NEPA document preparation, *Recommendations for Analyzing Accidents under the National Environmental Policy Act* (DIRS 172283-DOE 2002, p. 9) states that:

> "In determining which low frequency accident scenarios to analyze, document preparers should consider differences between natural phenomena and human-caused events with respect to the degree to which their consideration would inform decision making. It may not be useful to consider extremely low frequency accidents resulting from certain natural phenomena."

White Pine County's comment regards a low-frequency accident resulting from a natural phenomenon. The probability that a volcanic eruption would occur at the Yucca Mountain site and result in the release of radiologically contaminated tephra is more than 1 order of magnitude lower than the 10^{-7} threshold the DOE guidance suggests. On January 28, 2009, Peter Swift, Lead Laboratory Chief Scientist for Sandia National Laboratories, reported to the Nuclear Waste Technical Review Board that the mean annual intersection of a volcanic dike intersecting the repository footprint is estimated at 3.1×10^{-8}; an increase from 1.7×10^{-8}. With this increase, the release of radiologically contaminated tephra is still about 1 order of magnitude lower than the 10^{-7} threshold.

Even though below the low-probability threshold, DOE evaluated the consequences at a site 18 kilometers from the repository, the RMEI location, should a volcanic eruption occur. The results of this evaluation show the impacts at that location to be less than 1 millirem projected annual dose. These impacts are not considered "very large." DOE has not evaluated the impacts at locations 230 kilometers or 285 kilometers from the repository, as requested by White Pine County.

The Council on Environmental Quality and DOE regulations require discussion of potential mitigation measures only for reasonably foreseeable impacts. Because a volcanic eruption through the repository is not a reasonably foreseeable event, identification of potential mitigation measures for this event is not required.

A.3.3 LINCOLN COUNTY

Lincoln County also recommended that a SEIS include analysis and disclosure of the public health and environmental consequences of a volcanic eruption through the Yucca Mountain Repository upon areas located predominately downwind of the repository site, including Lincoln County. The County also recommended that the SEIS scope include a discussion of various measures for mitigating the public health and environmental consequences of a volcanic eruption through the Yucca Mountain Repository.

DOE's perspective regarding the comments from Lincoln County is the same as its perspective regarding the comments from White Pine County presented in Section A.1.2 above.

A.3.4 TIMBISHA SHOSHONE TRIBE

The following bullets are quoted from the Timbisha Shoshone Tribe comment letter; the Repository SEIS section that addresses the requested information follows each bullet. The Yucca Mountain FEIS, Repository SEIS, and accompanying comment-response documents address all of the points the Timbisha Shoshone Tribe raised in its comment letter.

- "Information concerning the interrelation between the ground and surface water within the Amargosa Desert and Ash Meadows alluvial aquifer" – See Repository SEIS, Sections 3.1.4.1 and 3.1.4.2 (DIRS 180751-DOE 2008, Sections 3.1.4.1 and 3.1.4.2).

- "Additional information concerning the possibility of water vapor contamination and water vapor routes and its potential effect on groundwater" – See Repository SEIS, Appendix F, pp. F-11 to F-13 (DIRS 180751-DOE 2008, Appendix F, pp. F-11 to F-13).

- "Information on the potential for groundwater Geothermal Hot Water Upwelling" – See Repository SEIS, Section 3.1.4.2.2, pp. 3-44 to 3-49; Volume III, comment response 1.7.4 (494) [DIRS 180751-DOE 2008, Section 3.1.4.2.2, pp. 3-44 to 3-49; DIRS 180751-DOE 2008, Volume III, comment response 1.7.4 (494)].

- "The effect of oxidizing groundwater and its potential to transport radionuclides" – See Repository SEIS, Section 5.1.2; Volume III, comment responses 1.6.5 (57) and 1.9 (4135) [DIRS 180751-DOE 2008, Section 5.1.2; DIRS 180751-DOE 2008, Volume III, comment responses 1.6.5 (57) and 1.9 (4135)].

- "The possibility of establishing a separate ground water standard for the YMP as opposed to using the standards promulgated by the Environmental Protection Agency" – The EPA established the groundwater standard, and the DOE does not have the authority to modify this standard.

- "Information concerning the potential of groundwater infiltration into nuclear waste packages and the potential release of radionuclides due to water infiltration and potential release rates" – See Repository SEIS, Volume III, comment responses 1.7.4 (3708) and 1.7.4 (3749) [DIRS 180751-DOE 2008, Volume III, comment responses 1.7.4 (3708) and 1.7.4 (3749)].

- "Travel time estimates concerning the length of time it takes for groundwater to travel to the surface both in and near the YMP project (including release rates to the Ash Meadows aquifer, if any)" – See

Repository SEIS Section 3.1.4.2.1, p. 3-34; Volume III, comment responses 1.7.4 (89), (4189), (325), (3708), (3749) and 1.11 (495) [DIRS 180751-DOE 2008, Section 3.1.4.2.1, p. 3-34; DIRS 180751-DOE 2008, Volume III, comment responses 1.7.4 (89), (4189), (325), (3708), (3749) and 1.11 (495)].

- "Seismic and tectonic activities potential effect on ground and surface water flows and aquifer water releases, including the effect of groundwater contamination due to a catastrophic flood of the YMP facility and impact area(s)" – The combined case results discussion in Chapter 3 of this Analysis of Postclosure Groundwater Impacts addresses potential postclosure health impacts from contaminated ground water as a result of seismic disruptive events. Flooding hazards at the repository site were addressed in the Repository SEIS Section 3.1.4.1 and the Yucca Mountain FEIS Section 3.1.4.1 (DIRS 180751-DOE 2008, Section 3.1.4.1; DIRS 155970-DOE 2002, Section 3.1.4.1).

- "Potential effect of release of nuclear waste, specifically heavy metals, due to corroded and structurally degraded nuclear waste containers into groundwater sources and aquifers" – See Chapter 3 of this Analysis of Postclosure Groundwater Impacts; Repository SEIS Section 5.7 (DIRS 180751-DOE 2008, Section 5.7).

- "A historical study on ground and surface water tables and water flow" – See Repository SEIS Sections 3.1.4.2.1 and 3.1.4.2 (DIRS 180751-DOE 2008, Sections 3.1.4.2.1 and 3.1.4.2).

- "The potential effect of dramatic and catastrophic climate change upon ground and surface water flows and aquifers at or near the YMP impact area(s)"– See Chapter 3 of this Analysis of Postclosure Groundwater Impacts; Repository SEIS p. 3-44 and Section 5.5 (DIRS 180751-DOE 2008, p. 3-44; DIRS 180751-DOE 2008, Section 5.5).

- "Groundwater infiltration and 'fracture flow' analysis on nuclear waste containers that were designed for 300-1,000 year durations, compared to the anticipated 10,000 year nuclear waste isolation period" – See Repository SEIS Appendix F, Section F.2.7 (DIRS 180751-DOE 2008, Appendix F, Section F.2.7).

- "Nuclear and hazardous waste groundwater contaminations potential effect on plant and animal life important to indigenous peoples within the YMP impact area(s)" – See Chapter 3 of this Analysis of Postclosure Groundwater Impacts; Repository SEIS Volume III, comment response 1.7.5 (157) [DIRS 180751-DOE 2008, Volume III, comment response 1.7.5 (157)].

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169989	BSC 2004	BSC (Bechtel SAIC Company) 2004. *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada.* ANL-MGR-GS-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041015.0002; DOC.20050718.0007; LLR.20080311.0079.
148102	Cappaert et al. v. United States et al. 1976	*Cappaert et al. v. United States et al.,* 426 U.S. 128; 96 S. Ct. 2026. Decided June 7, 1976. ACC: MOL.20010730.0380.
155970	DOE 2002	DOE (U.S. Department of Energy) 2002. *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada.* DOE/EIS-0250. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020524.0314; MOL.20020524.0315; MOL.20020524.0316; MOL.20020524.0317; MOL.20020524.0318; MOL.20020524.0319; MOL.20020524.0320.
172283	DOE 2002	DOE (U.S. Department of Energy) 2002. *Recommendations for Analyzing Accidents under the National Environmental Policy Act.* Washington, D.C.: U.S. Department of Energy, Office of NEPA Policy and Compliance. ACC: MOL.20041122.0199.
180751	DOE 2008	DOE (U.S. Department of Energy) 2008. *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada.* DOE/EIS-0250F-S1. Las Vegas, Nevada: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20080606.0001.
185814	DOE 2008	DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application.* DOE/RW-0573, Update No. 1. Docket No. 63-001. Las Vegas, Nevada: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20081023.0041.

186217	Ricci 2006	Ricci, H. 2006. "Ruling #5621, In the Matter of Protested Applications 72787, 72788, 72789, 72790, 72791, 72792, 72793, 72794, 72795, 72796 and 72797 Filed to Change the Point of Diversion and Place of Use of Underground Water Previously Appropriated Under Permit 53950, Permit 53951, Permit 54060, Permit 54062, Permit 54066, Permit 54068 and Permit 54069 Within the Three Lakes Valley-Southern Part, Hydrographic Basin (211), Clark County, Nevada." Carson City, Nevada: State of Nevada, Office of the State Engineer. ACC: MOL.20090324.0117.
177391	SNL 2007	SNL (Sandia National Laboratories) 2007. *Saturated Zone Site-Scale Flow Model.* MDL-NBS-HS-000011 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070626.0004; DOC.20071001.0013; LLR.20080408.0261; LLR.20080512.0162; DOC.20080623.0001; DOC.20090227.0001.
183478	SNL 2008	SNL (Sandia National Laboratories) 2008. *Total System Performance Assessment Model /Analysis for the License Application.* MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080312.0001; LLR.20080414.0037; LLR.20080507.0002; LLR.20080522.0113; DOC.20080724.0005; DOC.20090106.0001.
186186	SNL 2009	SNL (Sandia National Laboratories) 2009. *Inputs to Jason Associates Corporation in Support of the Postclosure Repository Supplemental Environmental Impact Statement (SEIS-3).* LSA-AR-037. Las Vegas, Nevada: Sandia National Laboratories.
186215	Williams 2009	Williams, J.R. 2009. "Yucca Mountain - Request for Additional Information Re: License Application (Safety Analysis Report Sections 2.3.9.2.2 and 2.3.9.2.3), Safety Evaluation Report Volume 3 - Postclosure Chapter 2.2.1.3.8 - Flow Path in the Saturated Zone, Set 1." Letter from J.R. Williams (DOE) to J.H. Sulima (NRC), January 30 , 2009, OTM: CJM-0395, Docket Number 63-001, with enclosures ACC: MOL.20090202.0001.

B. ENVIRONMENTAL IMPACTS OF POSTCLOSURE REPOSITORY PERFORMANCE

This appendix details the analysis carried out to track radionuclides and nonradiological contaminants in the groundwater and surface water system after release from the repository during the postclosure period. The appendix discusses the models used and presents detailed results.

The analysis started at the point where contaminants would be released from the unsaturated zone to the saturated zone underneath the repository. For the radionuclides, DOE used results from *Total System Performance Assessment Model/Analysis for the License Application* (DIRS 183478-SNL 2008, all; TSPA-LA) to characterize the release from the unsaturated zone, transport of radionuclides in the saturated zone to the Regulatory Compliance Point, and release of the radionuclides into the volcanic-alluvial aquifer beyond the Regulatory Compliance Point. From the Regulatory Compliance Point, DOE performed further analysis to track radionuclides out into the Death Valley region. While the analysis beyond the Regulatory Compliance Point is the main subject of this Analysis of Postclosure Groundwater Impacts, this appendix also presents some aspects of the TSPA-LA results to provide sufficient background information to allow for a comparison and understanding of results. This appendix also discusses an analysis of the release of nonradiological contaminants at the unsaturated zone and subsequent transport to the Regulatory Compliance Point. DOE carried out the same analysis for the nonradiological contaminants as that performed for the radionuclides for locations beyond the Regulatory Compliance Point.

REGULATORY COMPLIANCE POINT

This point is defined as the location over the highest concentration of contaminants in the plume as required by the U.S. Nuclear Regulatory Commission at 10 CFR 63.312(a). The TSPA-LA calculates radiologic dose to a reasonably maximally exposed individual (RMEI) located at a point on the Nevada Test Site boundary (36°40'13.66661" North Latitude) that is approximately 18 kilometers south of the repository. In this Analysis of Postclosure Groundwater Impacts, this location is referred to as the Regulatory Compliance Point.

In the *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE/EIS-0250F-S1; DIRS 180751-DOE 2008, all) (Repository SEIS), DOE analyzed postclosure performance using the TSPA-LA model. That analysis evaluated the transport of radionuclides to the Regulatory Compliance Point as the result of a number of scenario classes in the repository. DOE analyzed and presented results for a combined scenario case that included:

CONTAMINANTS

This Analysis of Postclosure Groundwater Impacts discusses two types of contaminants: radiological contaminants (also referred to as radionuclides) and nonradiological contaminants (such as toxic metals with a nonradiological toxicity). When the word "contaminants" is used by itself, then the reference is to both types of contaminants.

- The Nominal Scenario Class: undisturbed case where normal degradation processes, such a corrosion of waste packages, continued over time,
- Early Failure Scenario Class: failure of drip shields or waste packages caused by manufacturing defects,

- Igneous Scenario Class: events and processes initiated by eruption through the repository or intrusion of igneous material into the repository, and

- Seismic Scenario Class: events and processes initiated by ground motion or fault displacement.

The TSPA-LA is a probabilistic analysis that accounts for many types of uncertainties and presents statistical results in terms of mean, median, and various percentiles. In the TSPA-LA, many variables were treated as distributions; meaning that the values used for these variables (such as soil-water partition coefficients of contaminants) were analyzed as a range of values with specific probabilities of occurrence. The TSPA-LA model is a 300-realization simulation using a Monte Carlo technique; Appendix F of the Repository SEIS (DIRS 180751-DOE 2008, Appendix F) describes this in detail.

The TSPA-LA used a simulation of various climates occurring in fixed time periods. The model represented future climate shifts as a series of instant changes. During the first 10,000 years, there would be three changes from present-day (0 to 600 years) to monsoon (600 to 2,000 years) and then to glacial-transition climate (2,000 to 10,000 years). In its proposed changes to Title 10 of the Code of Federal Regulations (CFR) 63.342(c), the U.S. Nuclear Regulatory Commission directed DOE to represent climate change after 10,000 years (the post-10,000-year climate) with a constant value determined from a log-uniform probability distribution for deep percolation rates from 13 to 64 millimeters (0.5 to 2.5 inches) per year.

It should be noted that since the Repository SEIS and license application were submitted, the EPA issued a final rule (73 FR 61256, October 15, 2008) governing the post-10,000-year period. The NRC thereafter issued a final rule (74 FR 10811, March 13, 2009) revising 10 CFR Part 63 to implement the EPA's revision. The final NRC rule revised the deep percolation rate to be used in modeling the post-10,000-year climate slightly upward from that contained in the earlier proposed rule and which was used in the license application. In particular, the NRC's proposed rule permitted DOE to represent future climate change in the performance assessment by sampling constant-in-time deep percolation rates from a log-uniform distribution with a range of 13 to 64 millimeters (0.5 and 2.5 inches) per year and an average arithmetic mean of 32 millimeters (1.3 inches) per year. By way of comparison, the NRC final rule slightly raised the average arithmetic mean for the deep percolation rate to 37 millimeters (1.5 inches) per year, while broadening the range of the lognormal distribution to between 10 and 100 millimeters (0.39 and 3.9 inches) per year.

The radionuclide fluxes used for this Analysis of Postclosure Groundwater Impacts were the mean results obtained from the outputs of the TSPA-LA, which were developed in accordance with the NRC proposed rule. Because the NRC Final Rule increased the average arithmetic mean of the deep percolation rate distribution from 32 to 37 millimeters (1.3 to 1.5 inches) per year, one would expect the mean radionuclide flux at the location of the RMEI to show only minor, if any, increase. This conclusion is reflected in the NRC's responses to comments on the proposed amended rule in the *Federal Register* notice of the Final Rule (74 FR 10811, March 13, 2009): (from page 10820) "… dry-to-wet transients in performance assessments would have less influence on the mean of the distribution of projected doses than on any single projected dose used to construct the distribution. … Performance assessment models and analyses continue to improve; however, dry-to-wet conditions appear to have a limited effect on the mean dose within the constraints of current performance assessment approaches." Therefore, it is unlikely that this slight change in the distribution of deep percolation values would have any significant effect on the mean radionuclide fluxes used in this analysis.

The results of the TSPA-LA analysis combined case form the starting point for the analysis in this Analysis of Postclosure Groundwater Impacts.

B.1 Analysis Cases

The purpose of the Analysis of Postclosure Groundwater Impacts is to characterize how contaminants would move from the repository to the Regulatory Compliance Point and then beyond, possibly accumulate, and discharge to the surface. The mean value results of the TSPA-LA represented the analysis up to the Regulatory Compliance Point. Beyond that point, DOE analyzed a single-value deterministic result. Because DOE did not use a probabilistic analysis, many aspects of the analysis were biased toward conservative results to ensure that the results did not underestimate impacts.

The Analysis of Postclosure Groundwater Impacts focused on a number of analytical constructs to ensure representation of any possible future conditions within these varying constructs. DOE analyzed two climate conditions and two pumping scenarios. The two climate conditions were (1) a present-day climate existing from closure until 1 million years postclosure, and (2) a wetter climate equivalent to the post-10,000-year climate in the TSPA-LA existing from closure until 1 million years postclosure. Note that this analysis uses radionuclide fluxes derived from previous TSPA-LA model runs as input (for example, the radionuclide fluxes at the Regulatory Compliance Point). When the TSPA-LA model produced these fluxes, it was run with four climate changes occurring during the 1-million-year period. The climate changes in the TSPA-LA are primarily drivers to the infiltration into the repository rather than regional transport. Reprogramming and rerunning the TSPA-LA twice with a fixed climate for 1 million years solely to match each of the climate assumptions in this document would be unnecessary for the following reasons: (1) it would input conservative results for the present climate scenario and (2) it would input essentially the same results for the wetter climate (the TSPA-LA maintained the present climate for only 600 years and then the climate became progressively wetter). Therefore, this analysis used the TSPA-LA results as input to both the present and future, wetter climates for the regional analysis.

The two pumping scenarios were (1) regional flow when pumping in the Amargosa Farms area from repository closure time to 1 million years postclosure at a rate equivalent to the 2003 pumping rates (DIRS 185968-Moreo and Justet 2008, Figure 3, p. 5) (referred to as the pumping scenario) and (2) regional flow with no pumping from closure time to 1 million years postclosure (no-pumping scenario). DOE used the 2003 pumping rate because it represents the best available documented rates. Note that in this scenario, this pumping rate continues for the entire 1 million years. Such a pumping scenario would yield a drawdown in the vicinity of Devils Hole of about 78 meters (DIRS 186186-SNL 2009, p. 18), significantly below the level prescribed by the Supreme Court (DIRS 148102-Cappaert et al. v. United States et al. 1976, all) and later by the Nevada State Engineer in 2008 (DIRS 186145-Taylor 2008, all). Although this pumping rate may not be sustainable, this scenario maximizes, and thus bounds, the capture of contaminants in the Amargosa Farms area.

Sandia National Laboratories carried out a regional flow modeling effort to characterize flow directions and flow rates for contaminants in the Death Valley region beyond the Regulatory Compliance Point (DIRS 186186-SNL 2009, all). Both the TSPA-LA site-scale saturated zone flow model and the Death Valley regional groundwater flow system model modified with MODPATH include particle-tracking capabilities. Particle tracking allows simulation of water flow paths from one point to another. This allowed a computer simulation of adding particles at any location within the domain of the model and

being able to track where they would go as they moved with the water (that is, there is no adsorption, dispersion, filtering, decay, or other mechanisms that would prohibit the particles from moving with the water). As Chapter 2 of this Analysis of Postclosure Groundwater Impacts explains, the site-scale saturated zone model only extends southward to an area in Amargosa Farms. The Death Valley regional groundwater flow system model extends further south to encompass the entire Death Valley flow region. Therefore, the particle-tracking effort required the application of both models to determine where those particles would move in the regional flow system.

For the pumping scenario, the model identified one flow path extending from the Regulatory Compliance Point directly southward to the site of the pumping (the Amargosa Farms area) (DIRS 186186-SNL 2009, Figure 13). The model predicted that in this scenario, no particles would bypass the pumping in the area.

For the no-pumping scenario, the regional flow modeling identified two flow pathways: (1) a flow path extending from the Regulatory Compliance Point to the southeast then turning more westerly, terminating at a discharge location at the floor of Death Valley (in an area referred to as Middle Basin) via evapotranspiration and (2) a minor path extending from the Regulatory Compliance Point generally southward, terminating at Alkali Flat where discharge occurs via evapotranspiration (DIRS 186186-SNL 2009, Figure 11). The modeling results indicated that the path to Alkali Flat represented only two particles in 8,024 (less than 0.03 percent) going in that direction. Within the uncertainties of the model, this could mean that no flow or some minor flow might go in this direction. Other studies indicate that the flow paths will not vary for wetter climate (DIRS120425-D'Agnese et al. 1999, all).

DOE analyzed the transport of contaminants for the paths to the Amargosa Farms area and toward Death Valley discussed in the previous paragraph. The analysis consisted of calculating the resulting contaminant fluxes (in grams per year) arriving at the Amargosa Farms area and the Death Valley floor based on the input fluxes at the Regulatory Compliance Point. An assessment of the doses and intakes at Alkali Flat as a possible alternative location was also made. The evaluations used groundwater flow rates associated with the pumping scenario for the path to the Amargosa Farms area and the no-pumping scenario for the path to the Death Valley floor. DOE carried out all the transport analyses for the present climate and a wetter climate.

For the analysis of natural discharges in Death Valley, the regional flow model predicts that the flow would discharge as evapotranspiration from the alluvial deposits forming the floor of Death Valley in Middle Basin. Because the flow path from the Amargosa Desert includes passing through carbonate rocks under the Funeral Mountains, it is possible that some of the contaminants could be transported to the Furnace Creek springs in Death Valley, which are composed primarily of waters from the lower carbonate aquifer. Because DOE cannot preclude the possibility that contaminants could reach the Furnace Creek springs, this analysis includes both cases: (1) all of the contaminants discharge into the floor of Death Valley, and (2) all of the contaminants enter the Furnace Creek springs. These two cases ensure full disclosure of the potential impacts of natural discharges into Death Valley.

DOE performed the following additional analyses:

- Converted the fluxes of contaminants to water concentrations based on discharge rates of water at the Furnace Creek springs area and pumping rates in the Amargosa Farms area;

- Calculated annual radiological doses to individuals and daily intakes (for nonradiological contaminants) based on the water concentrations. In the case of nonradiological contaminants, DOE evaluated intakes as milligram per kilogram body-weight per day and compared with Oral Reference Dose standards (see Section B.3.5 below);

- Analyzed doses and intakes resulting from the Death Valley floor (Middle Basin). This analysis was based on an evapotranspiration scenario;

- Estimated inventories as a function of time for contaminants, adjusted for decay and growth (radionuclides only) at points in the flow system. This provided a mass balance of contaminants throughout the flow system;

- Evaluated soil concentrations at the Amargosa Farms area and the floor of Death Valley;

- Analyzed how results would compare if the contaminants were transported to Alkali Flats as a possible alternative destination; and

- Analyzed the influence of an additional natural discharge area suggested by paleoclimatological studies.

B.2 Analysis of Radionuclides

This section describes the various models used in each aspect of the analysis. DOE used Microsoft® Excel® to carry out the computations. The section describes models for transport, accumulation, dose, and soil concentration assessments.

B.2.1 TRANSPORT MODEL

This Analysis of Postclosure Groundwater Impacts models the transport of contaminants along flow paths using a model formulated as a one-dimensional "pipe" containing a porous solid with solution flowing through at constant velocity. The processes occurring in the pipe are longitudinal hydraulic dispersion and equilibrium adsorption of the dissolved species on the solid surfaces of the aquifer materials. This one-dimensional pipe approach is very suitable for the analysis because the lateral and vertical mixing in this aquifer system is extremely small (DIRS 184806-SNL 2008, p. 4-13). To the extent that this lateral and vertical mixing is ignored, the model is conservative. The regional flow model results indicate that the particles would travel through several different water-bearing components (aquifer systems) along the flow paths. Each of these components has somewhat different transport properties [that is, specific discharge, dispersion coefficient, bulk density, porosity, and contaminant-specific partition coefficients (K_d)]. The regional flow model results indicate the fraction of the path distance that would represent the total travel through any given component. A single set of transport properties was developed for each flow path by using a distance-weighted average of the properties for the individual structures. Values of the properties were derived from distributions used by the TSPA-LA and from other literature sources. Specific discharges were averaged directly from the regional flow model. Table B-1 presents these distance-weighted averaged properties for the pumping and non-pumping flow paths.

Table B-1. Transport properties of the flow paths.

Transport property	No-pumping flow path	Pumping flow path
Porosity (no units; fraction of solid volume occupied by voids)[a]	0.11	0.16
Bulk Density (grams per milliliter)[a]	2.32	2.00
Dispersion Coefficient (meters)[b]	100	100
Specific Discharge present climate (meters per day)[c]	0.00046	0.0061
Specific Discharge wetter climate (meters per day)[c]	0.0018	0.024
K_d for uranium (milliliters per gram)[a]	8.7	4.2
K_d for neptunium (milliliters per gram)[a]	44	6
K_d for plutonium (milliliters per gram)[a]	164	93
K_d for cesium (milliliters per gram)[d]	728	728
K_d for americium, thorium, protactinium, and actinium (milliliters per gram)[a]	3,008	4,762
K_d for strontium (milliliters per gram)[d]	210	210
K_d for radium (milliliters per gram)[d]	550	550
K_d for selenium (milliliters per gram)[d]	14	14
K_d for tin (milliliters per gram)[d]	1,916	1,916
K_d for carbon[d], technetium[d], iodine[d], chlorine[d], and molybdenum[e] (milliliters per gram)	0	0
K_d for nickel (milliliters per gram)[f]	15	15
K_d for vanadium (milliliters per gram)[g]	8	8

a. Source: DIRS 186221-Arnold 2009, all.
b. Source: DIRS 184806-SNL 2008, p. 4-13.
c. Source: DIRS 186186-SNL 2009, pp. 36 and 38.
d. Source: DIRS 185814-DOE 2008, Table 2.3.9-14.
e. Source: DIRS 186114-Jacobs 1993, p. 180.
f. Source: DIRS 160828-BSC 2001, p. 180.
g. Source: DIRS 186118-Mikkonen and Tummavuori 1994, p. 364.
K_d = partition coefficient.

An example of how the porosity is developed is as follows: The flow paths for the no-pumping scenario generally pass through alluvial sediments and undifferentiated volcanic and sedimentary basin-fill unconsolidated deposits before traveling through the lower carbonate aquifer prior to discharge by either evapotranspiration through the floor of Death Valley or by spring discharge at the Furnace Creek springs. Of the approximately 60-kilometer total travel path length from the Regulatory Compliance Point to these points of natural discharge (assuming no pumping), about 40 percent of the travel distance is through the lower carbonate aquifer (generally that portion of flow beneath the Funeral Mountains) and the remainder is through the alluvial or other unconsolidated basin fill deposits (with minor amounts predicted to flow through Cenozoic lava flow units). Considering the average porosity of the lower carbonate aquifer is 0.01 and the average porosity of the alluvial and other basin fill deposits is 0.18, the distance-weighted average porosity along the total travel path length is $(0.4 \times 0.01) + (0.6 \times 0.18)$ or 0.11.

TRANSPORT PROPERTIES

Specific discharge:
The volumetric flow of liquid through the aquifer divided by the cross-sectional area of the flow path.

Dispersion coefficient:
A measure of the influence of the structure of the solids in an aquifer on mixing in water flowing through it. When the dispersion coefficient (in length units) is multiplied by the fluid velocity (length/time) the result is the dispersivity (length^2/time) which is like a hydrodynamic diffusivity.

Bulk density:
The mass of the aquifer per unit volume.

Porosity:
The fraction of the aquifer that consists of voids.

Partition coefficient:
The ratio of the amount of contaminant adsorbed on the solid surfaces to the amount of contaminant in solution.

This approach to calculating the average transport properties is essentially equivalent to assuming that the rock matrix of the fractured lower carbonate aquifer is fully available for sorption of dissolved contaminants. Access to the sorptive capacity of the carbonate rock matrix would have to be via molecular diffusion of contaminants from the groundwater in fractures. This could result in somewhat smaller effective partition coefficients than those used. However, see Section B.5 concerning relative insensitivity of results to partition coefficients.

Note that K_d for cesium, strontium, radium, selenium, and tin do not appear to be sensitive to the path. This is because DOE has assumed that the K_d for these elements are the same in all media in the flow path. The impact of this assumption is very small because the fluxes of these radionuclides are generally very small or zero and their contribution to dose is usually negligible for the analysis performed. Further, tin has a high K_d in alluvium and volcanic rocks and would be expected to have a reasonably high K_d in just about any soil. As a result, tin is essentially immobile.

Note also the general insensitivity of the results to K_d since the zero K_d radionuclides dominate doses in most cases. The zero K_d elements are also insensitive to path because they tend to have a zero or near-zero K_d in all media.

The K_d for molybdenum, nickel, and vanadium also appear to be path-independent. For molybdenum, the assumption is justified because it is a zero K_d element (see discussion above). Nickel and vanadium appear to have a similar K_d in a wide variety of media. As with radionuclides, even at the low end of their range, these elements tend to give the same result and are fairly insensitive over a broad range.

The approach used for highly sorbing elements such as plutonium, americium, thorium, protactinium, cesium and tin does not account for the potential impact of colloid-facilitated transport. This would have a small effect on the results because:

- The TSPA-LA results, which include colloid-facilitated modeling, show only plutonium and thorium isotopes with a significant flux at the Regulatory Compliance Point. Except for plutonium-242, the isotopes of these elements generally contribute an insignificant amount to dose in the results of this

Analysis of Postclosure Groundwater Impacts and would not contribute a significant amount even if they were to arrive sooner at the evaluated exposure locations.

- Colloid transport involves only a fraction of any particular isotope.
- The sensitivity test in Section B.5 shows only a mild sensitivity of the results to K_d. The principle effect of colloid-facilitated transport is to lower the effective K_d.

The transport model is implemented with an analytical solution to a step function input to yield "breakthrough curves." Generally, the input to a flow path is not a simple step function, but rather a function of time (often it is a breakthrough curve from a previous path). Breakthrough curves are commonly known as response functions, meaning they describe the response of the flow path to a step input. The TSPA-LA used response functions in abstracted models for saturated zone transport (but these are developed for a much more complex transport system). An important principal for using response functions is that if the system is linear (as in the transport model used in this Analysis of Postclosure Groundwater Impacts), then responses can be superimposed linearly. DOE applied this principle by representing the input function as a series of step functions, using the breakthrough curve to calculate a function of time that represents the response to each step, and then adding all the step function responses together to obtain the overall response to the input function. This approach is equivalent to the convolution method the TSPA-LA model used to convert an input flux to an output flux represented with breakthrough curves. DOE employed this method for analysis of flow paths in the Amargosa Desert. Each pipe has an input flux versus time (from an upstream pipe or process) and an output flux versus time.

To analyze the flow paths from the Regulatory Compliance Point, DOE used this transport model to calculate the response based on the fluxes at the Regulatory Compliance Point supplied from the TSPA-LA for radionuclides and from additional analysis described later for nonradiological contaminants. In all cases, the analysis used the mean value of the fluxes for the radionuclides. Where distributions of the various parameters were available, the analysis used the mean value of those parameters. Where an uncertainty distribution was not known, the analysis used conservative values of parameters. For example, no distributions were available for the partition coefficients of molybdenum, nickel, and vanadium from the TSPA-LA. DOE surveyed literature values and found some limited information that was used to develop a range of possible values. Because the data are limited, DOE chose values near the low (conservative) end of the ranges and these are presented in Table B-1.

B.2.2 RADIONUCLIDE CHAINS

Several of the radionuclides of interest in the analysis are members of decay chains. Along these chains, some of the radionuclides can increase as parent radionuclides decay. These processes must be evaluated to get a more accurate measure of the fluxes of radionuclides. The radionuclides evaluated in this analysis are the same as those the TSPA-LA evaluated. Some of the radionuclides are members of decay chains. Four decay chains were identified for the purposes of transport analysis for the saturated zone transport model (DIRS 183750-SNL 2005, p. 6-26). These consist of the following:

1. Actinium Series:

   $^{243}Am \rightarrow {}^{239}Pu \rightarrow {}^{235}U \rightarrow {}^{231}Pa \rightarrow {}^{227}Ac$

2. Neptunium Series:

   $^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th$

3. Thorium Series:

   $^{240}Pu \rightarrow {}^{236}U \rightarrow {}^{232}Th \rightarrow {}^{228}Ra$

4. Uranium Series:

   $$\begin{array}{l} {}^{242}Pu \rightarrow {}^{238}U \searrow \\ \qquad\qquad\qquad {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \\ \qquad\quad {}^{238}Pu \nearrow \end{array}$$

The radionuclide transport analysis accounted for decay and growth in these chains.

B.2.3 DOSE CALCULATIONS

The radionuclide fluxes were converted to an annual dose at the end of each path. This was accomplished by first deriving an estimated concentration at the location and then converting the concentration to an estimated annual dose. The approach is somewhat different at the Amargosa Farms area where there is pumping compared with natural water discharge locations because of the different exposure pathways in water and soil.

The projection of radiological impacts at different potential receptor locations (Amargosa Farms area and Death Valley area) assuming different future climates (a dry climate such as exists today and a wetter climate that is based on the glacial transition climate state) has used a similar construct as employed in the TSPA-LA. The TSPA-LA model was based on the concept of taking the concentration of radionuclides (with units of curies per liter) in the annual water demand of the RMEI and multiplying this concentration by a radionuclide-specific biosphere dose conversion factor (with units of millirem per year per curies per liter) to generate a radionuclide-specific projected annual dose (in units of millirem per year) to the RMEI. The biosphere dose conversion factor provides the sum of the effective dose equivalent for external exposures and the effective dose equivalent for internal exposures. Compliance with the numerical requirements of 10 CFR 63.321 is based on the mean of the distribution of projected doses from DOE's performance assessment, where the distribution of projected doses accounts for aleatory and epistemic uncertainty. In the TSPA-LA analysis, four different scenario classes (early failure, igneous, nominal, and seismic) are analyzed separately, and the resulting projected mean annual doses are summed to provide a total mean annual dose for comparison with the numerical requirements of 10 CFR 63.321.

In this Analysis of Postclosure Groundwater Impacts, the total annual dose was estimated using radionuclide-specific concentrations and biosphere dose conversion factors for the pumping scenario and for discharge locations at springs in the Furnace Creek area. The concentrations were based on the mean value of the concentration at each receptor location and the mean value of the radionuclide-specific biosphere dose conversion factors. The upgradient source term input to the analysis of concentrations at each receptor location is the sum of the mean annual mass (or activity) flux of each radionuclide at the Regulatory Compliance Point for all the analyzed scenario classes from the results of the TSPA-LA

model. As a result, this source term includes the effects of the aleatory and epistemic uncertainty included in the TSPA-LA model used as the basis for the Repository SEIS.

The epistemic and aleatory uncertainty is not explicitly analyzed in this Analysis of Postclosure Groundwater Impacts, as was done in the TSPA-LA for the estimates of potential impacts to other receptors downgradient from the Regulatory Compliance Point. Instead, the mean values of the input parameters were employed to provide an estimate of the potential expected mean value of the radiological dose impact. The mean values used in the analysis are described in Section B.2.1 for the transport of radionuclides from the Regulatory Compliance Point to the other potential receptor locations and Sections B.2.3.1 and B.2.3.2 for the biosphere dose conversion factors at the different receptor locations. These sections present the potential radiological dose impacts as radionuclide-specific annual doses and a total annual dose, which is the sum of the dose from all individual radionuclides contributing to the dose.

B.2.3.1 Dose at the Amargosa Farms Area

The activities and lifestyle of people in the Amargosa Farms area were important inputs to the development of the biosphere dose conversion factors. The TSPA-LA and Repository SEIS used this hypothetical individual to present dose results. It is reasonable to assume that the RMEI dose pathways would apply to people in the Amargosa Farms area because the lifestyles and activities at that location are the same as those for the Regulatory Compliance Point. Table B-2 shows these pathways.

Table B-2. Biosphere dose pathways for the RMEI.

	Dose contributing parameters	
Exposure pathway	Group	Subgroup
External		
	Environment-specific exposure time (hours/day)	Active outdoors Inactive outdoors Active indoors Asleep indoors Away
Inhalation		
	Inhalation dose, soil particles (including Ra-226) Inhalation dose, evaporative cooler	
Ingestion		
	Ingestion dose for water	
	Ingestion dose for crops	Leafy vegetables Other vegetables Fruit Grain
	Ingestion dose for animal products	Meat Milk Poultry Eggs
	Ingestion dose for fish	
	Ingestion dose for soil	

Source: DIRS 177399-SNL 2007, pp. 6-261 to 6-264, Table 6.10-1.
RMEI = reasonably maximally exposed individual.

Thus, after deriving a well-water concentration, DOE calculated the dose using the same biosphere dose conversion factors as those used in the RMEI analysis for the TSPA-LA. Note that biosphere dose

conversion factors are, in part, a function of climate; that is, the distribution of the radionuclides in the biosphere is different for wetter climates than for dry climates. The biosphere dose conversion factors are higher for the present climate in part because humans would tend to use more groundwater during the drier climate conditions. Just as with TSPA-LA, the Analysis of Postclosure Groundwater Impacts ignored this variation. The dose conversion factors this analysis used are based on the dry (present) climate; therefore, the results in this analysis are conservative for the wetter climate. Table B-3 lists the biosphere dose conversion factors this analysis used for the Amargosa Farms area.

The key differences between the pumping location at the Amargosa Farms area and the Regulatory Compliance Point (or RMEI location that was evaluated in the TSPA-LA) are the larger, current pumping withdrawal rates (approximately 17,000 acre-feet per year) and spatial distribution of wells (DIRS 185968-Moreo and Justet 2008, Figure 3, p. 5). These differences are such that all of the radionuclides in the water pumped onto fields for irrigation would be recaptured into the system of wells. It is important to note that the effects of recycling were explicitly included in this Analysis of Postclosure Groundwater Impacts due to the large recapture and recycling fractions in the Amargosa Farms pumping scenario from the larger area affected by the larger withdrawals.

DOE used an analytical expression to calculate well water concentration. The concentration is a function of pumping rates from the wells, fraction of well water used for irrigation, well capture fraction, and flux of radionuclides (DIRS 182130-SNL 2007, p. 7-1). The amount of contaminants that are recycled depends essentially on the product of the recycling fraction (the fraction of contaminants that realistically could infiltrate back to the water table after initial groundwater withdrawal) and the recapture fraction (the percentage of contaminants that, once back in the water table, get recaptured and pumped back to the surface). To ensure that this analysis did not underestimate potential impacts of accumulation at the pumping location and did not allow contaminants to travel to natural discharge locations in the pumping scenario, DOE set the recapture rate to 100 percent.

The *Irrigation Recycle Model* (DIRS 182130-SNL 2007, all) evaluates the potential recapture fraction for 3,000 acre-feet of pumping to have a mean value of approximately 0.12. Even with the higher pumping rates evaluated as part of the pumping scenario (approximately 17,000 acre-feet), it would not be expected that 100 percent of the contaminants could be recaptured, therefore, this is a very conservative assumption.

The recycle fraction depends on the specific uses identified for the withdrawn water. For the TSPA-LA analyses, 85 percent was used for irrigation of alfalfa; 3 percent for commercial/industrial; 4 percent for individual/municipal; and 8 percent residual uncertainty. The average distribution of annual water withdrawals for purposes of irrigation over the 7-year period from 1997 to 2003 is about 86 percent (DIRS 185968-Moreo and Justet 2008, Figure 3, p. 5).

The Irrigation Recycle Model identifies that residential or commercial water use that is classified as "indoor water use" could also contribute to recycling because it could be a constant water flow path (that is, via a septic leach field). Any outdoor water use that is not a constant overwatering, such as irrigation, would not have the motive force to carry the contaminants back to the water table and therefore is not included in the recycle fraction. The combination of recycle and recapture fractions for the recycle report equates to about 0.11 (0.96×0.12) with an annual withdrawal rate of 3,000 acre-feet.

Table B-3. Biosphere dose conversion factors for the Amargosa Farms area.[a]

Radionuclide	Biosphere dose conversion factor
C-14	7.03×10^{-6}
Cl-36	3.00×10^{-5}
Se-79	8.88×10^{-5}
Sr-90	1.26×10^{-4}
Tc-99	4.07×10^{-6}
Sn-126	1.59×10^{-3}
I-129	4.81×10^{-4}
Cs-135	5.55×10^{-5}
Cs-137	4.81×10^{-4}
Pb-210	9.99×10^{-3}
Ra-226	1.41×10^{-2}
Ra-228	3.33×10^{-3}
Ac-227	4.81×10^{-3}
Th-228	1.15×10^{-3}
Th-229	9.62×10^{-3}
Th-230	4.07×10^{-3}
Th-232	7.03×10^{-3}
Pa-231	8.88×10^{-3}
U-232	2.22×10^{-3}
U-233	3.33×10^{-4}
U-234	3.03×10^{-4}
U-235	3.48×10^{-4}
U-236	2.85×10^{-4}
U-238	2.92×10^{-4}
Np-237	9.99×10^{-4}
Pu-238	2.81×10^{-3}
Pu-239	3.52×10^{-3}
Pu-240	3.52×10^{-3}
Pu-242	3.37×10^{-3}
Am-241	3.07×10^{-3}
Am-243	3.29×10^{-3}

Source: DIRS 185814-DOE 2008, Table 2.3.10-12
a. In rem per year per picocurie per liter.

Because DOE used a recapture fraction of 1.0, this Analysis of Postclosure Groundwater Impacts used a recycle fraction of 0.86. This reflects the fraction of water used in irrigation. Although some of the commercial/ residential/industrial water use could contribute to recycling via leaching through septic fields (unlikely because the leach fields are shallow and water is lost by evaporation), this contribution is

more than offset by the higher-than-expected recapture fraction. Also note that some radionuclides will be lost to soil erosion as well as via uptake in crops that are hauled away, in exported milk, and various other loss paths. This results in a combination of recycle and recapture fractions of 0.86 (compared with the 0.11 identified as the mean in the *Irrigation Recycle Model*; DIRS 182130-SNL 2007, p. 6-39).

B.2.3.2 Dose at Discharge Locations

At natural discharge locations, DOE calculated the dose differently from the evaluation at the Amargosa Farms area. At the discharge locations, there is no pumping and therefore no recycle. Instead, water is either discharged as a liquid or lost by evapotranspiration. In the present-day climate, the springs at Furnace Creek are flowing and so would likely continue flowing during a wetter climate. At the Death Valley floor and at Alkali Flat, water currently reaches the surface at a few locations but most is lost by evapotranspiration. In a wetter climate or wet episode of a dry climate, the evapotranspiration areas could have additional temporary springs or bodies of surface water.

B.2.3.2.1 Furnace Creek Springs Area

The receptors considered for this analysis include full-time residents in the Furnace Creek area, such as local members of the Timbisha Shoshone Tribe and employees of the National Park Service. Those persons would receive external exposure from contaminants deposited in soil from spring flows or use of spring water for landscaping, as well as from inhalation and inadvertent ingestion of contaminated soil particles. They also could be exposed by drinking spring water or using that water in evaporative coolers in their residences and offices.

Because there is no large-scale irrigation of agricultural fields in the Furnace Creek springs area, the irrigation recycle model was not used to calculate radionuclide concentrations in the soil. The concentration of radionuclides in the water (grams per unit volume) was estimated as the flux of radionuclides (grams per year) divided by the total discharge rate from the springs (volume per year).

To calculate the annual dose resulting from the radionuclide concentration in the water at the Furnace Creek area, DOE also used the biosphere dose conversion factors developed for the TSPA-LA. However, the biosphere dose conversion factors were modified because the dose pathways are different than those at the Amargosa Farms area. There is little agricultural production or other local production of foodstuffs in the Furnace Creek area, so DOE did not include food ingestion pathways. This resulted in reductions of the biosphere dose conversion factors by 40 to 60 percent for the radionuclides that are the principal contributors to dose.

Because the biosphere dose conversion factors were developed based on year-round exposure to soil and groundwater by residents, the calculated dose substantially overestimates to risk to visitors to Death Valley National Park or other non-residents in the Valley. Table B-4 presents the reduction percentages and resulting reduced biosphere dose conversion factors used in the analysis.

DOE also performed an analysis for use of water from springs in the Furnace Creek area using the full biosphere dose conversion factors given in Section B.2.3.1. This information was provided to compare the degree to which dose might be increased if local populations carried out a lifestyle that included gardening or other activities that would lead to ingestion of contaminated foodstuffs.

Table B-4. Biosphere dose conversion factors for the Furnace Creek springs area.[a]

Radionuclide	Percent of biosphere dose conversion factor that includes external exposure, inhalation, and soil ingestion[b]	Biosphere dose conversion factor
C-14	22.6	1.59×10^{-6}
Cl-36	9.5	2.80×10^{-6}
Se-79	9.1	8.08×10^{-6}
Sr-90	67.2	8.45×10^{-5}
Tc-99	44.1	1.79×10^{-6}
Sn-126	94.5	1.50×10^{-3}
I-129	60.5	2.91×10^{-4}
Cs-135	11.3	6.27×10^{-6}
Cs-137	43.5	2.09×10^{-4}
Pb-210	57.9	5.78×10^{-3}
Ra-226	94.7	1.33×10^{-2}
Ra-228	85.7	2.85×10^{-3}
Ac-227	95.9	4.61×10^{-3}
Th-228	89.5	1.03×10^{-3}
Th-229	93.9	9.03×10^{-3}
Th-230	94.5	3.85×10^{-3}
Th-232	94.2	6.62×10^{-3}
Pa-231	97.7	8.68×10^{-3}
U-232	91.1	2.02×10^{-3}
U-233	90.2	3.00×10^{-4}
U-234	89.7	2.72×10^{-4}
U-235	91.3	3.18×10^{-4}
U-236	89.6	2.55×10^{-4}
U-238	89.6	2.62×10^{-4}
Np-237	96.0	9.32×10^{-4}
Pu-238	94.6	2.66×10^{-3}
Pu-239	95.1	3.34×10^{-3}
Pu-240	95.2	3.35×10^{-3}
Pu-242	95.2	3.21×10^{-3}
Am-241	96.4	2.96×10^{-3}
Am-243	96.6	3.18×10^{-3}

a. In rem per year per picocurie per liter.
b. Source: DIRS 185814-DOE 2008, Tables 2.3.10-11 and -12

B.2.3.2.2 Death Valley Floor and Alkali Flat

The primary destination for radionuclides and nonradiological contaminants indentified by the particle tracking flow modeling was a location on the Death Valley floor designated in the modeling domain as a

unit called OBS-DV-MIDDL (DIRS 173179-Belcher et al. 2004, Table F-4, Figure 4-7). This unit coincides with an area to the southwest of the springs at Furnace Creek called Middle Basin, which typifies the many playas in the region. Playas in this region of Nevada and California have been classified as wet playas and dry playas (DIRS 186240-Reynolds et al. 2007, p. 1811). Wet playas are characterized as having groundwater less than 5 meters below the surface. The basins in this part of Death Valley are wet playas. In a wet playa, capillary action brings water to the surface, resulting in evaporation from the shallow groundwater. This action produces a soft surface of evaporite minerals that typically is rich in minerals such as calcium carbonate, hydrated calcium sulfate, sodium chloride (common salt), and sodium sulfate. The deposits originate from the dissolved solids in the groundwater and are found in the capillary fringe area and on the surface. Often the deposits are described as "fluffy" with large pore space and low density (DIRS 186240-Reynolds et al. 2007, p. 1812). As the evaporite mineral crystals form, they displace the rock-derived clastic minerals, expanding the sediments upward (DIRS 186240-Reynolds et al. 2007, p. 1812). Sometimes a more compact, but still friable, material forms, which contains a lower fraction of evaporites. These deposits are associated with lower rates of evaporation or lower salinity in the groundwater.

At times, durable, wind-resistant crusts of evaporite minerals can form a protective layer about 1 centimeter thick on top of unconsolidated and dry fine-grained sediment that might be as much as 10 centimeters thick. Breaking this crust can release material that is easily carried by the wind (DIRS 186240-Reynolds et al. 2007, p. 1823). It has been observed that changes occur in evaporite sediments due to wind erosion, rainfall events, and water table fluctuations (DIRS 186240-Reynolds et al. 2007, p. 1816). Thus, the deposits may take on many forms; some very susceptible to resuspension and some not. Over the course of an extended time there may be widely varying air concentration of these materials.

Occasional flooding of the playa would reduce, if not eliminate, the doses and intakes from the deposits. Any standing water or runoff water would be extremely brackish and non-potable so ingestion of water would not be expected.

The same receptor as was used in the analysis at the Furnace Creek springs area (a full-time resident of Death Valley) was considered in the analysis of health impacts from the deposition of contaminated evaporites on the soil surface at Middle Basin. Three exposure pathways, (1) external exposure to evaporite minerals, (2) inhalation of resuspended evaporites, and (3) ingestion of evaporites, were evaluated to estimate the annual dose that would occur if all radionuclides in the groundwater were to travel to the floor of Death Valley and rise to the surface soil via evapotranspiration of groundwater. Ingestion of water and other uses of contaminated water were not included in this analysis because it is more likely that residents would continue to rely upon water obtained from nearby existing springs and wells than from any mineral-laden seeps or other standing water that may occur in the valley bottom. The consequences of ingesting water from springs, and using that water for other purposes (for example, evaporative cooling), were included in the calculation of the annual dose from use of water from the springs in the Furnace Creek area.

As surface evaporite minerals form, they would precipitate any trace contaminants (such as radionuclides or other nonradiological contaminants) along with them. There is no mechanism for preferential precipitation by evaporation so the ratio of trace contaminants to evaporites is reflective of the ratio or concentration of trace contaminants to concentration of total-dissolved-solid minerals in the water that is

evaporating. Thus, the concentration of a radionuclide in the evaporite minerals was calculated as the concentration of the radionuclide in the water divided by the total-dissolved-solids in the water.

The total-dissolved-solids in the groundwater will increase the farther the water flows in the ground. To be conservative, DOE used the total-dissolved-solids of water from well J-13, which is close to Yucca Mountain. The total-dissolved-solids of groundwater flowing past that well would be lower than it would be after traveling south toward Death Valley (larger total-dissolved-solids values will reduce the concentration of the contaminant in the evaporites and therefore the estimate of dose or intake). The total-dissolved-solids for J-13 well water is 257 milligrams per liter (DIRS 169734-BSC 2004, Table 7-44).

The observed evapotranspiration rate of unit OBS-DV-MIDDL (Middle Basin) is 6,625 cubic meters per day during the present climate (DIRS 173179-Belcher et al. 2004, Table F-4). DOE estimates that during the wetter climate this value would increase by a factor of 3.9, resulting in an evapotranspiration rate of 25,837 cubic meters per day. The concentration of the contaminant in the water was calculated as the flux of contaminant in grams per year divided by the inflow of water (evapotranspiration rate).

The annual dose resulting from evapotranspiration was calculated using the concentrations of radionuclides in evaporite minerals that would result from evaporation of near-surface groundwater. The methods for calculating doses in the TSPA-LA biosphere model (DIRS 177399-SNL 2007, Section 6.4), were adapted to calculate the dose for each of the three pathways considered. Unless otherwise specified, the representative fixed values for input parameters to the TSPA-LA biosphere model (DIRS 177399-SNL 2007, Table 6.6-3) were used for this calculation.

To calculate external exposure and inhalation exposure of contaminated evaporites, DOE assumed that the receptor would always be in the inactive outdoor environment, as described in the *Biosphere Model Report* (DIRS 177399-SNL 2007, Section 6.4.2.1). This environment is representative of conditions that occur when a person is outdoors in areas where radionuclides may be present and engaged in activities that would not resuspend soil (that is, not operating heavy machinery, plowing, or driving large vehicles on dirt surface). It was also assumed that all particulates inhaled and inadvertently ingested would be contaminated evaporites. The dose calculation does not account for time spent indoors, where concentrations of resuspended particles would be lower and the receptor would be shielded from some radiation. Nor does it account for inhalation of particulates from soil-disturbing activities (when concentrations would be higher). Furthermore, the calculation does not account for time the receptor would spend outside of the limited area that would be contaminated by evapotranspiration of groundwater. In other words, it is assumed that the receptor is outdoors, exposed to and breathing contaminated evaporite minerals year-round. The maximum value of the distribution of mass loading for the inactive outdoor environment (0.1 milligram per cubic meter; DIRS 177399-SNL 2007, Table 6.6-3) was used in the calculation of inhalation exposure to account for high levels of resuspended particulates that may occur temporarily on or near the playa during high winds. Although much higher concentrations of resuspended particulates may occur during dust storms, such high values do not represent the average annual value of mass loading required for this calculation.

The total dose from radionuclides in evaporite minerals is the sum of doses from direct exposure, inhalation, and ingestion. Using dose coefficients and appropriate parameters from the TSPA-LA biosphere model, DOE estimated these individual dose components and the total dose from each radionuclide in the flux of contaminants estimated to arrive at Death Valley.

The estimate of doses and intakes at Middle Basin on the Death Valley floor included the following conservatisms:

- In the estimate of concentration of contaminants in the solids, DOE used a low level of total-dissolved-solids found in local groundwater. Higher values of total-dissolved-solids would reduce the estimated concentration and therefore dose and intakes.

- In the calculation of exposure from inhalation of airborne particulates:

  - DOE assumed that all resuspended particulates that the receptor breathes in are evaporite minerals. Inclusion of rock-based clastic soils would reduce the estimated concentration and therefore doses and intakes;

  - DOE used the maximum value for the concentration of resuspended particles for the environment considered in the analysis;

  - DOE assumed that the receptor would inhale air containing the estimated concentration of contaminants for the entire year; and

  - The single value of breathing rate used ignores the fact that people spend 8 or so hours asleep when their breathing rate would drop by at least half the assumed value.

- For ingestion of contaminated soil:

  - DOE assumed that all material that is inadvertently ingested consists of evaporite minerals, and

  - The daily ingestion rate is relatively high at 100 milligram per day (for example, the EPA recommends 50 milligrams per day for adults and 100 milligrams per day for children (DIRS 152549-EPA 1997, Table 4-23).

- For external exposure to radionuclides in soil:

  - DOE used dose coefficients developed for soil contaminated to an infinite depth, although most evaporites would be on or near the soil surface. Dose coefficients for a lesser depth would be lower and would reduce the estimate of dose; and

  - DOE assumed that the receptor would be outdoors and exposed to contaminated evaporites year-round.

B.2.4 RADIONUCLIDE INVENTORY CALCULATIONS

At various locations, the dose calculation used the mass flux to develop an inventory. This inventory is a decay- and growth-adjusted measure of the total amount of material that arrived at the specific location as a function of time. Note that for some radionuclides, this cumulative total could decrease after long times due to decay. The inventory included assessments for the following regions:

- Inventory released to the saturated zone at the repository,
- Inventory released beyond the Regulatory Compliance Point (RMEI location),
- Inventory accumulated at the Amargosa Farms area, and

- Inventory released into Death Valley.

DOE analyzed inventory for each radionuclide over time to provide a measure of how much material exists in a specific region at any time during the 1-million-year period.

DOE then constructed mass balances by using the inventories. For example, the amount of a radionuclide in the saturated zone path between the Regulatory Compliance Point and the Amargosa Farms area was the difference between the inventory released beyond the Regulatory Compliance Point and the inventory accumulated at the Amargosa Farms area. The mass balances provided an overall accounting of where radionuclides might travel to and where they might accumulate.

B.2.5 SOIL CONCENTRATIONS OF RADIONUCLIDES AT THE AMARGOSA FARMS AREA

In the Amargosa Farms area where irrigated farming takes place, water is pumped out of wells. If this well water contained radionuclides, these radionuclides could land on the surface soil during irrigation. Some fraction of the radionuclides would decay, some fraction would leach back into the aquifer, and some fraction would escape by soil erosion. In the formulation of the TSPA-LA biosphere model, DOE developed many modeling concepts that are useful for obtaining estimates of the fate of contaminants in an irrigated region. After some period of time at a constant flux, the processes of soil erosion, leaching, and decay would balance the influx of radionuclides, thus achieving a steady-state wherein the soil concentration became constant in time. That is, the soil concentration is a function of three rate constants (radioactive decay, erosion, and leaching) and the rate of influx of radionuclides. The erosion and leaching rate constants can be calculated from soil erosion rates, watering rates, and properties such as soil moisture content, porosity, and K_d. The time to steady-state can be hundreds or even thousands of years, but the fluxes vary slowly so that an assumption of constant steady-state is a reasonable approximation.

B.3 Analysis of Nonradiological Contaminants

Chemically toxic materials that could present a human health risk when released to the groundwater would be present in materials disposed of in the repository. These materials, referred to herein as nonradiological contaminants, would come from construction materials of the repository and waste packages and from the disposal materials within the waste packages.

B.3.1 MATERIALS OF CONCERN

During the preparation of the Yucca Mountain FEIS and Repository SEIS, DOE conducted various screening studies to determine which materials would be of sufficient concern to warrant further analysis of the postclosure transport of these materials from the repository and possible resulting impacts. During the development of the FEIS, DOE surveyed all of the materials and analyzed their potential hazard. It was found that the materials of concern were chromium, molybdenum, nickel, and vanadium. The analysis of the toxic materials in the FEIS was limited to 10,000 years postclosure. Because only a few percent of the packages would fail by 10,000 years, DOE assumed in the FEIS that the contribution from inside the packages was negligible. Thus, the FEIS contained a simple bounding analysis of chromium, molybdenum, nickel, and vanadium released as the products of corrosion of repository and waste package construction materials outside of the waste package; that is, of stainless steel and Alloy 22.

During development of the Repository SEIS, DOE conducted further screening studies. Significant additional volumes of stainless-steel material had been added to the repository design at this point. Since completion of the Yucca Mountain FEIS, new data showed that the corrosion of chromium-bearing materials would not likely result in the very soluble (and toxic) valence (+6) of chromium, but rather that the chromium would be in the insoluble (and non-toxic) valence (+3). Based on this, DOE removed chromium from the list of materials of concern (DIRS 180751-DOE 2008, p. F-38).

This Analysis of Postclosure Groundwater Impacts addresses the entire 1-million-year postclosure period and, as such, revisits materials inside of waste packages. DOE conducted additional screening studies that showed there were no new materials of concern; therefore, materials of concern for this analysis are still molybdenum, nickel, and vanadium. However, there is a fairly large quantity of materials bearing some of these elements within the waste package so that the quantities of these materials would increase over the 1-million-year period due to package failures.

B.3.2 DEVELOPMENT OF FLUX AT THE UNSATURATED ZONE-SATURATED ZONE INTERFACE

This Analysis of Postclosure Groundwater Impacts analyzes nonradiological contaminants during the 1-million-year postclosure period in a manner consistent with the radiological contaminant analysis. This analysis includes quantities of materials from inside the waste packages, as some fraction of waste packages would be likely to fail over time, exposing the internal materials to corrosion. Uranium is retained as a nonradiological contaminant as well as a radiological contaminant because uranium has a high toxicity as a heavy metal. Note that previous screening studies had not rejected uranium but rather had ignored uranium as a toxic material because only a few percent of the packages would fail in the first 10,000 years after closure. In this Analysis of Postclosure Groundwater Impacts, package failures, and thus materials within the package, are accounted for. Therefore, the contaminants of concern analyzed for the extended-time analysis in this document are molybdenum, nickel, vanadium, and uranium.

The bounding analysis in the Repository SEIS took no credit for any attenuating processes once the corrosion of the construction materials and waste packages released the nonradiological contaminants nickel, molybdenum, and vanadium. The flux of metal arriving at the hypothetical well at the Regulatory Compliance Point was the rate of release by corrosion. Thus, the flux was equal to the mobilization rate of the alloy times the fraction of alloy represented by the particular element. The mobilization rate was simply the area of exposed alloy times the thickness loss (that is, from corrosion) times the density. The concentration of metal in a hypothetical well was then the flux divided by the volumetric pumping rate of the well, assuming full capture of the metals by the well. This approach was extremely conservative. It did not allow for delays due to sorption processes or other possible attenuating processes. It also assumed that all of the available surface area of alloy was constantly exposed to water and corroding.

To develop a flux of metals from the repository to the unsaturated zone for this Analysis of Postclosure Groundwater Impacts, DOE used a similar analysis to that used in the Repository SEIS. However, because this analysis considers the 1-million-year period, it took into account the corrosion of materials inside the waste package.

The approach DOE used includes:

- Assessing the number of waste package failures for the combined scenario case at 100,000 years and 1 million years.

- Calculating mobilization rates based on exposed area (external plus internal for failed packages) for the combined scenario case at 100,000 and 1 million years.

- Characterizing the flux from the unsaturated zone to the saturated zone as a combination of step functions as follows: The flux is represented by a step function at postclosure time equal to 0 with magnitudes represented by the total external materials and the internal materials equal to that contained in the fraction of waste packages failed at 100,000 years. Another step function occurring at 500,000 years is then added. The magnitude of this step relates to the amount of internal material released from the fraction of waste packages failed at 1 million years. This is a conservative result because the values at time of closure really do not occur until 100,000 years and the values applied at 500,000 years do not occur until 1 million years.

B.3.3 FLUX AT THE REGULATORY COMPLIANCE POINT

This section addresses the transport of molybdenum, nickel, and vanadium from the point where they would enter the saturated zone under the repository to the Regulatory Compliance Point. (Note that the flux of uranium is already calculated in the radionuclide calculations; see Section B.2.) The starting point for this analysis is the release of the materials into the saturated zone during the 1-million-year postclosure period. Section B.3.2 describes how the release rates at the beginning of the saturated zone under the repository were calculated. The metals fluxes developed from those calculations are the input to the calculations in this section.

The variable having the greatest influence on transport is the sorption partition coefficient of each contaminant. The K_d is a measure of the partitioning between the contaminant in solution and the contaminant adsorbed on to the solid medium. Because little is known about interactions of the nonnuclear contaminants with colloids, this analysis neglects any effects of colloids. Colloid transport could result in a different transport speed of the metal than its retardation factor would indicate. In the case of molybdenum, which has an assumed K_d of zero, colloid transport might slow down its transport. Because the metals have no decay and dispersion has a minimal effect, the change in transport rate only changes the time of arrival, so there is little effect on the ultimate impacts.

All of the transport processes in the saturated zone that affect radionuclides could affect how the nonradiological contaminants move. Processes that can be accounted for are based on available data and the state of knowledge concerning nickel, molybdenum, and vanadium. The TSPA-LA showed some radionuclides that transport (travel) only as solutes (no colloidal processes). The parameters governing transport of these radionuclides are the K_d for adsorption on the solid, the specific discharge, and structure of the aquifer system (for example, fractures and matrix porosity). The TSPA-LA provided a set of standardized breakthrough curves developed from detailed modeling of the saturated zone. The transport of the metals can be simulated using standard breakthrough curves for radionuclides that transport in the solute mode (that is, no colloidal transport) with a matching K_d.

DOE used the TSPA-LA saturated zone transport model to generate breakthrough curves as a response to unit step functions. This was done by running the saturated zone transport model with all saturated zone parameters set to their mean values and the K_d set to a value corresponding to the values developed from

a literature study (DIRS 186186-SNL 2009, Section 4.6). Figure B-1 shows the resulting breakthrough curves for groundwater flow with glacial-transition climate conditions. The breakthrough curves in Figure B-1 were multiplied by the magnitude of the unsaturated zone step functions (Section B.3.2) with the appropriate delay (one step at repository closure and the next step at 500,000 years). The summation curve of the result represents the flux history of the metal at 18 kilometers.

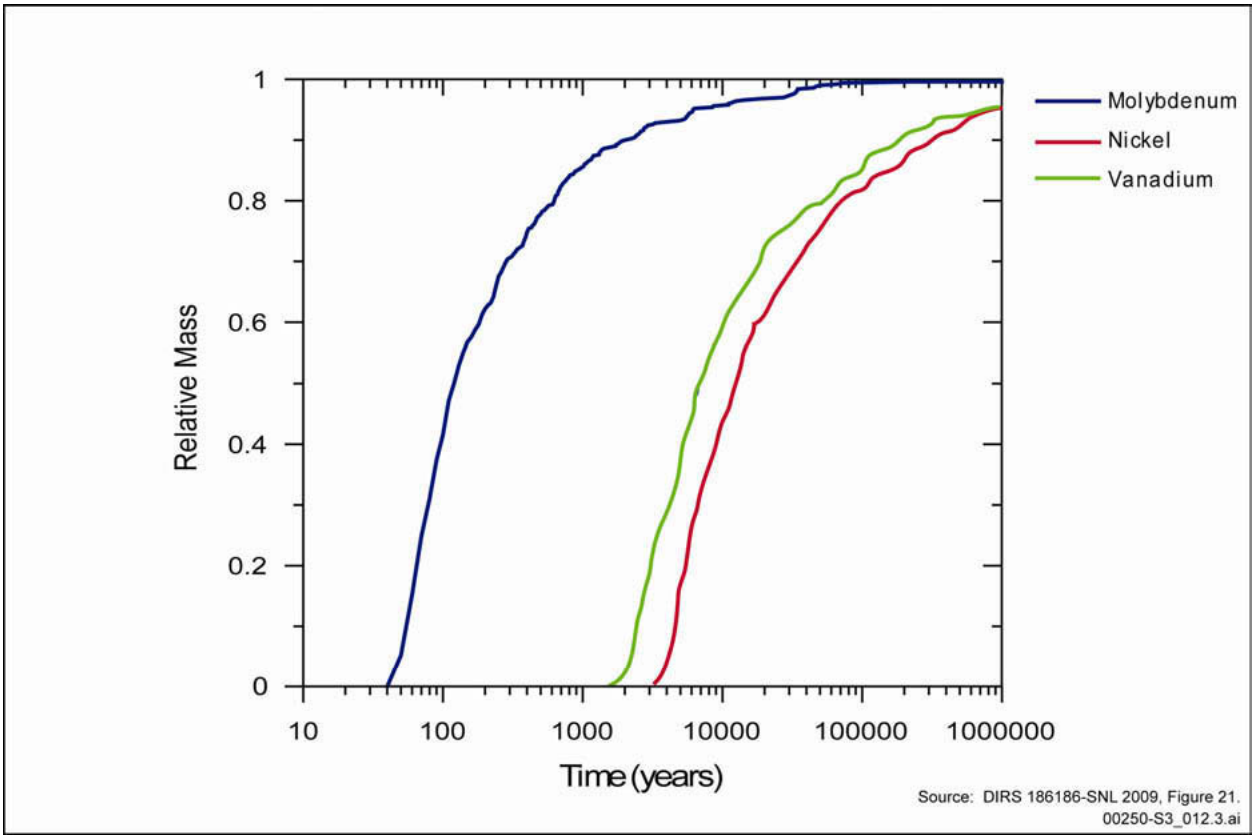

Figure B-1. Simulated breakthrough curves in the saturated zone for molybdenum, vanadium, and nickel.

B.3.4 FLUX OF NONRADIOLOGICAL CONTAMINANTS BEYOND THE REGULATORY COMPLIANCE POINT

The analysis used for molybdenum, nickel, and vanadium beyond the Regulatory Compliance Point is the same as that used for radionuclides. The same flow paths and termination points were analyzed. Rather than radiologic dose, however, the nonradiological analysis assessed the impact of the contaminants on humans by comparing calculated daily intakes with the Oral Reference Dose (see Section B.3.5 below).

The fluxes developed for release at the Regulatory Compliance Point are the starting point for the transport analysis, just as with the radionuclides.

ORAL REFERENCE DOSE

The Oral Reference Dose is based on the assumption that thresholds exist for certain toxic effects such as cellular necrosis. It is expressed in units of milligrams per kilograms per day. In general, the Oral Reference Dose is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime.

B.3.5 DAILY INTAKES

Daily intakes were evaluated at the Amargosa Farms area, the springs at Furnace Creek, and the Death Valley floor (Middle Basin) using the fluxes developed for the nonradiological contaminants. The following sections describe daily intakes and how they were estimated.

B.3.5.1 Amargosa Farms Area and the Springs at Furnace Creek

Fluxes of nonradiological contaminants into the Amargosa Farms area and the springs at Furnace Creek provide water concentrations of molybdenum, nickel, and vanadium in the same manner as for radionuclides (see Section B.2.3.1). DOE developed the water concentration of uranium by adding all the isotopes of uranium together from the radionuclide analysis. DOE based daily intakes on a 70-kilogram person drinking 2 liters of water per day. The daily intake is therefore equal to the water concentration (milligrams per liter) times 2 (liters) divided by 70 (kilograms) and expressed as milligrams per kilogram of body-weight per day. Oral Reference Doses are daily intake guidelines set by the U.S. Environmental Protection Agency (DIRS 148228-EPA 1999, all; DIRS 148229-EPA 1999, all; DIRS 103705-EPA 1997, all; DIRS 102173-EPA 1994, all).

B.3.5.2 Death Valley Floor (Middle Basin)

Section B.2.3.2.2 discusses the processes at the Death Valley floor (Middle Basin). The method for estimating the concentration of nonradiological contaminants in the evaporite minerals is the same as that for the radionuclides. Daily intakes to receptors at this site can occur from inhalation and inadvertent ingestion. Inhalation exposure occurs by breathing respirable contaminant particles in the air. DOE estimated the concentration of respirable contaminant particles from the concentration of contaminants in the evaporite minerals and an air burden (concentration of resuspended particles in the air), the latter of which was calculated using the methods from the TSPA-LA biosphere model. DOE used the high end of the statistical range for the air burden concentration (DIRS 177399-SNL 2007, Table 6.6-3). The analysis estimated the ingestion of contaminants using the same inadvertent soil ingestion rate as that used for the radionuclide dose estimates. Thus, from inhalation and ingestion exposures, DOE estimated an intake rate in milligrams per day. That rate was divided by the 70-kilogram body-weight to calculate daily intake in milligrams per kilogram of body-weight per day. These intakes were then compared with the same Oral Reference Dose values as was done for the analysis of intake at the Amargosa Farms area and the springs at Furnace Creek.

B.3.6 SOIL CONCENTRATIONS AT THE AMARGOSA FARMS AREA

Section B.2.5 discusses the calculation of radionuclide soil concentrations at the Amargosa Farms area. The same approach was used to calculate the soil concentrations for molybdenum, nickel, and vanadium. The uranium soil concentrations were calculated as individual radionuclides. The total uranium

concentration was obtained by adding the concentrations of all the uranium isotopes. The uranium totals are reported along with the other nonradiological contaminants.

B.4 Results and Discussion

The following sections provide detailed results obtained through the use of the models described in this appendix.

B.4.1 DOSES AND INTAKES

DOE evaluated radiological dose and daily intakes of nonradiological contaminants at three locations where the regional flow model projects discharge of contaminants: the Amargosa Farms area, the Furnace Creek springs area, and the Death Valley floor (Middle Basin). DOE also estimated doses and intakes that might occur if, under the no-pumping scenario, all flow went to Alkali Flat.

B.4.1.1 Amargosa Farms Area

As described above, the doses and intakes at the Amargosa Farms area are a function of the pumping rates and the fraction of pumped water used to irrigate fields. Based on data from 1994 to 2003, DOE established an average pumping rate of 16,828 acre-feet per year (DIRS 185968-Moreo and Justet 2008, Figure 3, p. 5). DOE used 0.86 for the fraction of radionuclides recycled to the well in analyses of the irrigation recycling process at the Amargosa Farms area (see Section B.2.3.1).

Figures B-2 through B-9 are plots of the total dose and dose by radionuclide for the two climate conditions at the Amargosa Farms area. These plots all represent the pumping scenario.

CONTAMINANTS NOT SHOWN ON PLOTS

Generally, all of the contaminants studied do not appear on the detailed plots of radionuclides and nonradiological contaminants. This is because a particular contaminant may sometimes not reach that location within 1 million years or is estimated to contribute an extremely small amount to the total dose. In such cases, the contaminant does not appear on the plot.

The TSPA-LA model estimated that some radionuclides would release much earlier in the repository than might be expected from normal degradation processes. This is due to the probabilistic contribution of seismic events that the model postulated to damage the packages and the repository. Figures B-2 through B-5 demonstrate this phenomenon. An example of an early released radionuclide is neptunium-237. Note that iodine-129 and technetium-99 are important radionuclides throughout the dose history.

Figures B-6 through B-9 show the results for the 10,000-year analysis for the Amargosa Farms area. This analysis was carried out because the 1-million-year analysis used a fairly coarse time step, which introduced considerable uncertainty in the value at 10,000 years. There was interest in the peak dose at 10,000 years, especially at the Amargosa Farms area due to the similarities with the RMEI location evaluated in the Repository SEIS. Therefore, DOE carried out an analysis with a finer time step over 10,000 years to more accurately estimate the radiological dose at the Amargosa Farms area for the first 10,000 years.

WHY ARE THE DOSE PLOTS SO JAGGED?

Anyone used to viewing plots of dose histories from the TSPA-LA might wonder why the dose histories in this Analysis of Postclosure Groundwater Impacts appear so jagged. There are two basic reasons for this:

1. The TSPA-LA model resulted in similar abrupt changes in dose histories per time step, but those changes were less apparent because of the use in TSPA-LA reports of logarithmic-scaled plots that depicted changes over long time periods. The results of the TSPA-LA model used as input to the modeling for this document have similar abrupt changes per time step, but those changes are more evident in this analysis because a linear, rather than logarithmic, scale is used for the total dose plots. Logarithmic scales are used to present results that vary by several orders of magnitude.

2. The coarser (that is, longer) time step used in the analyses for this document resulted in curves having a jagged appearance. This longer time step was appropriate for the purposes of this analysis. Using a shorter time step would have resulted in smoother curves, but would not have changed any of the results or conclusions of the analyses.

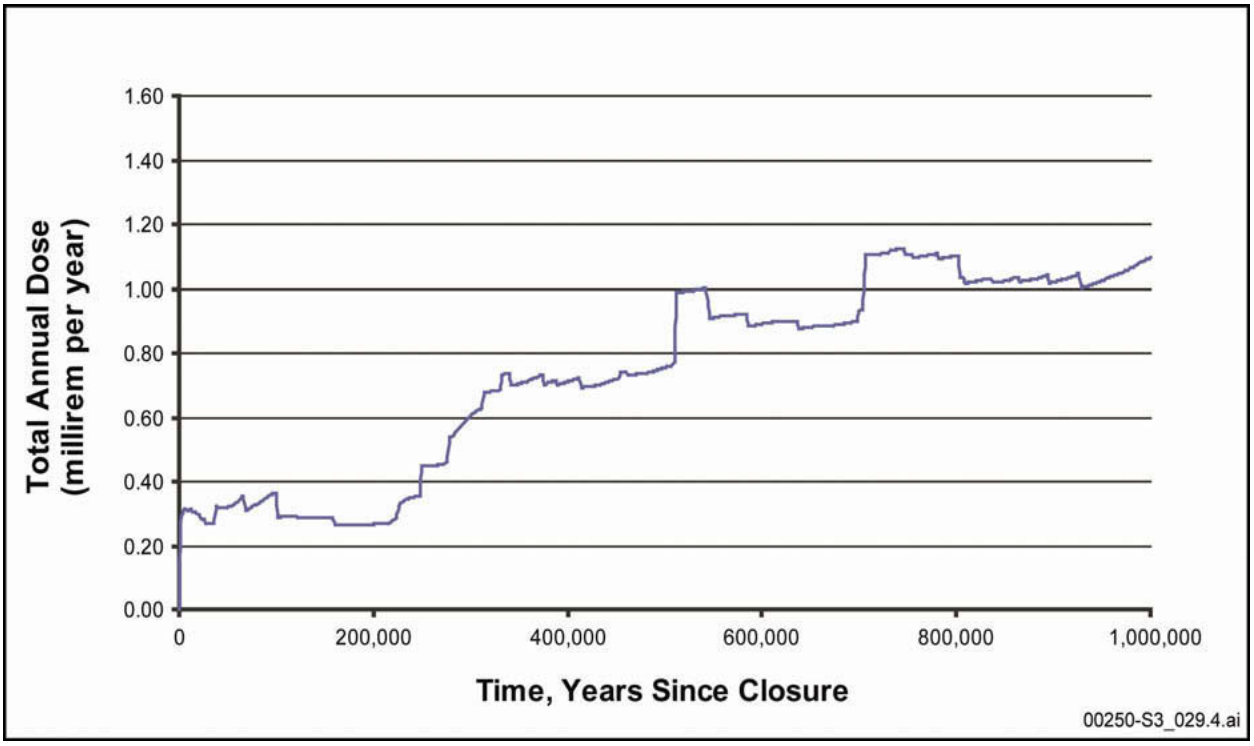

Figure B-2. Total dose at the Amargosa Farms area for present climate.

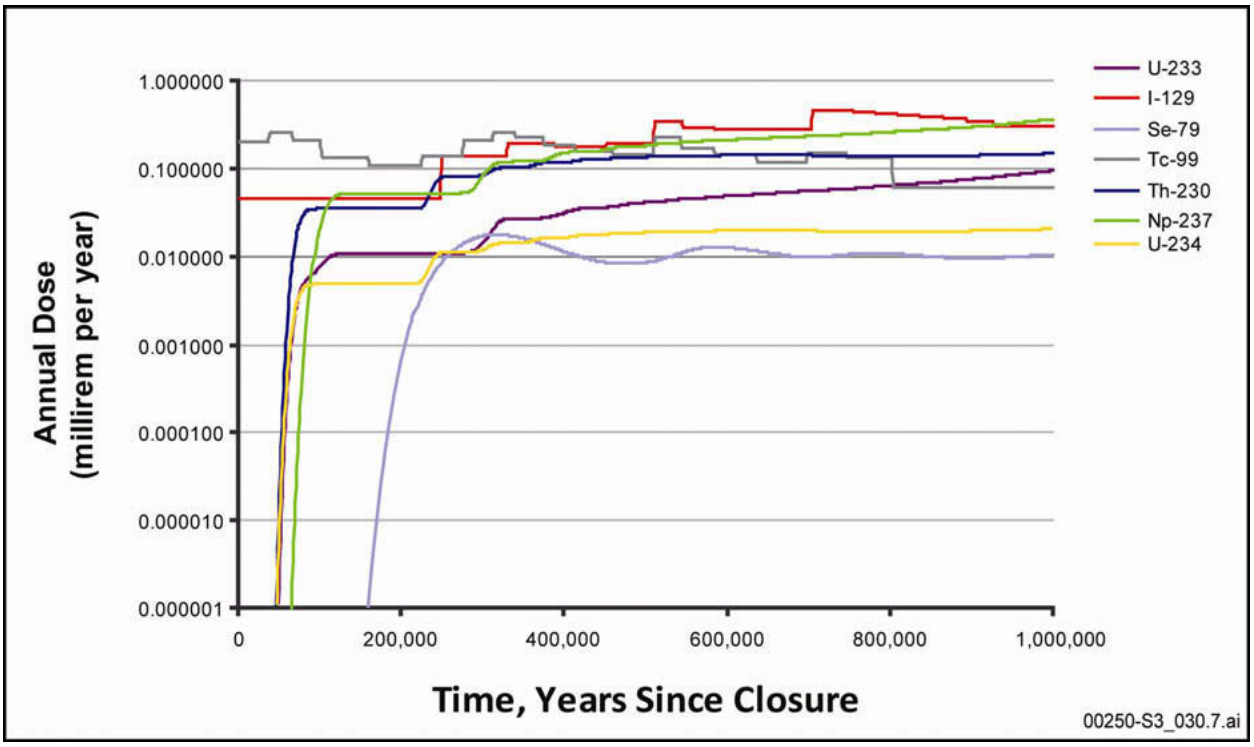

Figure B-3. Dose by radionuclide at the Amargosa Farms area for present climate.

Figure B-4. Total dose at the Amargosa Farms area for wetter climate.

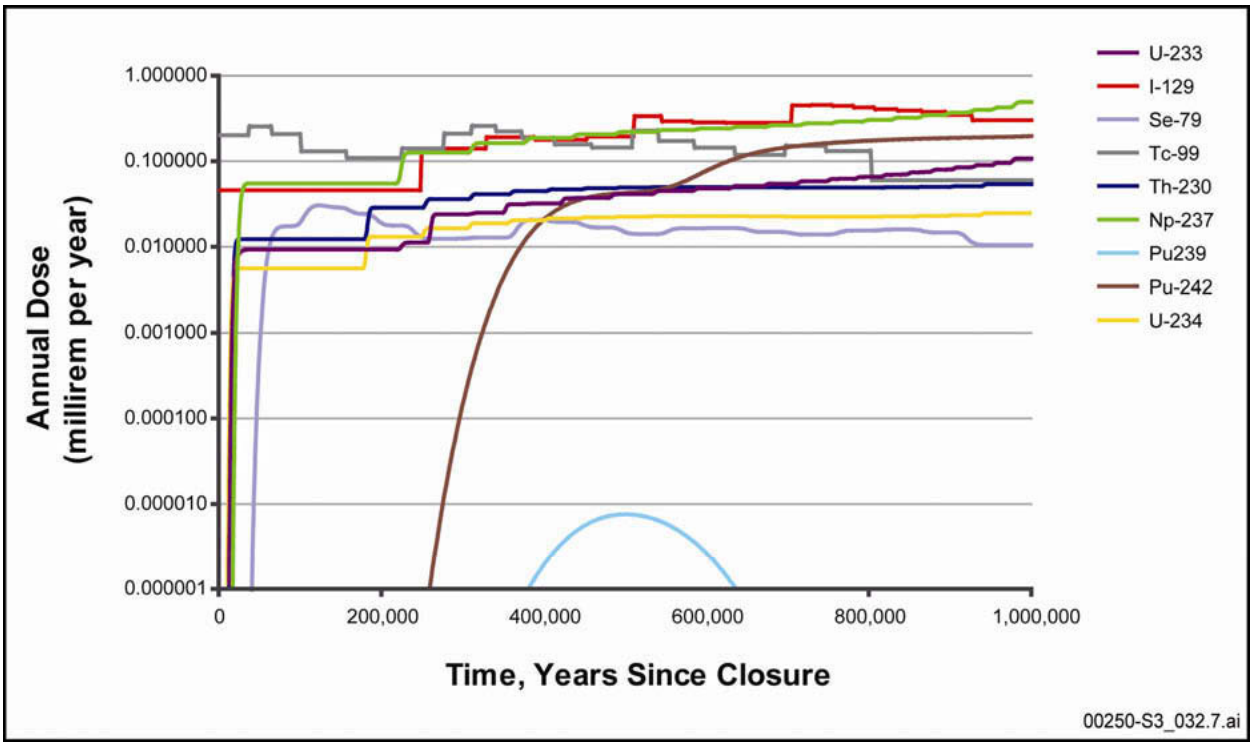

Figure B-5. Dose by radionuclide at the Amargosa Farms area for wetter climate.

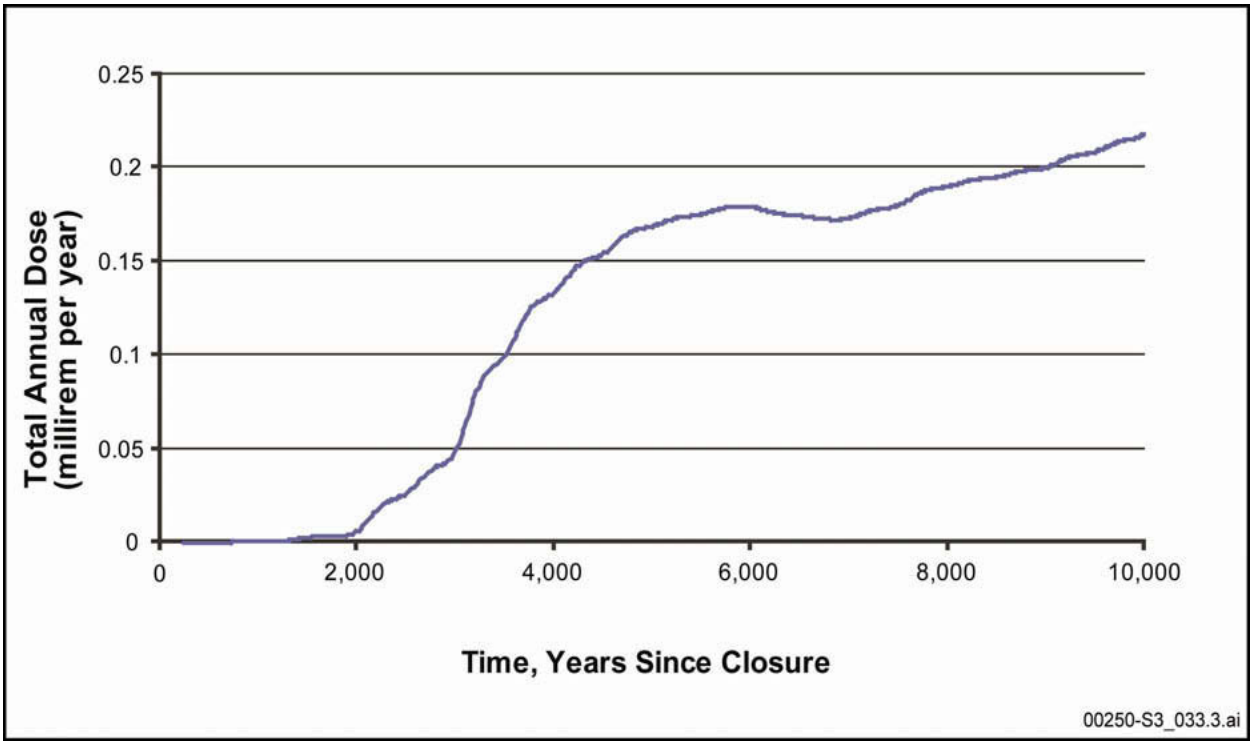

Figure B-6. Total dose at the Amargosa Farms area, present climate, 10,000-year case.

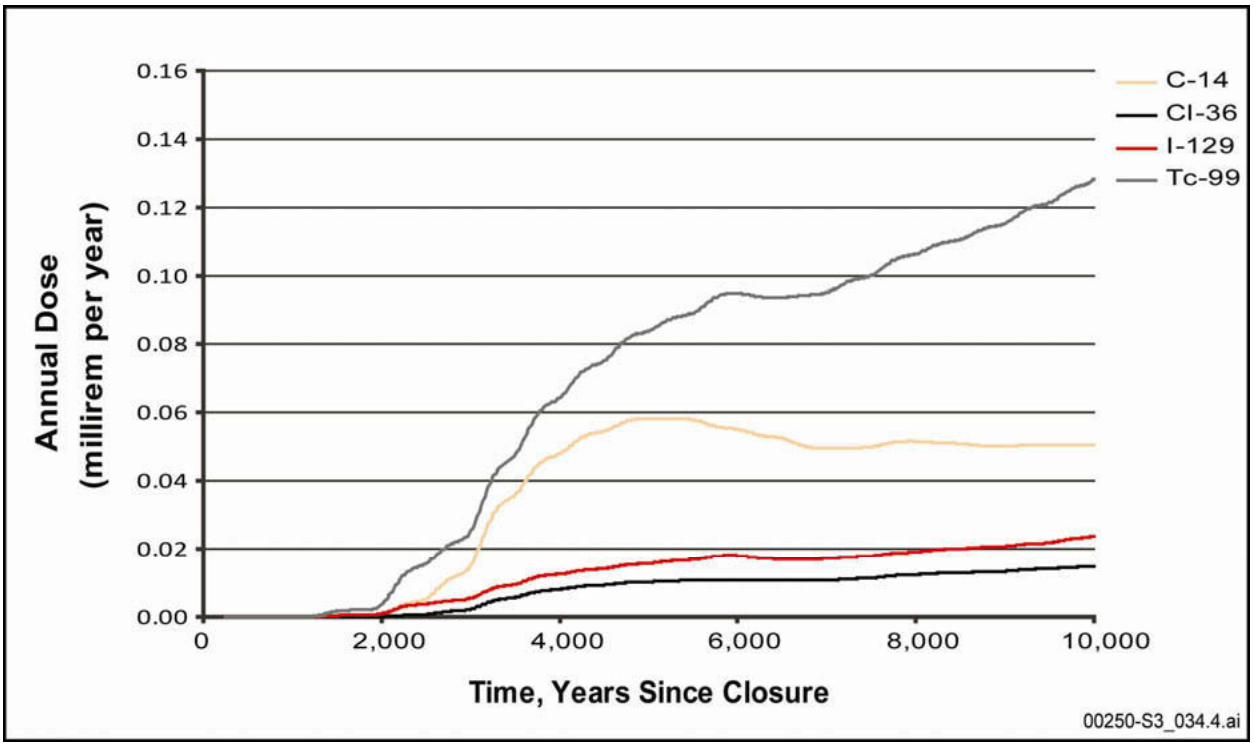

Figure B-7. Dose by radionuclide at the Amargosa Farms area, present climate, 10,000-year case.

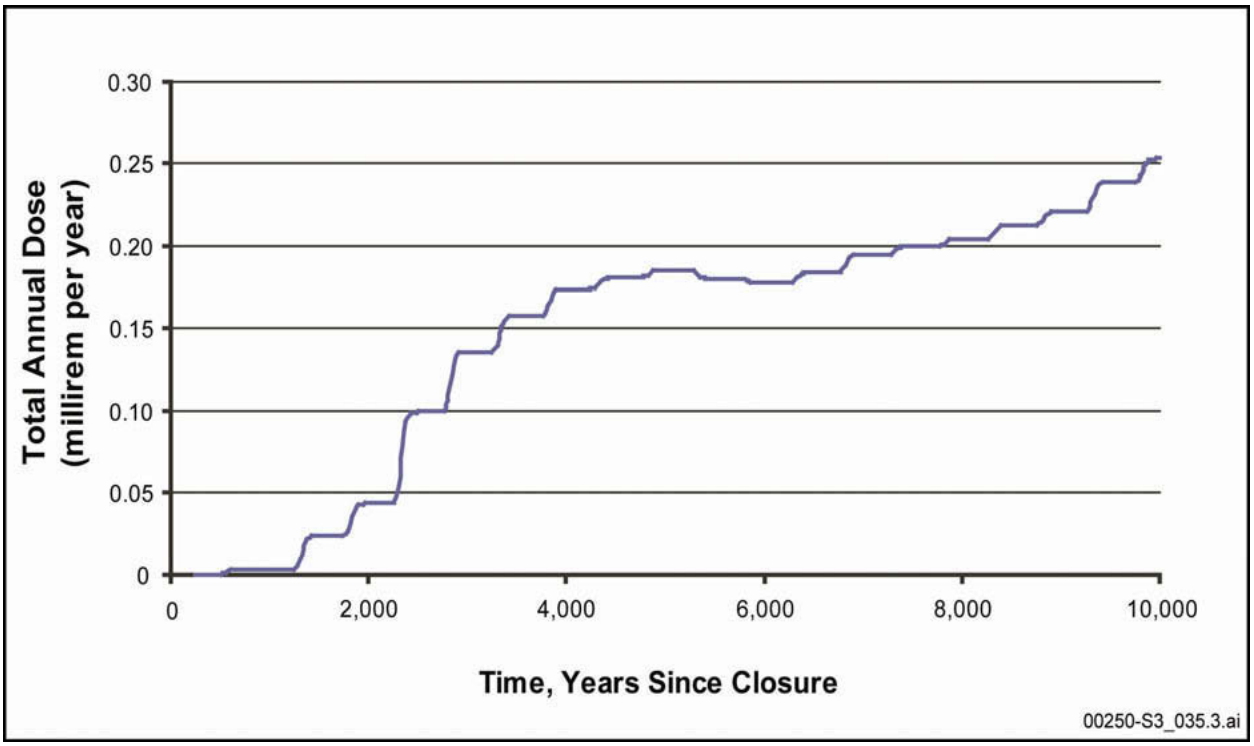

Figure B-8. Total dose at the Amargosa Farms area, wetter climate, 10,000-year case.

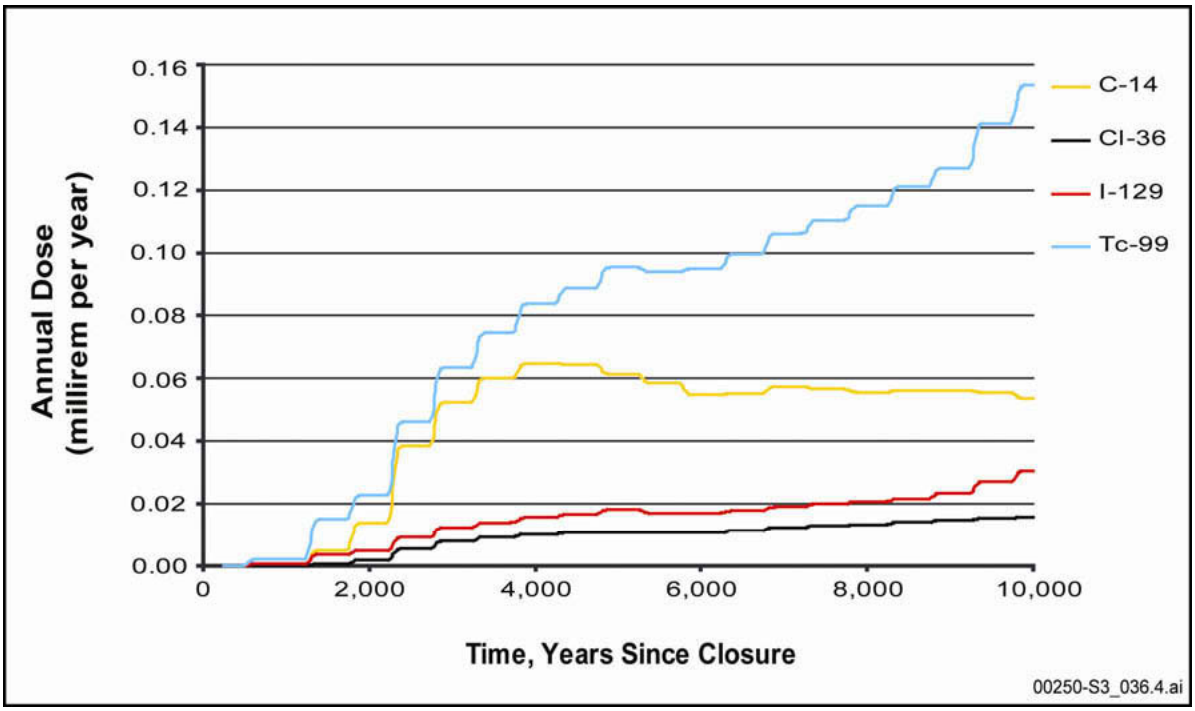

Figure B-9. Dose by radionuclide at the Amargosa Farms area, wetter climate, 10,000-year case.

Figures B-10 and B-11 show the daily intakes for nonradiological contaminants and compare these intakes with the Oral Reference Doses (DIRS 148228-EPA 1999, all; DIRS 148229-EPA 1999, all; DIRS 103705-EPA 1997, all; DIRS 102173-EPA 1994, all). All the estimated daily intakes are below the Oral Reference Dose.

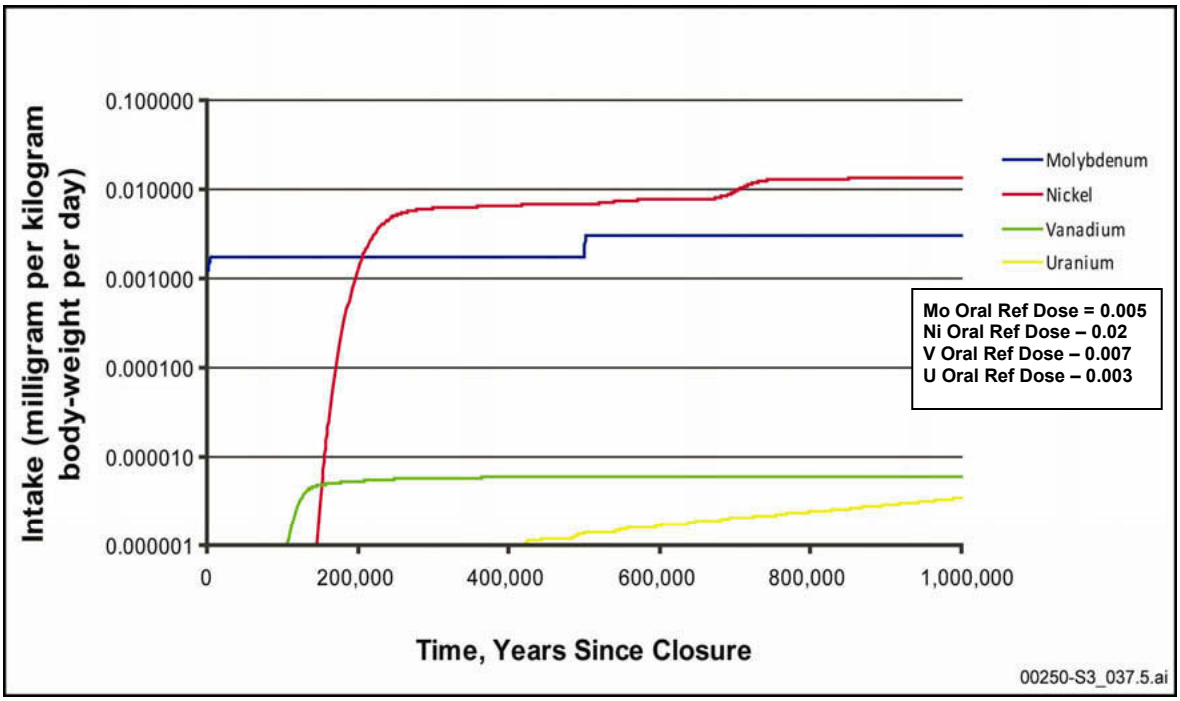

Figure B-10. Intakes of nonradiological contaminants at the Amargosa Farms area, present climate.

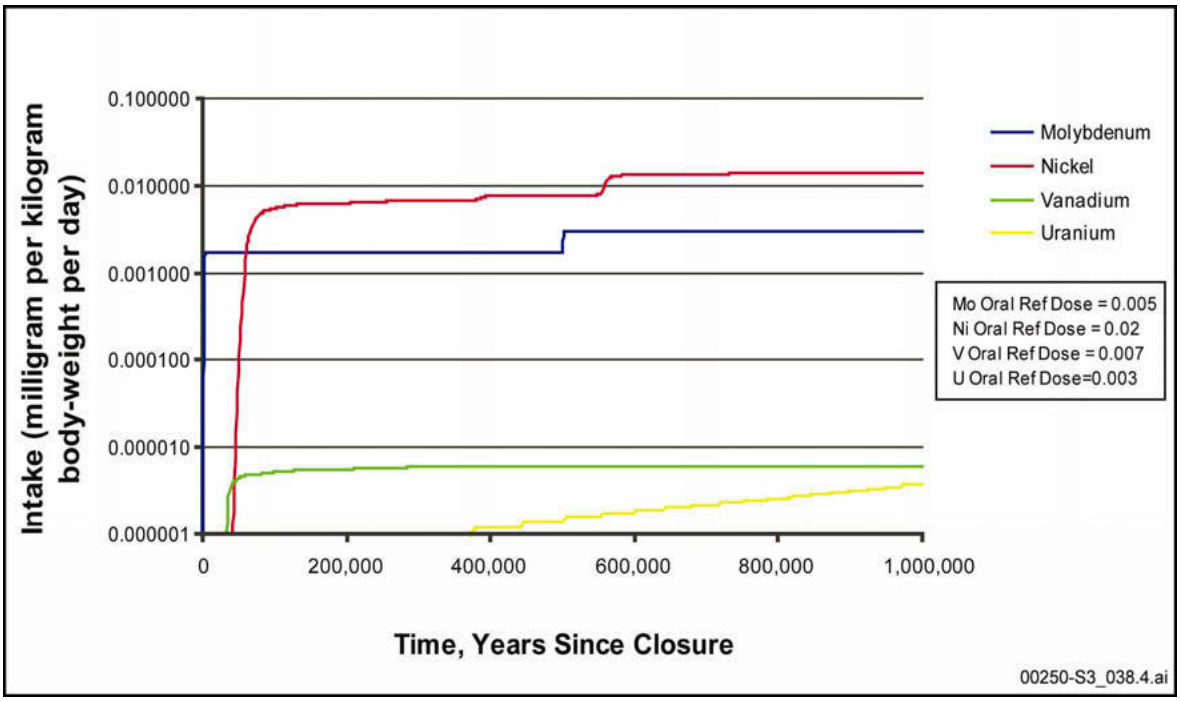

Figure B-11. Intakes of nonradiological contaminants at the Amargosa Farms area, wetter climate.

B.4.1.2 Death Valley

The regional flow modeling indicates that essentially all of the contaminants will flow to Death Valley and that the most likely termination point is the valley floor (see Section B.1). However, it is possible that the contaminants could flow to the Furnace Creek springs area very close to where the particles terminate at the floor of Death Valley. This section presents two types of doses and daily intakes associated with contaminants reaching Death Valley. The first set of doses and daily intakes represents those received by individuals using contaminated water if it arrived at the Furnace Creek springs area. The second set represents doses and intakes that individuals might receive when exposed to contaminated soils at the Death Valley floor where there is no liquid water present and to contaminated water when it is present. In the case of radiological doses from contaminated water in the Furnace Creek springs area, the dose factors have been adjusted to reflect the exposure scenarios (see Section B.2.3.2.1).

B.4.1.2.1 Death Valley Floor (Middle Basin)

The particle tracks strongly indicate that the contaminants would flow to the Death Valley floor at Middle Basin instead of the Furnace Creek springs area. The Death Valley floor in this area is normally an evapotranspiration area with no water emerging as liquid on the surface. DOE estimated doses and intakes at this location using the methods described in Sections B.2.3.2.2 and B.3.5.2.

Figures B-12 through B-15 show the results for radionuclide doses. In all cases the estimated doses are very low when compared with doses at any of the other locations. During the 1-million-year analysis period, the only nonradiological contaminant reaching the Death Valley floor would be molybdenum. Figures B-16 and B-17 present daily intakes for molybdenum. In all cases the molybdenum intake is well below the EPA guidelines for Oral Reference Dose.

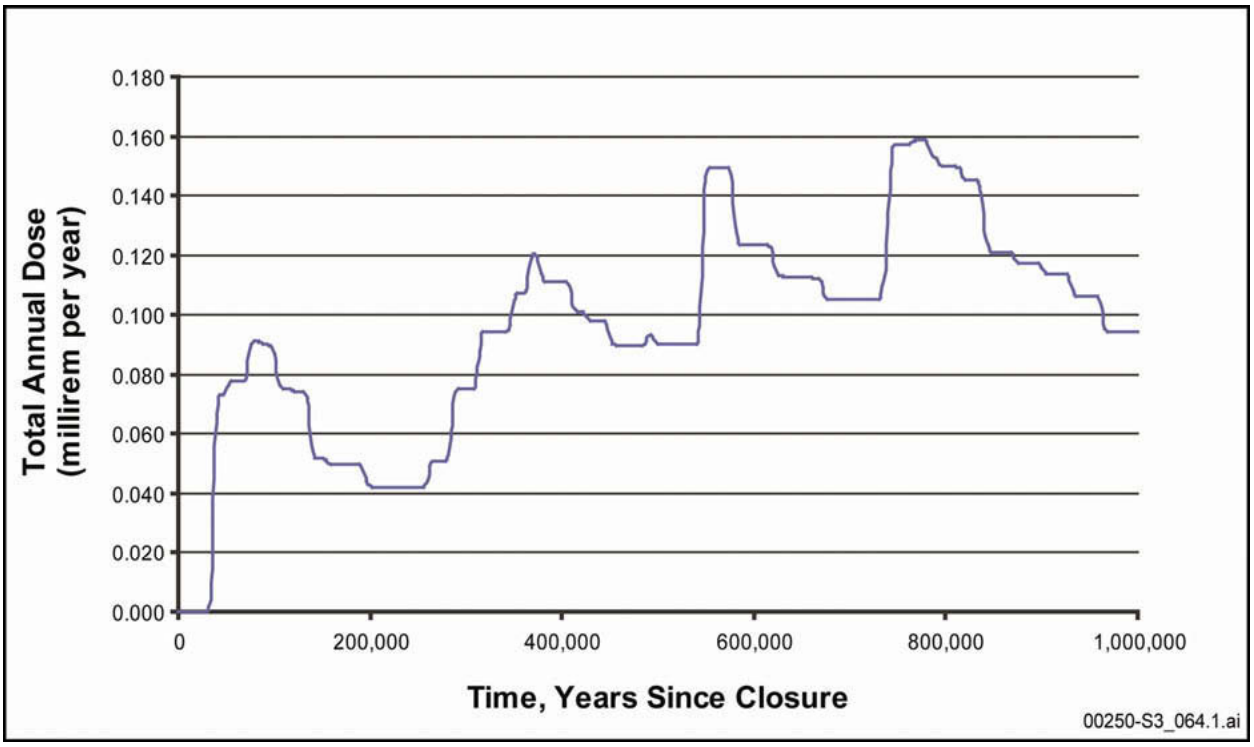

Figure B-12. Total dose at Middle Basin, present climate.

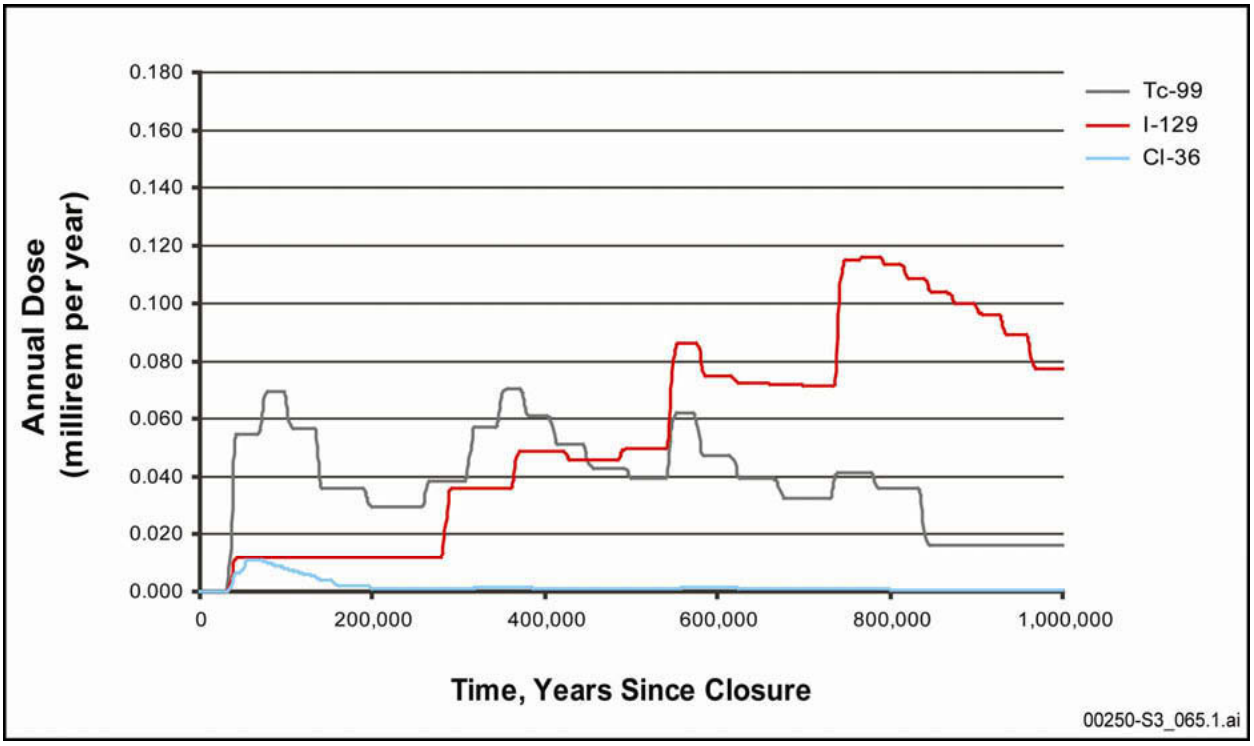

Figure B-13. Dose by radionuclide at Middle Basin, present climate.

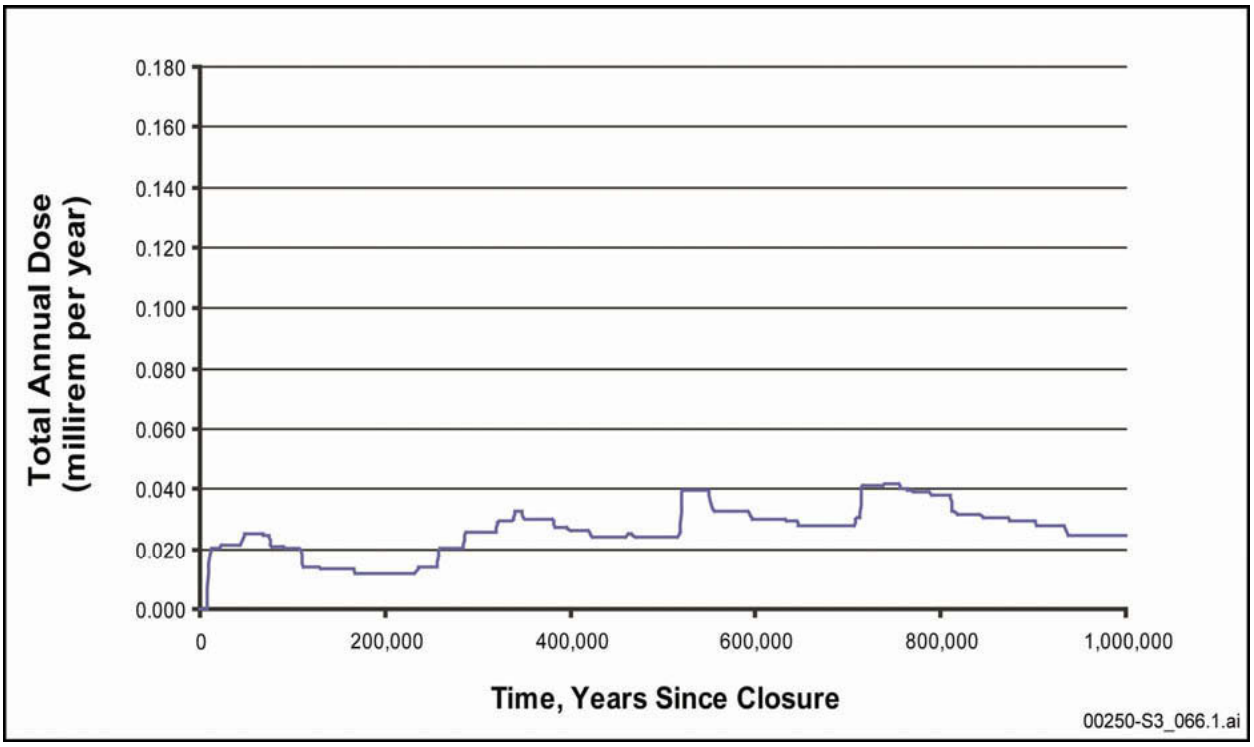

Figure B-14. Total dose at Middle Basin, wetter climate.

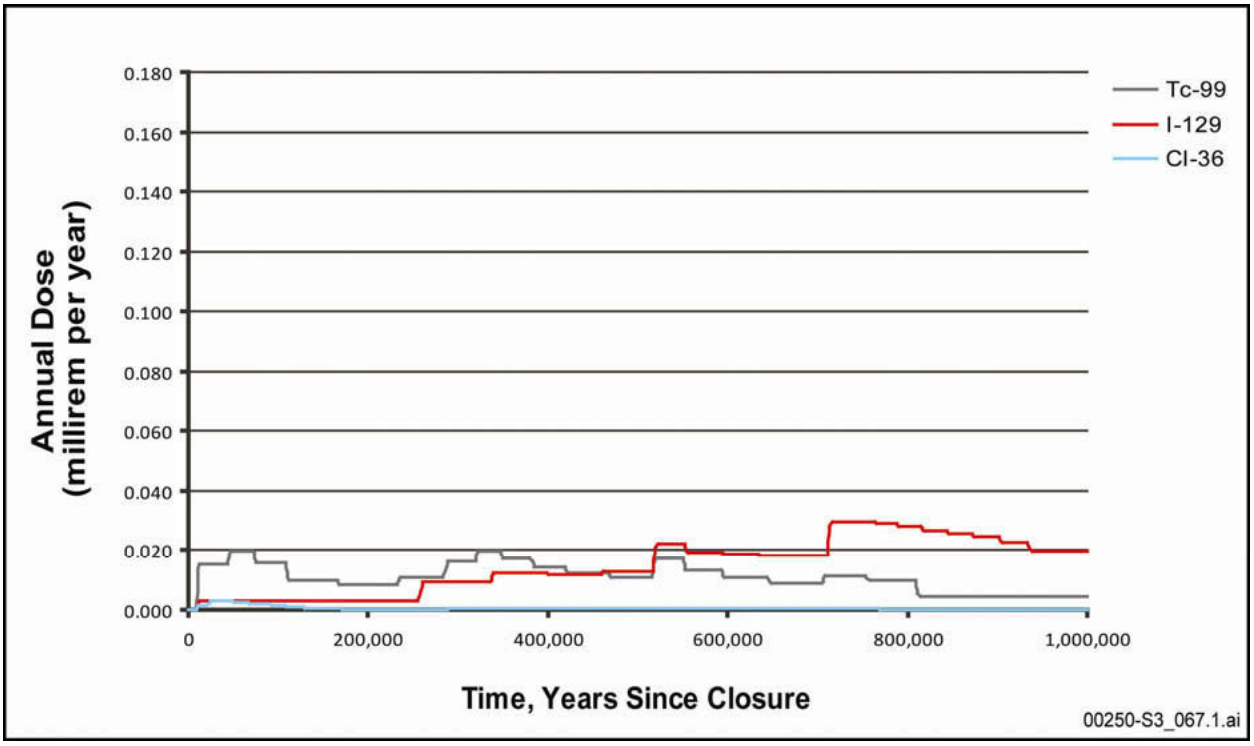

Figure B-15. Dose by radionuclide at Middle Basin, wetter climate.

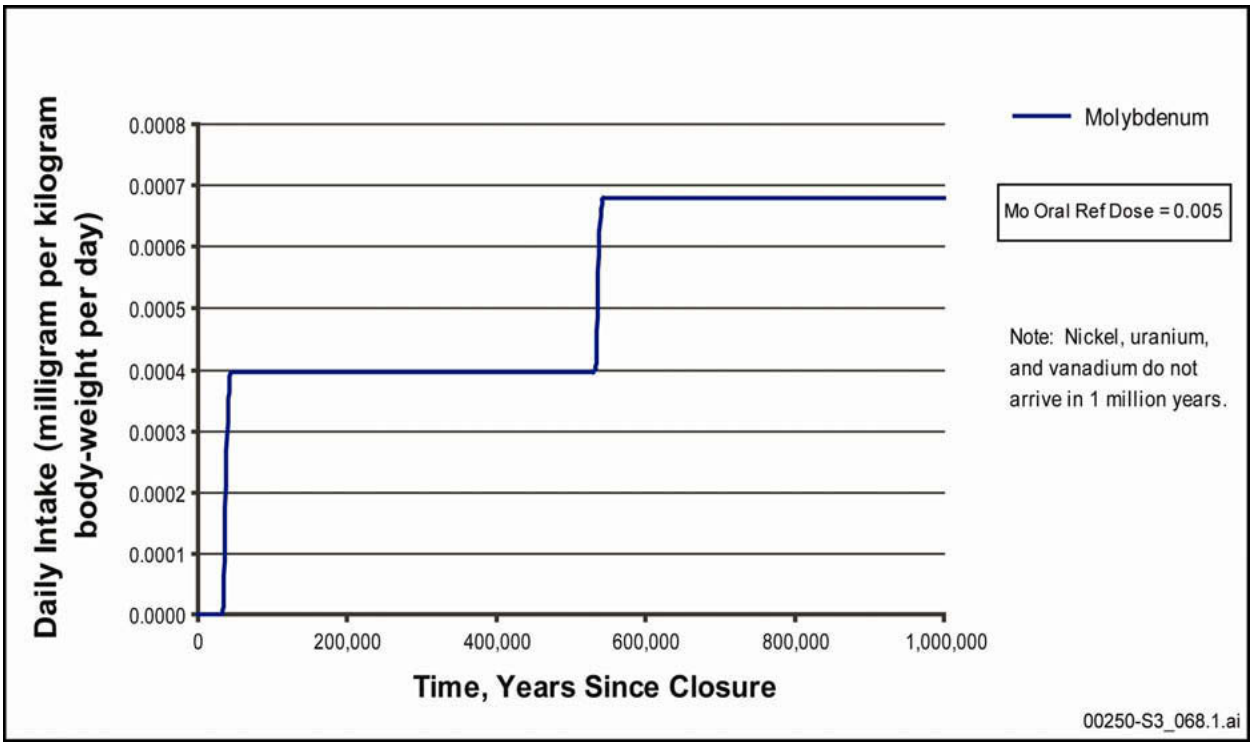

Figure B-16. Molybdenum Intake at Middle Basin, present climate.

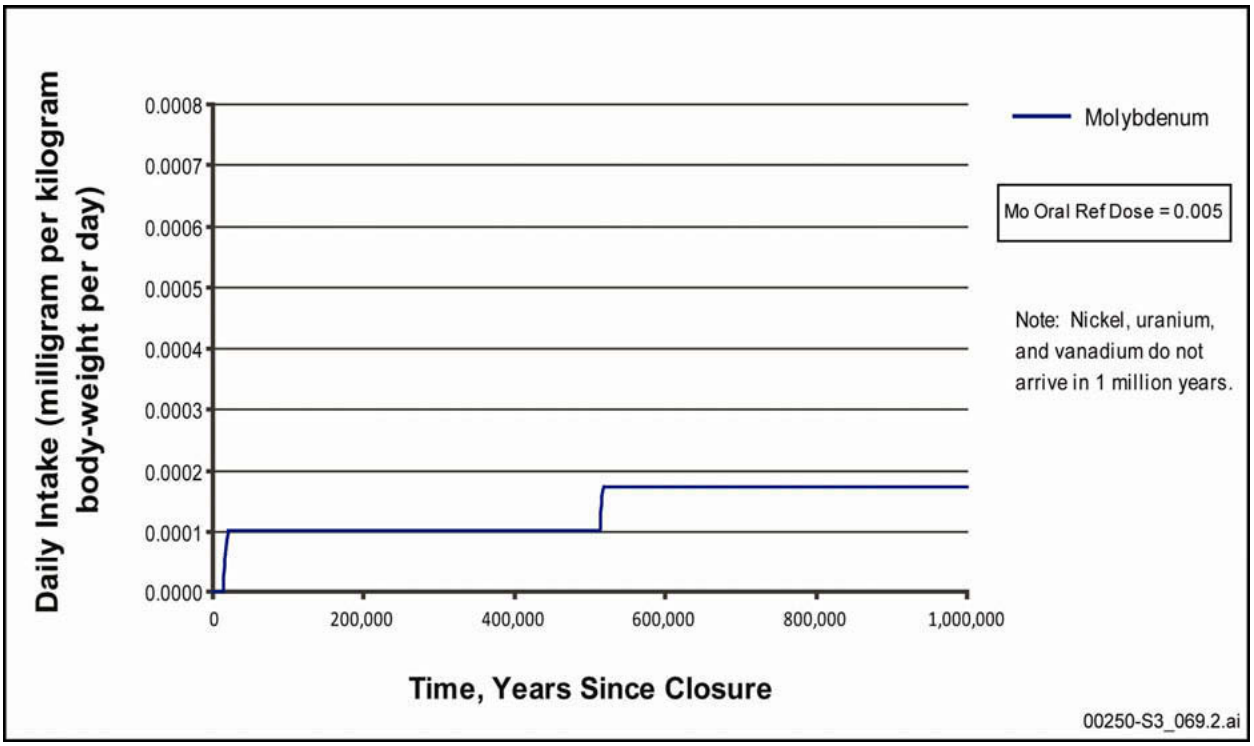

Figure B-17. Molybdenum Intake at Middle Basin, wetter climate.

The mass concentration of contaminants in the soil at the discharge site on the floor of Death Valley would not increase over time due to accumulation because contaminants would continue to be precipitated along with the same or similar mass of dissolved solids. Evaporite minerals deposited on the surface of wet playas in this region often are eroded by wind (Reynolds et al. 2007, pp. 1815 through 1820). Similarly, over time, contaminants and the evaporite minerals would be removed from the playa surface by eolian processes and dispersed over a large area within and surrounding Death Valley. The mass concentration of contaminants at those sites would be less than that in Middle Basin because the contaminants and associated evaporites would be mixed with uncontaminated, rock-based clastic soils and uncontaminated evaporites blown or washed in from other locations. Thus, even after many years of dispersal, the dose or intake at locations surrounding the playa where contaminants could be redeposited would be less than that estimated for Middle Basin on the floor of Death Valley.

The above doses and intakes are based on the scenario that the wet playa continues to exist for the entire analysis period. Occasional dust storms, rain storms, or runoff may alter the evaporite deposits causing erosion, silt coverage, compaction, and consolidation. These alterations may change the concentration of resuspended particles, but a high concentration for the environment considered was used in the analysis. In fact, compaction and consolidation tend to reduce air emissions. Occasional flooding of the playa would reduce, if not eliminate, exposure to the evaporite minerals because the flood waters would likely deposit soil particles on the surface of evaporite deposits. Any standing water or runoff water would be extremely brackish and non-potable (even to animals) so ingestion of water would not be expected. At the Franklin Lake Playa (Alkali Flat), stagnant water has a total-dissolved-solids content of 70,000 to 80,000 milligrams per liter, and drainage paths have water with total-dissolved-solids of 6,000 to 20,000 milligrams per liter (DIRS 186240-Reynolds et al. 2007, p. 1814). With the exception of the dose from external exposure, which would be no greater than the dose from the dry surface materials, doses and intakes during the wetter climate would be greatly reduced or eliminated because of permanent standing non-potable water (especially since the analysis assumed infinite depth).

B.4.1.2.2 Furnace Creek Springs Area

Figures B-18 and B-19 show the estimated radiological dose for the Furnace Creek springs area for the present-day climate. Figures B-20 and B-21 show the estimated radiological doses for the Furnace Creek springs area for the wetter climate. These results are based on the annual flow to the valley with the annual flux of radionuclides totally captured within that flow.

In both the present and wetter climates, only radionuclides with a zero partition coefficient make it to the valley during the 1-million-year analysis period. Of these, the major contributors are technetium-99, iodine-129, and chlorine-36.

Of all the nonradiological contaminants, only molybdenum arrives in any significant amount at the Furnace Creek springs area during the 1-million-year analysis period. Figures B-22 and B-23 show the daily intakes of molybdenum at the Furnace Creek area from exposure to annual flows. The daily intakes for this case are below the Oral Reference Dose.

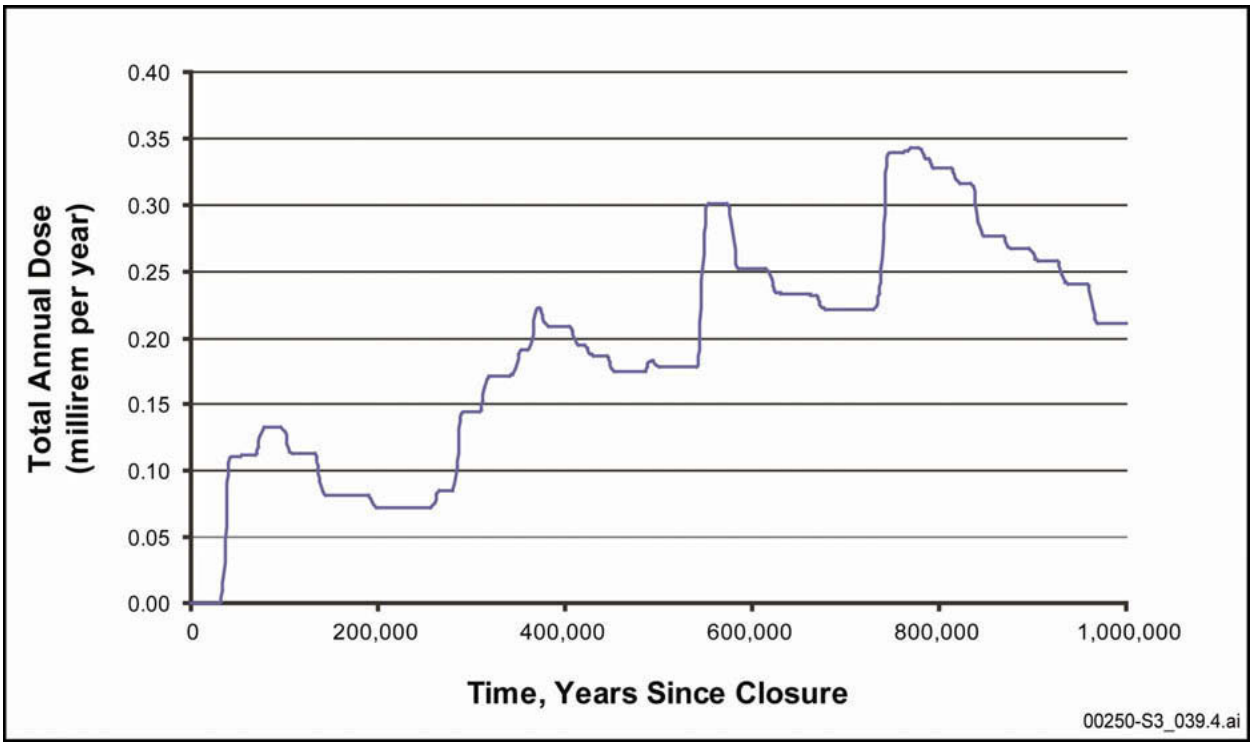

Figure B-18. Total dose at the Furnace Creek springs area, no-pumping, present climate.

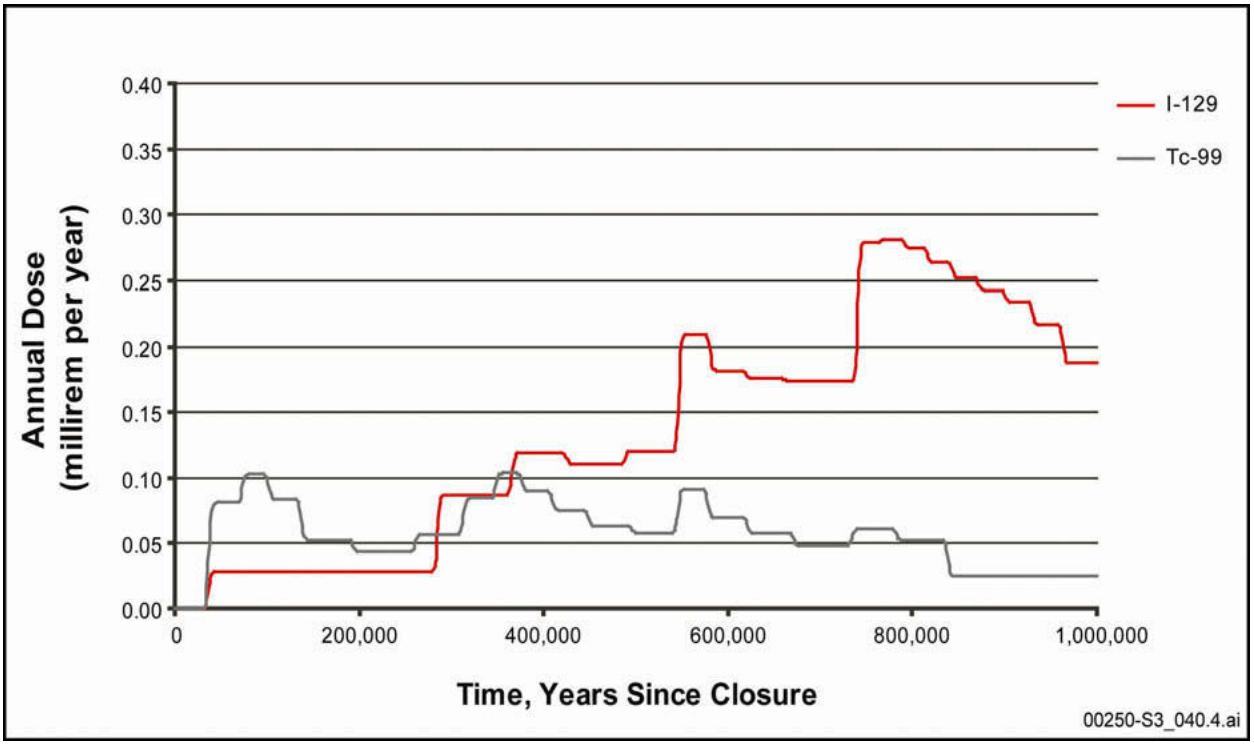

Figure B-19. Dose by radionuclide at the Furnace Creek springs area, no-pumping, present climate.

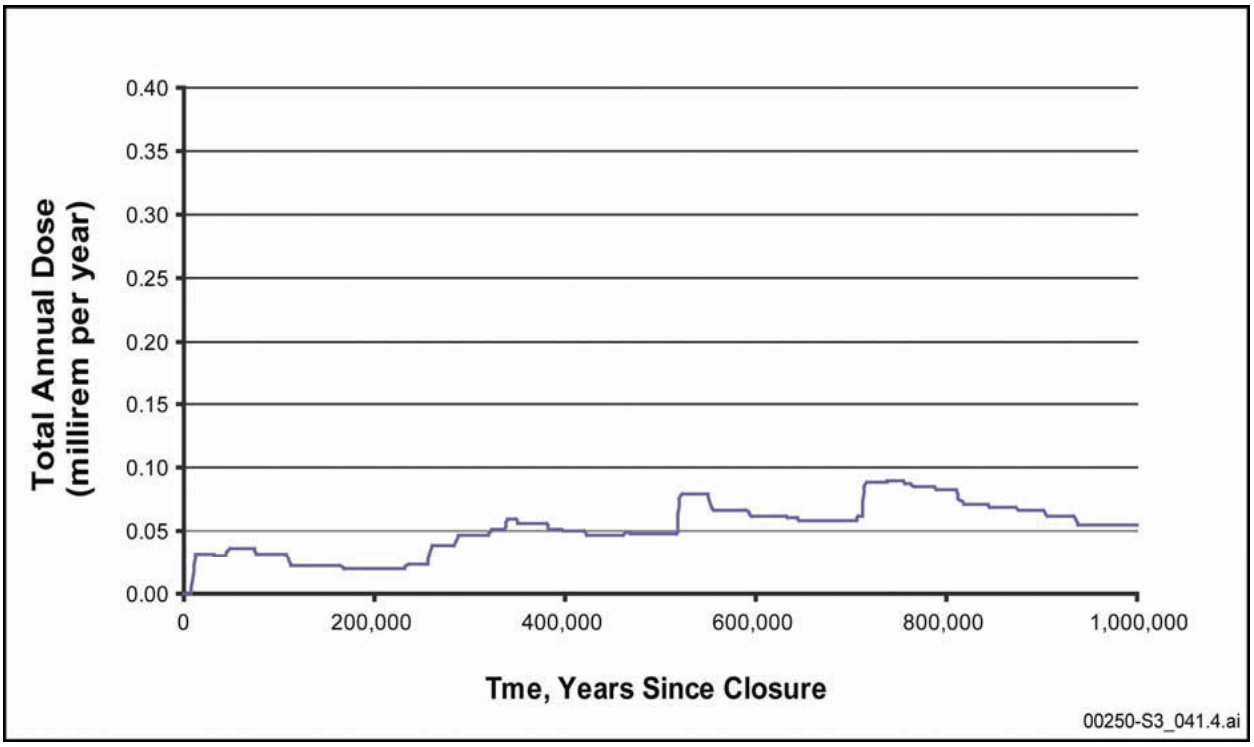

Figure B-20. Total dose at the Furnace Creek springs area, no-pumping, wetter climate.

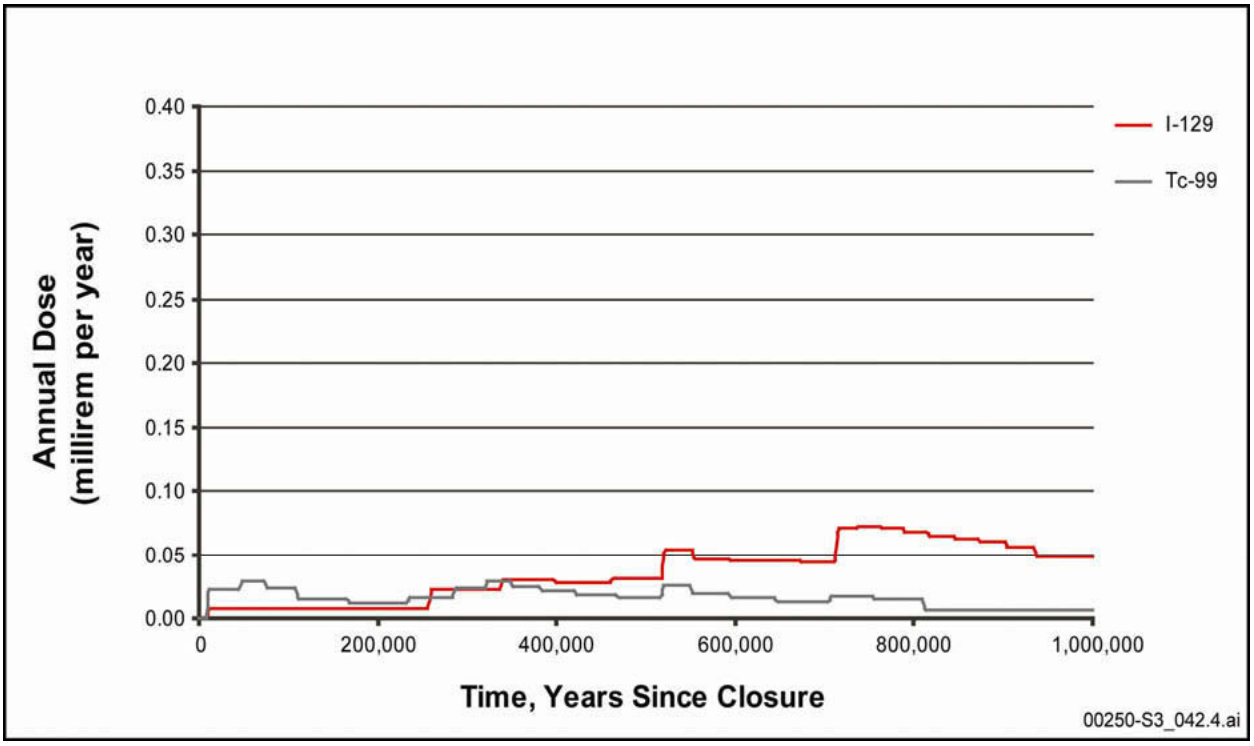

Figure B-21. Dose by radionuclide at the Furnace Creek springs area, no-pumping, wetter climate.

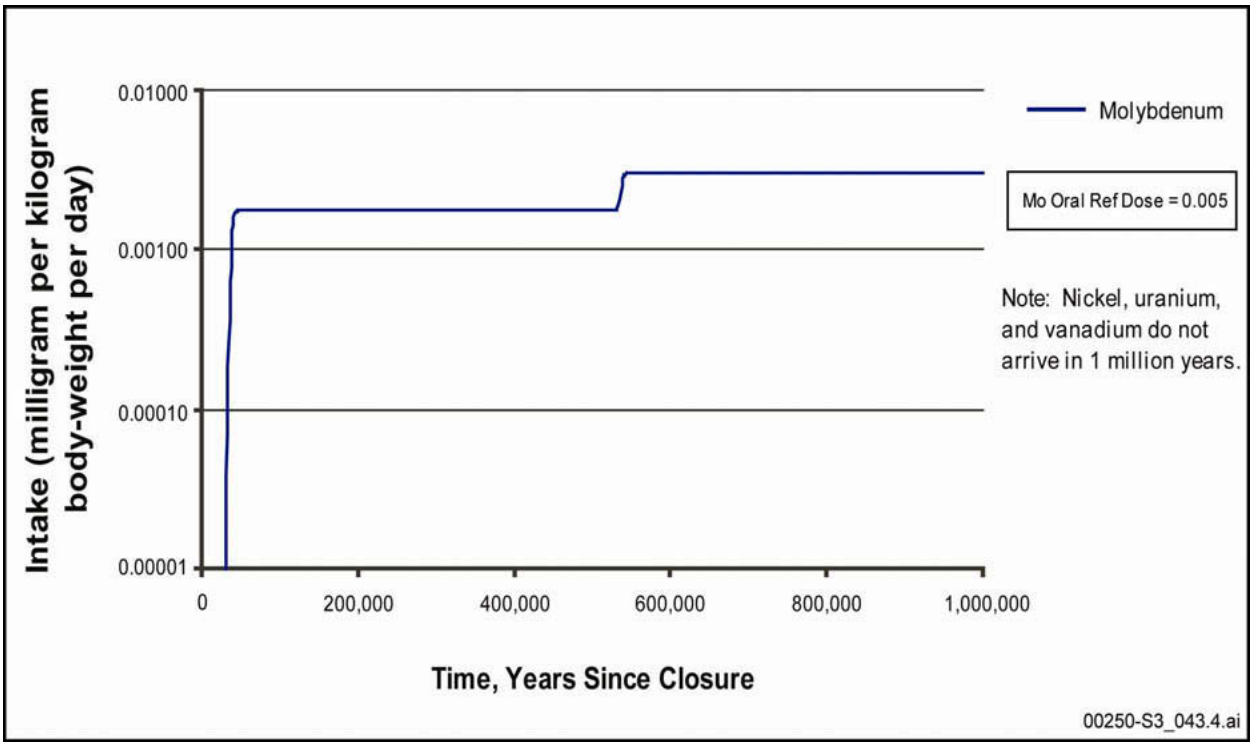

Figure B-22. Daily intakes of molybdenum at the Furnace Creek springs area, no-pumping, present climate.

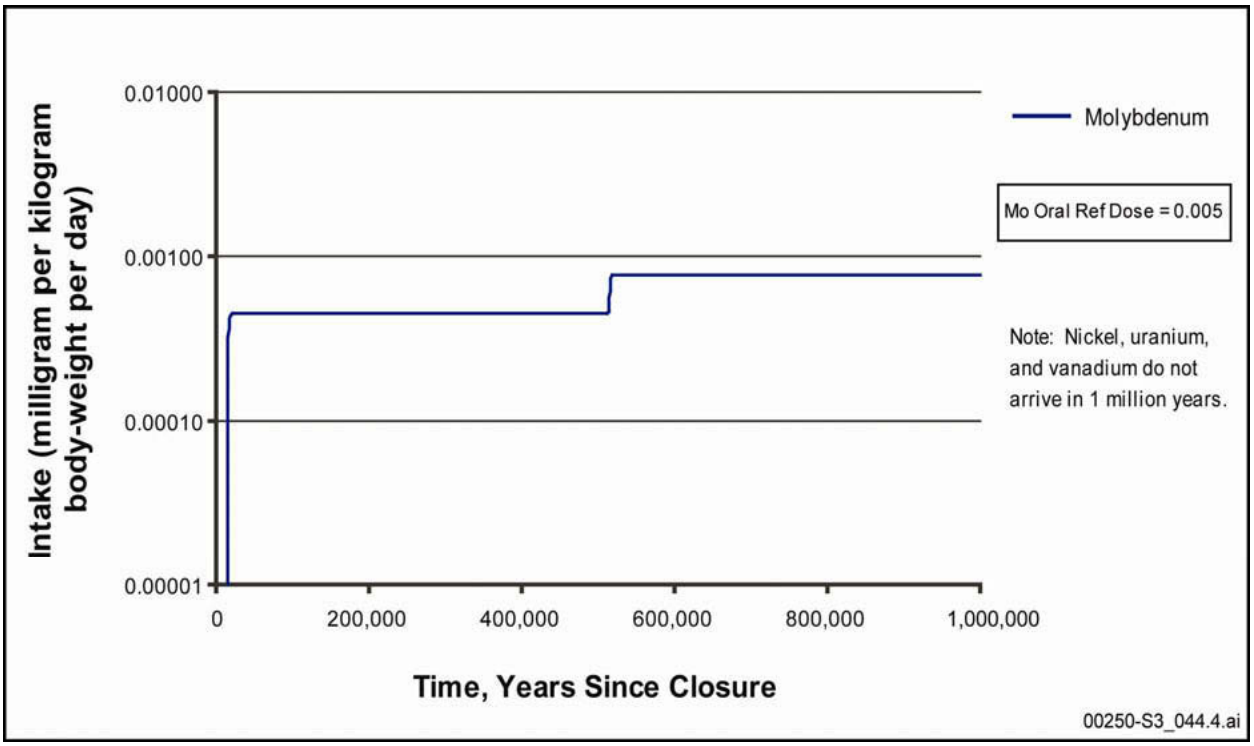

Figure B-23. Daily intakes of molybdenum at the Furnace Creek springs area, no-pumping, wetter climate.

B.4.1.3 Alkali Flat

According to the regional flow model, a small fraction of the contaminant plume from the Regulatory Compliance Point would follow a path toward Alkali Flat for the no-pumping case. Two particles out of the 8,024 were shown going to Alkali Flat from the Regulatory Compliance Point. Therefore, it would be expected that only small amounts of radiological or nonradiological contaminants would arrive at Alkali Flat during the 1-million-year postclosure period. The Franklin Lake Playa at Alkali Flat is a wet playa similar to the location on the Death Valley floor analyzed above. Even though the contaminant fluxes would be about the same, the amount of evapotranspiration at Franklin Lake Playa is currently about one-half that of Middle Basin in Death Valley. Because the doses and intakes are inversely proportional to the evapotranspiration rate, if all the contaminants went to Alkali Flat instead of Death Valley, then the doses and intakes would be about twice the values estimated for Death Valley.

This estimated result applies a very conservative assumption, in that if all of the contaminants were to divert to Alkali Flat, the evapotranspiration rate at that location would not increase from its current measured value. It would be very likely that any diversion of contaminants would be the result of increased groundwater flow in the direction of Alkali Flat and that there would be increases in the evapotranspiration rate at the playa. Since these parameters are not known, DOE made this conservative, qualitative estimate.

B.4.2 MASS BALANCES

Using the decay- and growth-adjusted inventories (see Section B.2.4), DOE estimated mass balances for radionuclides and nonradiological contaminants with significant inventories. These balances provide some insight concerning where material would be located as a function of time for the scenarios evaluated.

B.4.2.1 Radionuclides

It is important to note that at all times radionuclides are decaying, and in some cases radionuclides of interest are increasing in mass, as the result of decay of parent radionuclides. The inventories that make up these mass balances are adjusted for this decay and growth. This means that the term *release to the saturated zone* means the cumulative release adjusted for growth and decay and thus means it is possible for this amount to actually decrease with time or increase with time at a rate that looks faster than the mass flux. The adjustment is made to allow calculation of a true inventory in between release points by the difference in inflow and outflow. This Analysis of Postclosure Groundwater Impacts presents these mass balances to provide a picture of trends and relative location of radionuclides.

Tables B-5 through B-8 present the mass balances for radionuclides important to dose for the 4 scenarios in the analysis (pumping, present climate; pumping, wetter climate; no-pumping, present climate; and no-pumping, wetter climate). The total mass arriving at the Furnace Creek springs area or the Death Valley floor would be the same and is designated in the tables as “released at Death Valley.” The total amounts released at Alkali Flat would be similar if all flow was diverted in that direction. Note that in some of the tables, some radionuclides have zero inventories further down the flow path. This indicates that after 1 million years, some slower-moving radionuclides had not traveled the full length of the path and had not reached a discharge location. Generally speaking, there are significant inventories of radionuclides

distributed throughout the flow paths. These accumulated materials do not have an impact because they have no path by which to reach the biosphere.

An important note about the "accumulated" mass in the Amargosa Farms area:

In the case of the pumping scenario, 14 percent of the mass is actually not accumulated, but is assumed to be transported out of the Amargosa Farms area (water released to septic tanks or swamp coolers or used for other industrial purposes); that is, that fraction of mass and activity is assumed to be removed. All other activity (that does not decay) is assumed to be recycled even though some fraction of that activity would be removed via plant (notably alfalfa) uptake and used for fodder and the milk and meat products leaving the area (however this is conservatively not included in the analysis). Other portions of the mass and activity would be removed by soil erosion and dispersed across southern Nevada and California (again this loss is conservatively not included in the analysis).

Table B-5. Mass balance (grams), pumping, present climate.

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 km and the Amargosa Farms area	Accumulated at the Amargosa Farms area
Uranium-235					
1.00×10^{4}	7.66×10^{3}	1.26×10^{3}	6.40×10^{3}	6.40×10^{3}	0.0
5.00×10^{4}	4.31×10^{4}	7.78×10^{3}	3.54×10^{4}	3.54×10^{4}	3.23×10^{-1}
1.00×10^{5}	8.90×10^{4}	1.70×10^{4}	7.20×10^{4}	5.24×10^{4}	1.96×10^{4}
3.00×10^{5}	3.47×10^{5}	7.09×10^{4}	2.76×10^{5}	1.12×10^{5}	1.64×10^{5}
5.00×10^{5}	9.41×10^{5}	1.48×10^{5}	7.94×10^{5}	2.23×10^{5}	5.71×10^{5}
8.00×10^{5}	2.42×10^{6}	2.91×10^{5}	2.12×10^{6}	3.92×10^{5}	1.73×10^{6}
1.00×10^{6}	4.00×10^{6}	4.26×10^{5}	3.58×10^{6}	6.05×10^{5}	2.97×10^{6}
Neptunium-237					
1.00×10^{4}	2.43×10^{3}	3.92×10^{2}	2.04×10^{3}	2.04×10^{3}	0.0
5.00×10^{4}	1.33×10^{4}	2.15×10^{3}	1.11×10^{4}	1.11×10^{4}	1.23×10^{-9}
1.00×10^{5}	2.67×10^{4}	4.31×10^{3}	2.24×10^{4}	2.17×10^{4}	6.33×10^{2}
3.00×10^{5}	1.17×10^{5}	2.00×10^{4}	9.69×10^{4}	5.50×10^{4}	4.19×10^{4}
5.00×10^{5}	2.84×10^{5}	3.75×10^{4}	2.47×10^{5}	9.32×10^{4}	1.53×10^{5}
8.00×10^{5}	6.02×10^{5}	6.56×10^{4}	5.37×10^{5}	1.36×10^{5}	4.00×10^{5}
1.00×10^{6}	9.21×10^{5}	9.63×10^{4}	8.25×10^{5}	2.09×10^{5}	6.15×10^{5}
Uranium-233					
1.00×10^{4}	9.00×10^{1}	1.48×10^{1}	7.52×10^{1}	7.52×10^{1}	0.0
5.00×10^{4}	6.25×10^{2}	1.02×10^{2}	5.23×10^{2}	5.23×10^{2}	2.05×10^{-3}
1.00×10^{5}	1.56×10^{3}	2.54×10^{2}	1.30×10^{3}	1.16×10^{3}	1.43×10^{2}
3.00×10^{5}	1.07×10^{4}	1.84×10^{3}	8.83×10^{3}	4.60×10^{3}	4.24×10^{3}
5.00×10^{5}	3.28×10^{4}	4.39×10^{3}	2.84×10^{4}	1.01×10^{4}	1.83×10^{4}
8.00×10^{5}	8.12×10^{4}	9.05×10^{3}	7.21×10^{4}	1.79×10^{4}	5.43×10^{4}
1.00×10^{6}	1.28×10^{5}	1.37×10^{4}	1.15×10^{5}	2.86×10^{4}	8.60×10^{4}
Thorium-229					
1.00×10^{4}	4.78	4.29	4.96×10^{-1}	4.96×10^{-1}	0.0
5.00×10^{4}	2.54×10^{1}	1.41×10^{1}	1.13×10^{1}	1.13×10^{1}	1.99×10^{-6}
1.00×10^{5}	5.49×10^{1}	2.03×10^{1}	3.47×10^{1}	3.22×10^{1}	2.52
3.00×10^{5}	2.96×10^{2}	8.05×10^{1}	2.16×10^{2}	1.03×10^{2}	1.13×10^{2}
5.00×10^{5}	9.30×10^{2}	1.88×10^{2}	7.41×10^{2}	2.64×10^{2}	4.78×10^{2}
8.00×10^{5}	2.57×10^{3}	3.89×10^{2}	2.18×10^{3}	5.31×10^{2}	1.65×10^{3}
1.00×10^{6}	4.26×10^{3}	6.11×10^{2}	3.64×10^{3}	8.15×10^{2}	2.83×10^{3}

Table B-5. Mass balance (grams), pumping, present climate (continued).

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 km and the Amargosa Farms area	Accumulated at the Amargosa Farms area
Uranium-236					
1.00×10^{4}	2.75×10^{3}	6.78×10^{2}	2.07×10^{3}	2.07×10^{3}	0.0
5.00×10^{4}	1.51×10^{4}	3.70×10^{3}	1.14×10^{4}	1.14×10^{4}	1.05×10^{-1}
1.00×10^{5}	3.06×10^{4}	7.53×10^{3}	2.30×10^{4}	1.67×10^{4}	6.34×10^{3}
3.00×10^{5}	1.19×10^{5}	3.49×10^{4}	8.40×10^{4}	3.13×10^{4}	5.28×10^{4}
5.00×10^{5}	3.54×10^{5}	8.70×10^{4}	2.67×10^{5}	8.06×10^{4}	1.86×10^{5}
8.00×10^{5}	9.46×10^{5}	1.96×10^{5}	7.50×10^{5}	1.40×10^{5}	6.10×10^{5}
1.00×10^{6}	1.54×10^{6}	2.97×10^{5}	1.24×10^{6}	2.00×10^{5}	1.04×10^{6}
Thorium-232					
1.00×10^{4}	1.58×10^{3}	1.40×10^{3}	1.78×10^{2}	1.78×10^{2}	0.0
5.00×10^{4}	8.70×10^{3}	7.71×10^{3}	9.91×10^{2}	9.91×10^{2}	1.55×10^{-4}
1.00×10^{5}	1.76×10^{4}	1.56×10^{4}	2.04×10^{3}	2.02×10^{3}	1.88×10^{1}
3.00×10^{5}	6.06×10^{4}	5.39×10^{4}	6.70×10^{3}	6.24×10^{3}	4.68×10^{2}
5.00×10^{5}	1.69×10^{5}	1.46×10^{5}	2.35×10^{4}	2.07×10^{4}	2.75×10^{3}
8.00×10^{5}	5.07×10^{5}	4.28×10^{5}	7.91×10^{4}	6.47×10^{4}	1.44×10^{4}
1.00×10^{6}	1.02×10^{6}	8.67×10^{5}	1.57×10^{5}	1.27×10^{5}	3.05×10^{4}
Uranium-234					
1.00×10^{4}	8.69×10^{1}	7.99×10^{1}	7.99×10^{1}	7.99×10^{1}	0.0
5.00×10^{4}	4.53×10^{2}	4.16×10^{2}	4.16×10^{2}	4.16×10^{2}	3.32×10^{-3}
1.00×10^{5}	8.56×10^{2}	7.87×10^{2}	7.87×10^{2}	5.92×10^{2}	1.94×10^{2}
3.00×10^{5}	3.76×10^{3}	3.55×10^{3}	3.55×10^{3}	1.74×10^{3}	1.81×10^{3}
5.00×10^{5}	6.92×10^{3}	7.27×10^{3}	7.27×10^{3}	2.36×10^{3}	4.91×10^{3}
8.00×10^{5}	9.73×10^{3}	1.06×10^{4}	1.06×10^{4}	2.39×10^{3}	8.17×10^{3}
1.00×10^{6}	1.15×10^{4}	1.19×10^{4}	1.19×10^{4}	2.61×10^{3}	9.30×10^{3}
Thorium-230					
1.00×10^{4}	7.45×10^{1}	7.99×10^{1}	3.56	3.56	0.0
5.00×10^{4}	3.26×10^{2}	4.16×10^{2}	5.19×10^{1}	5.19×10^{1}	6.90×10^{-4}
1.00×10^{5}	5.05×10^{2}	7.87×10^{2}	1.48×10^{2}	1.03×10^{2}	4.48×10^{1}
3.00×10^{5}	1.12×10^{3}	3.55×10^{3}	7.69×10^{2}	3.74×10^{2}	3.96×10^{2}
5.00×10^{5}	1.27×10^{3}	7.27×10^{3}	1.19×10^{3}	4.30×10^{2}	7.65×10^{2}
8.00×10^{5}	9.90×10^{2}	1.06×10^{4}	1.04×10^{3}	2.89×10^{2}	7.49×10^{2}
1.00×10^{6}	7.65×10^{2}	1.19×10^{4}	7.95×10^{2}	2.08×10^{2}	5.87×10^{2}
Uranium-238					
1.00×10^{4}	3.54×10^{5}	8.93×10^{4}	2.65×10^{5}	2.65×10^{5}	0.0
5.00×10^{4}	1.95×10^{6}	4.92×10^{5}	1.46×10^{6}	1.46×10^{6}	1.34×10^{1}
1.00×10^{5}	3.94×10^{6}	9.94×10^{5}	2.95×10^{6}	2.14×10^{6}	8.12×10^{5}
3.00×10^{5}	1.53×10^{7}	4.52×10^{6}	1.07×10^{7}	3.96×10^{6}	6.78×10^{6}
5.00×10^{5}	4.48×10^{7}	1.10×10^{7}	3.38×10^{7}	1.00×10^{7}	2.37×10^{7}
8.00×10^{5}	1.20×10^{8}	2.51×10^{7}	9.51×10^{7}	1.78×10^{7}	7.73×10^{7}
1.00×10^{6}	1.98×10^{8}	3.91×10^{7}	1.59×10^{8}	2.61×10^{7}	1.33×10^{8}
Iodine-129					
1.00×10^{4}	1.44×10^{4}	5.30×10^{2}	1.39×10^{4}	2.38×10^{1}	1.38×10^{4}
5.00×10^{4}	7.92×10^{4}	2.92×10^{3}	7.63×10^{4}	2.75×10^{1}	7.63×10^{4}
1.00×10^{5}	1.60×10^{5}	5.90×10^{3}	1.54×10^{5}	3.21×10^{1}	1.54×10^{5}
3.00×10^{5}	6.64×10^{5}	3.47×10^{4}	6.29×10^{5}	1.10×10^{3}	6.28×10^{5}
5.00×10^{5}	1.92×10^{6}	6.77×10^{4}	1.85×10^{6}	4.45×10^{3}	1.85×10^{6}
8.00×10^{5}	5.43×10^{6}	1.74×10^{5}	5.26×10^{6}	3.95×10^{3}	5.25×10^{6}
1.00×10^{6}	7.80×10^{6}	1.91×10^{5}	7.61×10^{6}	1.31×10^{3}	7.61×10^{6}

Table B-5. Mass balance (grams), pumping, present climate (continued).

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 km and the Amargosa Farms area	Accumulated at the Amargosa Farms area
Selenium-79					
1.00×10^{4}	7.38×10^{2}	3.68×10^{2}	3.70×10^{2}	3.70×10^{2}	0.0
5.00×10^{4}	4.53×10^{3}	2.48×10^{3}	2.04×10^{3}	2.04×10^{3}	0.0
1.00×10^{5}	8.98×10^{3}	3.78×10^{3}	5.20×10^{3}	5.20×10^{3}	2.65×10^{-15}
3.00×10^{5}	1.34×10^{4}	4.36×10^{3}	9.08×10^{3}	7.40×10^{3}	1.68×10^{3}
5.00×10^{5}	1.69×10^{4}	4.75×10^{3}	1.21×10^{4}	7.18×10^{3}	4.97×10^{3}
8.00×10^{5}	1.87×10^{4}	4.77×10^{3}	1.39×10^{4}	6.67×10^{3}	7.25×10^{3}
1.00×10^{6}	1.68×10^{4}	3.67×10^{3}	1.31×10^{4}	5.31×10^{3}	7.78×10^{3}
Technetium-99					
1.00×10^{4}	8.28×10^{4}	8.58×10^{3}	7.42×10^{4}	4.46×10^{2}	7.38×10^{4}
5.00×10^{4}	4.52×10^{5}	3.96×10^{4}	4.12×10^{5}	2.61×10^{3}	4.10×10^{5}
1.00×10^{5}	8.23×10^{5}	4.18×10^{4}	7.81×10^{5}	3.56×10^{3}	7.77×10^{5}
3.00×10^{5}	1.33×10^{6}	5.67×10^{4}	1.27×10^{6}	3.56×10^{3}	1.27×10^{6}
5.00×10^{5}	1.86×10^{6}	6.09×10^{4}	1.79×10^{6}	6.04×10^{3}	1.79×10^{6}
8.00×10^{5}	1.91×10^{6}	6.02×10^{4}	1.85×10^{6}	8.67×10^{3}	1.84×10^{6}
1.00×10^{6}	1.38×10^{6}	3.16×10^{4}	1.34×10^{6}	6.18×10^{3}	1.34×10^{6}

Table B-6. Mass balance (grams), pumping, wetter climate.

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released Beyond 18 kilometers	Held in path between 18 km and the Amargosa Farms area	Accumulated at the Amargosa Farms area
Uranium-235					
1.00×10^{4}	7.66×10^{3}	1.26×10^{3}	6.40×10^{3}	6.40×10^{3}	7.14×10^{-7}
5.00×10^{4}	4.31×10^{4}	7.78×10^{3}	3.54×10^{4}	1.29×10^{4}	2.24×10^{4}
1.00×10^{5}	8.90×10^{4}	1.70×10^{4}	7.20×10^{4}	1.36×10^{4}	5.84×10^{4}
3.00×10^{5}	3.47×10^{5}	7.09×10^{4}	2.76×10^{5}	3.48×10^{4}	2.41×10^{5}
5.00×10^{5}	9.41×10^{5}	1.48×10^{5}	7.94×10^{5}	6.13×10^{4}	7.33×10^{5}
8.00×10^{5}	2.42×10^{6}	2.91×10^{5}	2.12×10^{6}	1.04×10^{5}	2.02×10^{6}
1.00×10^{6}	4.00×10^{6}	4.26×10^{5}	3.58×10^{6}	1.61×10^{5}	3.42×10^{6}
Neptunium-237					
1.00×10^{4}	2.43×10^{3}	3.92×10^{2}	2.04×10^{3}	2.04×10^{3}	0.0
5.00×10^{4}	1.33×10^{4}	2.15×10^{3}	1.11×10^{4}	5.89×10^{3}	5.25×10^{3}
1.00×10^{5}	2.67×10^{4}	4.31×10^{3}	2.24×10^{4}	5.99×10^{3}	1.64×10^{4}
3.00×10^{5}	1.17×10^{5}	2.00×10^{4}	9.69×10^{4}	1.64×10^{4}	8.06×10^{4}
5.00×10^{5}	2.84×10^{5}	3.75×10^{4}	2.47×10^{5}	2.58×10^{4}	2.21×10^{5}
8.00×10^{5}	6.02×10^{5}	6.56×10^{4}	5.37×10^{5}	3.75×10^{4}	4.99×10^{5}
1.00×10^{6}	9.21×10^{5}	9.63×10^{4}	8.25×10^{5}	6.02×10^{4}	7.64×10^{5}
Uranium-233					
1.00×10^{4}	9.00×10^{1}	1.48×10^{1}	7.52×10^{1}	7.52×10^{1}	6.84×10^{-9}
5.00×10^{4}	6.25×10^{2}	1.02×10^{2}	5.23×10^{2}	2.14×10^{2}	3.08×10^{2}
1.00×10^{5}	1.56×10^{3}	2.54×10^{2}	1.30×10^{3}	2.71×10^{2}	1.03×10^{3}
3.00×10^{5}	1.07×10^{4}	1.84×10^{3}	8.83×10^{3}	1.31×10^{3}	7.52×10^{3}
5.00×10^{5}	3.28×10^{4}	4.39×10^{3}	2.84×10^{4}	2.75×10^{3}	2.56×10^{4}
8.00×10^{5}	8.12×10^{4}	9.05×10^{3}	7.21×10^{4}	4.92×10^{3}	6.72×10^{4}
1.00×10^{6}	1.28×10^{5}	1.37×10^{4}	1.15×10^{5}	8.20×10^{3}	1.06×10^{5}
Thorium-229					
1.00×10^{4}	4.78	4.29	4.96×10^{-1}	4.96×10^{-1}	1.48×10^{-14}
5.00×10^{4}	2.54×10^{1}	1.41×10^{1}	1.13×10^{1}	6.51	4.76
1.00×10^{5}	5.49×10^{1}	2.03×10^{1}	3.47×10^{1}	1.00×10^{1}	2.47×10^{1}
3.00×10^{5}	2.96×10^{2}	8.05×10^{1}	2.16×10^{2}	3.21×10^{1}	1.84×10^{2}
5.00×10^{5}	9.30×10^{2}	1.88×10^{2}	7.41×10^{2}	7.41×10^{1}	6.67×10^{2}
8.00×10^{5}	2.57×10^{3}	3.89×10^{2}	2.18×10^{3}	1.49×10^{2}	2.03×10^{3}
1.00×10^{6}	4.26×10^{3}	6.11×10^{2}	3.64×10^{3}	2.33×10^{2}	3.41×10^{3}
Uranium-236					
1.00×10^{4}	2.75×10^{3}	6.78×10^{2}	2.07×10^{3}	2.07×10^{3}	2.31×10^{-7}
5.00×10^{4}	1.51×10^{4}	3.70×10^{3}	1.14×10^{4}	4.13×10^{3}	7.27×10^{3}
1.00×10^{5}	3.06×10^{4}	7.53×10^{3}	2.30×10^{4}	4.13×10^{3}	1.89×10^{4}
3.00×10^{5}	1.19×10^{5}	3.49×10^{4}	8.40×10^{4}	1.21×10^{4}	7.19×10^{4}
5.00×10^{5}	3.54×10^{5}	8.70×10^{4}	2.67×10^{5}	2.22×10^{4}	2.45×10^{5}
8.00×10^{5}	9.46×10^{5}	1.96×10^{5}	7.50×10^{5}	3.67×10^{4}	7.13×10^{5}
1.00×10^{6}	1.54×10^{6}	2.97×10^{5}	1.24×10^{6}	5.26×10^{4}	1.19×10^{6}
Thorium 232					
1.00×10^{4}	1.58×10^{3}	1.40×10^{3}	1.78×10^{2}	1.78×10^{2}	6.85×10^{-11}
5.00×10^{4}	8.70×10^{3}	7.71×10^{3}	9.91×10^{2}	9.81×10^{2}	1.08×10^{1}
1.00×10^{5}	1.76×10^{4}	1.56×10^{4}	2.04×10^{3}	1.98×10^{3}	5.60×10^{1}
3.00×10^{5}	6.06×10^{4}	5.39×10^{4}	6.70×10^{3}	6.07×10^{3}	6.38×10^{2}
5.00×10^{5}	1.69×10^{5}	1.46×10^{5}	2.35×10^{4}	1.98×10^{4}	3.61×10^{3}
8.00×10^{5}	5.07×10^{5}	4.28×10^{5}	7.91×10^{4}	6.23×10^{4}	1.68×10^{4}
1.00×10^{6}	1.02×10^{6}	8.67×10^{5}	1.57×10^{5}	1.22×10^{5}	3.49×10^{4}

Table B-6. Mass balance (grams), pumping, wetter climate (continued).

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released Beyond 18 kilometers	Held in path between 18 km and the Amargosa Farms area	Accumulated at the Amargosa Farms area
Uranium-234					
1.00×10^{4}	8.69×10^{1}	7.99×10^{1}	7.99×10^{1}	7.99×10^{1}	8.55×10^{-9}
5.00×10^{4}	4.53×10^{2}	4.16×10^{2}	4.16×10^{2}	1.58×10^{2}	2.58×10^{2}
1.00×10^{5}	8.56×10^{2}	7.87×10^{2}	7.87×10^{2}	1.59×10^{2}	6.28×10^{2}
3.00×10^{5}	3.76×10^{3}	3.55×10^{3}	3.55×10^{3}	5.09×10^{2}	3.04×10^{3}
5.00×10^{5}	6.92×10^{3}	7.27×10^{3}	7.27×10^{3}	6.59×10^{2}	6.61×10^{3}
8.00×10^{5}	9.73×10^{3}	1.06×10^{4}	1.06×10^{4}	6.60×10^{2}	9.91×10^{3}
1.00×10^{6}	1.15×10^{4}	1.19×10^{4}	1.19×10^{4}	7.22×10^{2}	1.12×10^{4}
Thorium-230					
1.00×10^{4}	7.45×10^{1}	7.99×10^{1}	3.56	3.56	6.10×10^{-10}
5.00×10^{4}	3.26×10^{2}	4.16×10^{2}	5.19×10^{1}	1.54×10^{1}	3.65×10^{1}
1.00×10^{5}	5.05×10^{2}	7.87×10^{2}	1.48×10^{2}	2.44×10^{1}	1.24×10^{2}
3.00×10^{5}	1.12×10^{3}	3.55×10^{3}	7.69×10^{2}	1.11×10^{2}	6.58×10^{2}
5.00×10^{5}	1.27×10^{3}	7.27×10^{3}	1.19×10^{3}	1.24×10^{2}	1.07×10^{3}
8.00×10^{5}	9.90×10^{2}	1.06×10^{4}	1.04×10^{3}	8.18×10^{1}	9.57×10^{2}
1.00×10^{6}	7.65×10^{2}	1.19×10^{4}	7.95×10^{2}	5.87×10^{1}	7.36×10^{2}
Uranium-238					
1.00×10^{4}	3.54×10^{5}	8.93×10^{4}	2.65×10^{5}	2.65×10^{5}	2.96×10^{-5}
5.00×10^{4}	1.95×10^{6}	4.92×10^{5}	1.46×10^{6}	5.28×10^{5}	9.29×10^{5}
1.00×10^{5}	3.94×10^{6}	9.94×10^{5}	2.95×10^{6}	5.28×10^{5}	2.42×10^{6}
3.00×10^{5}	1.53×10^{7}	4.52×10^{6}	1.07×10^{7}	1.50×10^{6}	9.24×10^{6}
5.00×10^{5}	4.48×10^{7}	1.10×10^{7}	3.38×10^{7}	2.71×10^{6}	3.11×10^{7}
8.00×10^{5}	1.20×10^{8}	2.51×10^{7}	9.51×10^{7}	4.63×10^{6}	9.05×10^{7}
1.00×10^{6}	1.98×10^{8}	3.91×10^{7}	1.59×10^{8}	6.82×10^{6}	1.52×10^{8}
Iodine-129					
1.00×10^{4}	1.44×10^{4}	5.30×10^{2}	1.39×10^{4}	2.11×10^{-1}	1.39×10^{4}
5.00×10^{4}	7.92×10^{4}	2.92×10^{3}	7.63×10^{4}	1.16	7.63×10^{4}
1.00×10^{5}	1.60×10^{5}	5.90×10^{3}	1.54×10^{5}	2.35	1.54×10^{5}
3.00×10^{5}	6.64×10^{5}	3.47×10^{4}	6.29×10^{5}	9.59	6.29×10^{5}
5.00×10^{5}	1.92×10^{6}	6.77×10^{4}	1.85×10^{6}	2.82×10^{1}	1.85×10^{6}
8.00×10^{5}	5.43×10^{6}	1.74×10^{5}	5.26×10^{6}	8.03×10^{1}	5.26×10^{6}
1.00×10^{6}	7.80×10^{6}	1.91×10^{5}	7.61×10^{6}	1.16×10^{2}	7.61×10^{6}
Selenium-79					
1.00×10^{4}	7.38×10^{2}	3.68×10^{2}	3.70×10^{2}	3.70×10^{2}	0.0
5.00×10^{4}	4.53×10^{3}	2.48×10^{3}	2.04×10^{3}	2.04×10^{3}	2.49
1.00×10^{5}	8.98×10^{3}	3.78×10^{3}	5.20×10^{3}	3.84×10^{3}	1.35×10^{3}
3.00×10^{5}	1.34×10^{4}	4.36×10^{3}	9.08×10^{3}	1.71×10^{3}	7.37×10^{3}
5.00×10^{5}	1.69×10^{4}	4.75×10^{3}	1.21×10^{4}	1.96×10^{3}	1.02×10^{4}
8.00×10^{5}	1.87×10^{4}	4.77×10^{3}	1.39×10^{4}	2.16×10^{3}	1.18×10^{4}
1.00×10^{6}	1.68×10^{4}	3.67×10^{3}	1.31×10^{4}	1.44×10^{3}	1.17×10^{4}
Technetium-99					
1.00×10^{4}	8.28×10^{4}	8.58×10^{3}	7.42×10^{4}	8.34×10^{1}	7.41×10^{4}
5.00×10^{4}	4.52×10^{5}	3.96×10^{4}	4.12×10^{5}	4.63×10^{2}	4.12×10^{5}
1.00×10^{5}	8.23×10^{5}	4.18×10^{4}	7.81×10^{5}	8.76×10^{2}	7.80×10^{5}
3.00×10^{5}	1.33×10^{6}	5.67×10^{4}	1.27×10^{6}	1.43×10^{3}	1.27×10^{6}
5.00×10^{5}	1.86×10^{6}	6.09×10^{4}	1.79×10^{6}	2.02×10^{3}	1.79×10^{6}
8.00×10^{5}	1.91×10^{6}	6.02×10^{4}	1.85×10^{6}	2.08×10^{3}	1.85×10^{6}
1.00×10^{6}	1.38×10^{6}	3.16×10^{4}	1.34×10^{6}	1.51×10^{3}	1.34×10^{6}

Table B-7. Mass balance (grams), no-pumping, present climate.

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometers and Death Valley	Released at Death Valley
Uranium-235					
1.00×10^4	7.66×10^3	1.26×10^3	6.40×10^3	6.40×10^3	0.0
5.00×10^4	4.31×10^4	7.78×10^3	3.54×10^4	3.54×10^4	0.0
1.00×10^5	8.90×10^4	1.70×10^4	7.20×10^4	7.20×10^4	0.0
3.00×10^5	3.47×10^5	7.09×10^4	2.76×10^5	2.76×10^5	0.0
5.00×10^5	9.41×10^5	1.48×10^5	7.94×10^5	7.94×10^5	0.0
8.00×10^5	2.42×10^6	2.91×10^5	2.12×10^6	2.12×10^6	0.0
1.00×10^6	4.00×10^6	4.26×10^5	3.58×10^6	3.58×10^6	0.0
Neptunium-237					
1.00×10^4	2.43×10^3	3.92×10^2	2.04×10^3	2.04×10^3	0.0
5.00×10^4	1.33×10^4	2.15×10^3	1.11×10^4	1.11×10^4	0.0
1.00×10^5	2.67×10^4	4.31×10^3	2.24×10^4	2.24×10^4	0.0
3.00×10^5	1.17×10^5	2.00×10^4	9.69×10^4	9.69×10^4	0.0
5.00×10^5	2.84×10^5	3.75×10^4	2.47×10^5	2.47×10^5	0.0
8.00×10^5	6.02×10^5	6.56×10^4	5.37×10^5	5.37×10^5	0.0
1.00×10^6	9.21×10^5	9.63×10^4	8.25×10^5	8.25×10^5	0.0
Uranium-233					
1.00×10^4	9.00×10^1	1.48×10^1	7.52×10^1	7.52×10^1	0.0
5.00×10^4	6.25×10^2	1.02×10^2	5.23×10^2	5.23×10^2	0.0
1.00×10^5	1.56×10^3	2.54×10^2	1.30×10^3	1.30×10^3	0.0
3.00×10^5	1.07×10^4	1.84×10^3	8.83×10^3	8.83×10^3	0.0
5.00×10^5	3.28×10^4	4.39×10^3	2.84×10^4	2.84×10^4	0.0
8.00×10^5	8.12×10^4	9.05×10^3	7.21×10^4	7.21×10^4	0.0
1.00×10^6	1.28×10^5	1.37×10^4	1.15×10^5	1.15×10^5	0.0
Thorium-229					
1.00×10^4	4.78	4.29	4.96×10^{-1}	4.96×10^{-1}	0.0
5.00×10^4	2.54×10^1	1.41×10^1	1.13×10^1	1.13×10^1	0.0
1.00×10^5	5.49×10^1	2.03×10^1	3.47×10^1	3.47×10^1	0.0
3.00×10^5	2.96×10^2	8.05×10^1	2.16×10^2	2.16×10^2	0.0
5.00×10^5	9.30×10^2	1.88×10^2	7.41×10^2	7.41×10^2	0.0
8.00×10^5	2.57×10^3	3.89×10^2	2.18×10^3	2.18×10^3	0.0
1.00×10^6	4.26×10^3	6.11×10^2	3.64×10^3	3.64×10^3	0.0
Uranium-236					
1.00×10^4	2.75×10^3	6.78×10^2	2.07×10^3	2.07×10^3	0.0
5.00×10^4	1.51×10^4	3.70×10^3	1.14×10^4	1.14×10^4	0.0
1.00×10^5	3.06×10^4	7.53×10^3	2.30×10^4	2.30×10^4	0.0
3.00×10^5	1.19×10^5	3.49×10^4	8.40×10^4	8.40×10^4	0.0
5.00×10^5	3.54×10^5	8.70×10^4	2.67×10^5	2.67×10^5	0.0
8.00×10^5	9.46×10^5	1.96×10^5	7.50×10^5	7.50×10^5	0.0
1.00×10^6	1.54×10^6	2.97×10^5	1.24×10^6	1.24×10^6	0.0
Thorium-232					
1.00×10^4	1.58×10^3	1.40×10^3	1.78×10^2	1.78×10^2	0.0
5.00×10^4	8.70×10^3	7.71×10^3	9.91×10^2	9.91×10^2	0.0
1.00×10^5	1.76×10^4	1.56×10^4	2.04×10^3	2.04×10^3	0.0
3.00×10^5	6.06×10^4	5.39×10^4	6.70×10^3	6.70×10^3	0.0
5.00×10^5	1.69×10^5	1.46×10^5	2.35×10^4	2.35×10^4	0.0
8.00×10^5	5.07×10^5	4.28×10^5	7.91×10^4	7.91×10^4	0.0
1.00×10^6	1.02×10^6	8.67×10^5	1.57×10^5	1.57×10^5	0.0

Table B-7. Mass balance (grams), no-pumping, present climate (continued).

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometers and Death Valley	Released at Death Valley
Uranium-234					
1.00×10^4	8.69×10^1	7.04	7.99×10^1	7.99×10^1	0.0
5.00×10^4	4.53×10^2	3.67×10^1	4.16×10^2	4.16×10^2	0.0
1.00×10^5	8.56×10^2	6.93×10^1	7.87×10^2	7.87×10^2	0.0
3.00×10^5	3.76×10^3	2.12×10^2	3.55×10^3	3.55×10^3	0.0
5.00×10^5	6.92×10^3	0.0	7.27×10^3	7.27×10^3	0.0
8.00×10^5	9.73×10^3	0.0	1.06×10^4	1.06×10^4	0.0
1.00×10^6	1.15×10^4	0.0	1.19×10^4	1.19×10^4	0.0
Thorium-230					
1.00×10^4	7.45×10^1	7.09×10^1	3.56	3.56	0.0
5.00×10^4	3.26×10^2	2.74×10^2	5.19×10^1	5.19×10^1	0.0
1.00×10^5	5.05×10^2	3.57×10^2	1.48×10^2	1.48×10^2	0.0
3.00×10^5	1.12×10^3	3.50×10^2	7.69×10^2	7.69×10^2	0.0
5.00×10^5	1.27×10^3	7.86×10^1	1.19×10^3	1.19×10^3	0.0
8.00×10^5	9.90×10^2	0.0	1.04×10^3	1.04×10^3	0.0
1.00×10^6	7.65×10^2	0.0	7.95×10^2	7.95×10^2	0.0
Uranium-238					
1.00×10^4	3.54×10^5	8.93×10^4	2.65×10^5	2.65×10^5	0.0
5.00×10^4	1.95×10^6	4.92×10^5	1.46×10^6	1.46×10^6	0.0
1.00×10^5	3.94×10^6	9.94×10^5	2.95×10^6	2.95×10^6	0.0
3.00×10^5	1.53×10^7	4.52×10^6	1.07×10^7	1.07×10^7	0.0
5.00×10^5	4.48×10^7	1.10×10^7	3.38×10^7	3.38×10^7	0.0
8.00×10^5	1.20×10^8	2.51×10^7	9.51×10^7	9.51×10^7	0.0
1.00×10^6	1.98×10^8	3.91×10^7	1.59×10^8	1.59×10^8	0.0
Iodine-129					
1.00×10^4	1.44×10^4	5.30×10^2	1.39×10^4	1.39×10^4	0.0
5.00×10^4	7.92×10^4	2.92×10^3	7.63×10^4	5.59×10^4	2.04×10^4
1.00×10^5	1.60×10^5	5.90×10^3	1.54×10^5	5.59×10^4	9.83×10^4
3.00×10^5	6.64×10^5	3.47×10^4	6.29×10^5	1.73×10^5	4.56×10^5
5.00×10^5	1.92×10^6	6.77×10^4	1.85×10^6	2.39×10^5	1.61×10^6
8.00×10^5	5.43×10^6	1.74×10^5	5.26×10^6	5.30×10^5	4.73×10^6
1.00×10^6	7.80×10^6	1.91×10^5	7.61×10^6	3.68×10^5	7.24×10^6
Selenium-79					
1.00×10^4	7.38×10^2	3.68×10^2	3.70×10^2	3.70×10^2	0.0
5.00×10^4	4.53×10^3	2.48×10^3	2.04×10^3	2.04×10^3	0.0
1.00×10^5	8.98×10^3	3.78×10^3	5.20×10^3	5.20×10^3	0.0
3.00×10^5	1.34×10^4	4.36×10^3	9.08×10^3	9.08×10^3	0.0
5.00×10^5	1.69×10^4	4.75×10^3	1.21×10^4	1.21×10^4	0.0
8.00×10^5	1.87×10^4	4.77×10^3	1.39×10^4	1.39×10^4	0.0
1.00×10^6	1.68×10^4	3.67×10^3	1.31×10^4	1.31×10^4	0.0
Technetium-99					
1.00×10^4	8.28×10^4	8.58×10^3	7.42×10^4	7.42×10^4	0.0
5.00×10^4	4.52×10^5	3.96×10^4	4.12×10^5	3.16×10^5	9.63×10^4
1.00×10^5	8.23×10^5	4.18×10^4	7.81×10^5	3.00×10^5	4.81×10^5
3.00×10^5	1.33×10^6	5.67×10^4	1.27×10^6	2.66×10^5	1.00×10^6
5.00×10^5	1.86×10^6	6.09×10^4	1.79×10^6	2.11×10^5	1.58×10^6
8.00×10^5	1.91×10^6	6.02×10^4	1.85×10^6	1.92×10^5	1.66×10^6
1.00×10^6	1.38×10^6	3.16×10^4	1.34×10^6	8.95×10^4	1.25×10^6

Table B-8. Mass balance (grams), no-pumping, wetter climate.

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometers and Furnace Creek	Released at Death Valley
Uranium-235					
1.00×10^4	7.66×10^3	1.26×10^3	6.40×10^3	6.40×10^3	0.0
5.00×10^4	4.31×10^4	7.78×10^3	3.54×10^4	3.54×10^4	0.0
1.00×10^5	8.90×10^4	1.70×10^4	7.20×10^4	7.20×10^4	0.0
3.00×10^5	3.47×10^5	7.09×10^4	2.76×10^5	2.76×10^5	0.0
5.00×10^5	9.41×10^5	1.48×10^5	7.94×10^5	7.94×10^5	0.0
8.00×10^5	2.42×10^6	2.91×10^5	2.12×10^6	2.12×10^6	0.0
1.00×10^6	4.00×10^6	4.26×10^5	3.58×10^6	3.58×10^6	0.0
Neptunium-237					
1.00×10^4	2.43×10^3	3.92×10^2	2.04×10^3	2.04×10^3	0.0
5.00×10^4	1.33×10^4	2.15×10^3	1.11×10^4	1.11×10^4	0.0
1.00×10^5	2.67×10^4	4.31×10^3	2.24×10^4	2.24×10^4	0.0
3.00×10^5	1.17×10^5	2.00×10^4	9.69×10^4	9.69×10^4	0.0
5.00×10^5	2.84×10^5	3.75×10^4	2.47×10^5	2.47×10^5	0.0
8.00×10^5	6.02×10^5	6.56×10^4	5.37×10^5	5.37×10^5	0.0
1.00×10^6	9.21×10^5	9.63×10^4	8.25×10^5	8.25×10^5	0.0
Uranium-233					
1.00×10^4	9.00×10^1	1.48×10^1	7.52×10^1	7.52×10^1	0.0
5.00×10^4	6.25×10^2	1.02×10^2	5.23×10^2	5.23×10^2	0.0
1.00×10^5	1.56×10^3	2.54×10^2	1.30×10^3	1.30×10^3	0.0
3.00×10^5	1.07×10^4	1.84×10^3	8.83×10^3	8.83×10^3	0.0
5.00×10^5	3.28×10^4	4.39×10^3	2.84×10^4	2.84×10^4	0.0
8.00×10^5	8.12×10^4	9.05×10^3	7.21×10^4	7.21×10^4	0.0
1.00×10^6	1.28×10^5	1.37×10^4	1.15×10^5	1.15×10^5	0.0
Thorium-229					
1.00×10^4	4.78	4.29	4.96×10^{-1}	4.96×10^{-1}	0.0
5.00×10^4	2.54×10^1	1.41×10^1	1.13×10^1	1.13×10^1	0.0
1.00×10^5	5.49×10^1	2.03×10^1	3.47×10^1	3.47×10^1	0.0
3.00×10^5	2.96×10^2	8.05×10^1	2.16×10^2	2.16×10^2	0.0
5.00×10^5	9.30×10^2	1.88×10^2	7.41×10^2	7.41×10^2	0.0
8.00×10^5	2.57×10^3	3.89×10^2	2.18×10^3	2.18×10^3	0.0
1.00×10^6	4.26×10^3	6.11×10^2	3.64×10^3	3.64×10^3	0.0
Uranium-236					
1.00×10^4	2.75×10^3	6.78×10^2	2.07×10^3	2.07×10^3	0.0
5.00×10^4	1.51×10^4	3.70×10^3	1.14×10^4	1.14×10^4	0.0
1.00×10^5	3.06×10^4	7.53×10^3	2.30×10^4	2.30×10^4	0.0
3.00×10^5	1.19×10^5	3.49×10^4	8.40×10^4	8.40×10^4	0.0
5.00×10^5	3.54×10^5	8.70×10^4	2.67×10^5	2.67×10^5	0.0
8.00×10^5	9.46×10^5	1.96×10^5	7.50×10^5	7.50×10^5	0.0
1.00×10^6	1.54×10^6	2.97×10^5	1.24×10^6	1.24×10^6	0.0
Thorium 232					
1.00×10^4	1.58×10^3	1.40×10^3	1.78×10^2	1.78×10^2	0.0
5.00×10^4	8.70×10^3	7.71×10^3	9.91×10^2	9.91×10^2	0.0
1.00×10^5	1.76×10^4	1.56×10^4	2.04×10^3	2.04×10^3	0.0
3.00×10^5	6.06×10^4	5.39×10^4	6.70×10^3	6.70×10^3	0.0
5.00×10^5	1.69×10^5	1.46×10^5	2.35×10^4	2.35×10^4	0.0
8.00×10^5	5.07×10^5	4.28×10^5	7.91×10^4	7.91×10^4	0.0
1.00×10^6	1.02×10^6	8.67×10^5	1.57×10^5	1.57×10^5	0.0

Table B-8. Mass balance (grams), no-pumping, wetter climate (continued).

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometers and Furnace Creek	Released at Death Valley
Uranium-234					
1.00×10^4	8.69×10^1	7.04	7.99×10^1	7.99×10^1	0.0
5.00×10^4	4.53×10^2	3.67×10^1	4.16×10^2	4.16×10^2	0.0
1.00×10^5	8.56×10^2	6.93×10^1	7.87×10^2	7.87×10^2	0.0
3.00×10^5	3.76×10^3	2.12×10^2	3.55×10^3	3.55×10^3	0.0
5.00×10^5	6.92×10^3	0.0	7.27×10^3	7.27×10^3	0.0
8.00×10^5	9.73×10^3	0.0	1.06×10^4	1.06×10^4	0.0
1.00×10^6	1.15×10^4	0.0	1.19×10^4	1.19×10^4	0.0
Thorium-230					
1.00×10^4	7.45×10^1	7.09×10^1	3.56	3.56	0.0
5.00×10^4	3.26×10^2	2.74×10^2	5.19×10^1	5.19×10^1	0.0
1.00×10^5	5.05×10^2	3.57×10^2	1.48×10^2	1.48×10^2	0.0
3.00×10^5	1.12×10^3	3.50×10^2	7.69×10^2	7.69×10^2	0.0
5.00×10^5	1.27×10^3	7.86×10^1	1.19×10^3	1.19×10^3	0.0
8.00×10^5	9.90×10^2	0.0	1.04×10^3	1.04×10^3	0.0
1.00×10^6	7.65×10^2	0.0	7.95×10^2	7.95×10^2	0.0
Uranium-238					
1.00×10^4	3.54×10^5	8.93×10^4	2.65×10^5	2.65×10^5	0.0
5.00×10^4	1.95×10^6	4.92×10^5	1.46×10^6	1.46×10^6	0.0
1.00×10^5	3.94×10^6	9.94×10^5	2.95×10^6	2.95×10^6	0.0
3.00×10^5	1.53×10^7	4.52×10^6	1.07×10^7	1.07×10^7	0.0
5.00×10^5	4.48×10^7	1.10×10^7	3.38×10^7	3.38×10^7	0.0
8.00×10^5	1.20×10^8	2.51×10^7	9.51×10^7	9.51×10^7	0.0
1.00×10^6	1.98×10^8	3.91×10^7	1.59×10^8	1.59×10^8	0.0
Iodine-129					
1.00×10^4	1.44×10^4	5.30×10^2	1.39×10^4	1.27×10^4	1.15×10^3
5.00×10^4	7.92×10^4	2.92×10^3	7.63×10^4	1.31×10^4	6.32×10^4
1.00×10^5	1.60×10^5	5.90×10^3	1.54×10^5	1.31×10^4	1.41×10^5
3.00×10^5	6.64×10^5	3.47×10^4	6.29×10^5	4.18×10^4	5.87×10^5
5.00×10^5	1.92×10^6	6.77×10^4	1.85×10^6	5.88×10^4	1.79×10^6
8.00×10^5	5.43×10^6	1.74×10^5	5.26×10^6	1.24×10^5	5.14×10^6
1.00×10^6	7.80×10^6	1.91×10^5	7.61×10^6	8.67×10^4	7.52×10^6
Selenium-79					
1.00×10^4	7.38×10^2	3.68×10^2	3.70×10^2	3.70×10^2	0.0
5.00×10^4	4.53×10^3	2.48×10^3	2.04×10^3	2.04×10^3	0.0
1.00×10^5	8.98×10^3	3.78×10^3	5.20×10^3	5.20×10^3	0.0
3.00×10^5	1.34×10^4	4.36×10^3	9.08×10^3	9.08×10^3	0.0
5.00×10^5	1.69×10^4	4.75×10^3	1.21×10^4	1.21×10^4	0.0
8.00×10^5	1.87×10^4	4.77×10^3	1.39×10^4	1.39×10^4	0.0
1.00×10^6	1.68×10^4	3.67×10^3	1.31×10^4	1.31×10^4	0.0
Technetium-99					
1.00×10^4	8.28×10^4	8.58×10^3	7.42×10^4	6.82×10^4	6.06×10^3
5.00×10^4	4.52×10^5	3.96×10^4	4.12×10^5	9.10×10^4	3.21×10^5
1.00×10^5	8.23×10^5	4.18×10^4	7.81×10^5	7.30×10^4	7.08×10^5
3.00×10^5	1.33×10^6	5.67×10^4	1.27×10^6	7.64×10^4	1.19×10^6
5.00×10^5	1.86×10^6	6.09×10^4	1.79×10^6	5.60×10^4	1.74×10^6
8.00×10^5	1.91×10^6	6.02×10^4	1.85×10^6	5.19×10^4	1.80×10^6
1.00×10^6	1.38×10^6	3.16×10^4	1.34×10^6	2.56×10^4	1.32×10^6

B.4.2.2 Nonradiological Contaminants

This section presents mass balances for nickel, vanadium, and molybdenum (Tables B-9 through B-12). Unlike the radionuclides, these nonradiological contaminants do not decay so there is no decay or growth adjustment. The major uranium isotopes were included in the radionuclide mass balances. Uranium-238 represents nearly all the uranium.

Table B-9. Mass balance (grams), pumping, present climate.

Time (year)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometers and Amargosa Farms	Accumulated at Amargosa Farms
Molybdenum					
1.00×10^{4}	1.74×10^{9}	1.94×10^{8}	1.55×10^{9}	1.19×10^{8}	1.43×10^{9}
5.00×10^{4}	8.89×10^{9}	4.22×10^{8}	8.46×10^{9}	1.19×10^{8}	8.34×10^{9}
1.00×10^{5}	1.78×10^{10}	7.07×10^{8}	1.71×10^{10}	1.19×10^{8}	1.70×10^{10}
3.00×10^{5}	5.35×10^{10}	1.85×10^{9}	5.17×10^{10}	1.19×10^{8}	5.16×10^{10}
5.00×10^{5}	8.94×10^{10}	3.13×10^{9}	8.63×10^{10}	1.19×10^{8}	8.62×10^{10}
8.00×10^{5}	1.87×10^{11}	1.18×10^{10}	1.75×10^{11}	1.19×10^{8}	1.75×10^{11}
1.00×10^{6}	2.52×10^{11}	1.75×10^{10}	2.34×10^{11}	1.19×10^{8}	2.34×10^{11}
Nickel					
1.00×10^{4}	8.12×10^{9}	6.95×10^{9}	1.17×10^{9}	1.17×10^{9}	0.0
5.00×10^{4}	4.14×10^{10}	2.10×10^{10}	2.04×10^{10}	2.04×10^{10}	0.0
1.00×10^{5}	8.30×10^{10}	3.31×10^{10}	4.99×10^{10}	4.99×10^{10}	7.21×10^{-6}
3.00×10^{5}	2.50×10^{11}	6.99×10^{10}	1.80×10^{11}	1.40×10^{11}	4.01×10^{10}
5.00×10^{5}	4.17×10^{11}	8.87×10^{10}	3.28×10^{11}	1.60×10^{11}	1.68×10^{11}
8.00×10^{5}	8.77×10^{11}	1.55×10^{11}	7.22×10^{11}	2.89×10^{11}	4.33×10^{11}
1.00×10^{6}	1.18×10^{12}	1.90×10^{11}	9.93×10^{11}	2.94×10^{11}	6.99×10^{11}
Vanadium					
1.00×10^{4}	6.83×10^{6}	5.02×10^{6}	1.80×10^{6}	1.80×10^{6}	0.0
5.00×10^{4}	3.48×10^{7}	1.47×10^{7}	2.01×10^{7}	2.01×10^{7}	1.13×10^{-11}
1.00×10^{5}	6.98×10^{7}	2.39×10^{7}	4.59×10^{7}	4.58×10^{7}	7.16×10^{4}
3.00×10^{5}	2.10×10^{8}	5.06×10^{7}	1.59×10^{8}	6.69×10^{7}	9.23×10^{7}
5.00×10^{5}	3.50×10^{8}	7.35×10^{7}	2.76×10^{8}	6.80×10^{7}	2.08×10^{8}
8.00×10^{5}	5.60×10^{8}	1.05×10^{8}	4.55×10^{8}	6.93×10^{7}	3.86×10^{8}
1.00×10^{6}	7.00×10^{8}	1.25×10^{8}	5.74×10^{8}	6.93×10^{7}	5.05×10^{8}

Table B-10. Mass balance (grams), pumping, wetter climate.

Time (year)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometers and Amargosa Farms	Accumulated at Amargosa Farms
Molybdenum					
1.00×10^4	1.74×10^9	1.94×10^8	1.55×10^9	8.63×10^7	1.46×10^9
5.00×10^4	8.89×10^9	4.22×10^8	8.46×10^9	8.63×10^7	8.38×10^9
1.00×10^5	1.78×10^{10}	7.07×10^8	1.71×10^{10}	8.63×10^7	1.70×10^{10}
3.00×10^5	5.35×10^{10}	1.85×10^9	5.17×10^{10}	8.63×10^7	5.16×10^{10}
5.00×10^5	8.94×10^{10}	3.13×10^9	8.63×10^{10}	8.63×10^7	8.62×10^{10}
8.00×10^5	1.87×10^{11}	1.18×10^{10}	1.75×10^{11}	8.63×10^7	1.75×10^{11}
1.00×10^6	2.52×10^{11}	1.75×10^{10}	2.34×10^{11}	8.63×10^7	2.34×10^{11}
Nickel					
1.00×10^4	8.12×10^9	6.95×10^9	1.17×10^9	1.17×10^9	0.0
5.00×10^4	4.14×10^{10}	2.10×10^{10}	2.04×10^{10}	2.04×10^{10}	1.40×10^7
1.00×10^5	8.30×10^{10}	3.31×10^{10}	4.99×10^{10}	3.25×10^{10}	1.75×10^{10}
3.00×10^5	2.50×10^{11}	6.99×10^{10}	1.80×10^{11}	3.69×10^{10}	1.43×10^{11}
5.00×10^5	4.17×10^{11}	8.87×10^{10}	3.28×10^{11}	4.20×10^{10}	2.86×10^{11}
8.00×10^5	8.77×10^{11}	1.55×10^{11}	7.22×10^{11}	7.51×10^{10}	6.47×10^{11}
1.00×10^6	1.18×10^{12}	1.90×10^{11}	9.93×10^{11}	7.51×10^{10}	9.18×10^{11}
Vanadium					
1.00×10^4	6.83×10^6	5.02×10^6	1.80×10^6	1.80×10^6	0.0
5.00×10^4	3.48×10^7	1.47×10^7	2.01×10^7	1.40×10^7	6.09×10^6
1.00×10^5	6.98×10^7	2.39×10^7	4.59×10^7	1.55×10^7	3.04×10^7
3.00×10^5	2.10×10^8	5.06×10^7	1.59×10^8	1.74×10^7	1.42×10^8
5.00×10^5	3.50×10^8	7.35×10^7	2.76×10^8	1.74×10^7	2.59×10^8
8.00×10^5	5.60×10^8	1.05×10^8	4.55×10^8	1.77×10^7	4.38×10^8
1.00×10^6	7.00×10^8	1.25×10^8	5.74×10^8	1.77×10^7	5.57×10^8

Table B-11. Mass balance (grams), no-pumping, present climate.

Time (years)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometers	Held in path between 18 kilometer and Death Valley	Released into Death Valley
Molybdenum					
1.00×10^4	1.74×10^9	1.94×10^8	1.55×10^9	1.55×10^9	0.0
5.00×10^4	8.89×10^9	4.22×10^8	8.46×10^9	6.30×10^9	2.17×10^9
1.00×10^5	1.78×10^{10}	7.07×10^8	1.71×10^{10}	6.30×10^9	1.08×10^{10}
3.00×10^5	5.35×10^{10}	1.85×10^9	5.17×10^{10}	6.30×10^9	4.54×10^{10}
5.00×10^5	8.94×10^{10}	3.13×10^9	8.63×10^{10}	6.30×10^9	8.00×10^{10}
8.00×10^5	1.87×10^{11}	1.18×10^{10}	1.75×10^{11}	1.07×10^{10}	1.64×10^{11}
1.00×10^6	2.52×10^{11}	1.75×10^{10}	2.34×10^{11}	1.07×10^{10}	2.23×10^{11}
Nickel					
1.00×10^4	8.12×10^9	6.95×10^9	1.17×10^9	1.17×10^9	0.0
5.00×10^4	4.14×10^{10}	2.10×10^{10}	2.04×10^{10}	2.04×10^{10}	0.0
1.00×10^5	8.30×10^{10}	3.31×10^{10}	4.99×10^{10}	4.99×10^{10}	0.0
3.00×10^5	2.50×10^{11}	6.99×10^{10}	1.80×10^{11}	1.80×10^{11}	0.0
5.00×10^5	4.17×10^{11}	8.87×10^{10}	3.28×10^{11}	3.28×10^{11}	0.0
8.00×10^5	8.77×10^{11}	1.55×10^{11}	7.22×10^{11}	7.22×10^{11}	0.0
1.00×10^6	1.18×10^{12}	1.90×10^{11}	9.93×10^{11}	9.93×10^{11}	0.0
Vanadium					
1.00×10^4	6.83×10^6	5.02×10^6	1.80×10^6	1.80×10^6	0.0
5.00×10^4	3.48×10^7	1.47×10^7	2.01×10^7	2.01×10^7	0.0
1.00×10^5	6.98×10^7	2.39×10^7	4.59×10^7	4.59×10^7	0.0
3.00×10^5	2.10×10^8	5.06×10^7	1.59×10^8	1.59×10^8	0.0
5.00×10^5	3.50×10^8	7.35×10^7	2.76×10^8	2.76×10^8	0.0
8.00×10^5	5.60×10^8	1.05×10^8	4.55×10^8	4.55×10^8	0.0
1.00×10^6	7.00×10^8	1.25×10^8	5.74×10^8	5.74×10^8	0.0

Table B-12. Mass balance (grams), no-pumping, wetter climate.

Time (year)	Released from the unsaturated zone to the saturated zone	Held in path between the unsaturated zone and 18 kilometers	Released beyond 18 kilometer	Held in path between 18 kilometers and Death Valley	Released into Death Valley
Molybdenum					
1.00×10^{4}	1.74×10^{9}	1.94×10^{8}	1.55×10^{9}	1.55×10^{9}	6.50×10^{-6}
5.00×10^{4}	8.89×10^{9}	4.22×10^{8}	8.46×10^{9}	2.62×10^{9}	5.85×10^{9}
1.00×10^{5}	1.78×10^{10}	7.07×10^{8}	1.71×10^{10}	2.62×10^{9}	1.45×10^{10}
3.00×10^{5}	5.35×10^{10}	1.85×10^{9}	5.17×10^{10}	2.62×10^{9}	4.91×10^{10}
5.00×10^{5}	8.94×10^{10}	3.13×10^{9}	8.63×10^{10}	2.62×10^{9}	8.37×10^{10}
8.00×10^{5}	1.87×10^{11}	1.18×10^{10}	1.75×10^{11}	4.39×10^{9}	1.71×10^{11}
1.00×10^{6}	2.52×10^{11}	1.75×10^{10}	2.34×10^{11}	4.39×10^{9}	2.30×10^{11}
Nickel					
1.00×10^{4}	8.12×10^{9}	6.95×10^{9}	1.17×10^{9}	1.17×10^{9}	0.0
5.00×10^{4}	4.14×10^{10}	2.10×10^{10}	2.04×10^{10}	2.04×10^{10}	0.0
1.00×10^{5}	8.30×10^{10}	3.31×10^{10}	4.99×10^{10}	4.99×10^{10}	0.0
3.00×10^{5}	2.50×10^{11}	6.99×10^{10}	1.80×10^{11}	1.80×10^{11}	0.0
5.00×10^{5}	4.17×10^{11}	8.87×10^{10}	3.28×10^{11}	3.28×10^{11}	0.0
8.00×10^{5}	8.77×10^{11}	1.55×10^{11}	7.22×10^{11}	7.22×10^{11}	0.0
1.00×10^{6}	1.18×10^{12}	1.90×10^{11}	9.93×10^{11}	9.93×10^{11}	0.0
Vanadium					
1.00×10^{4}	6.83×10^{6}	5.02×10^{6}	1.80×10^{6}	1.80×10^{6}	0.0
5.00×10^{4}	3.48×10^{7}	1.47×10^{7}	2.01×10^{7}	2.01×10^{7}	0.0
1.00×10^{5}	6.98×10^{7}	2.39×10^{7}	4.59×10^{7}	4.59×10^{7}	0.0
3.00×10^{5}	2.10×10^{8}	5.06×10^{7}	1.59×10^{8}	1.59×10^{8}	0.0
5.00×10^{5}	3.50×10^{8}	7.35×10^{7}	2.76×10^{8}	2.76×10^{8}	0.0
8.00×10^{5}	5.60×10^{8}	1.05×10^{8}	4.55×10^{8}	4.55×10^{8}	0.0
1.00×10^{6}	7.00×10^{8}	1.25×10^{8}	5.74×10^{8}	5.74×10^{8}	8.13

B.4.3 SOIL CONCENTRATIONS AT THE AMARGOSA FARMS AREA

Soil concentrations at the Amargosa Farms area refer to concentrations of contaminants contained in a surface soil layer. This surface layer contains some of the contaminants. The balance of the contaminants remains in the entire soil column of the unsaturated zone or migrate to the saturated zone, where some are recycled. Note that according to the assumptions in this Analysis of Postclosure Groundwater Impacts, some fraction of contaminants (about 14 percent) are removed because the water is not used for irrigation. This percentage could be in homes, swamp cooler filters, septic systems—any place other than irrigation.

Note that to obtain these concentrations as grams-per-cubic-meter values, divide by the thickness of the soil surface layer (0.25 meter). Note also that grams-per-cubic-meter is equivalent to milligrams per liter.

Table B-13 lists soil concentrations of radionuclides which have significant soil adsorption and are the most important to dose at certain times. Table B-14 lists soil concentrations of nonradiological contaminants.

Table B-13. Soil concentrations of radionuclides at the Amargosa Farms area.

Time (year)	Soil concentration (grams per square meter)					
	Np-237	Pu-242	U-235	Th-230	U-238	U-233
Present Climate						
10,000	0.0	0.0	0.0	0.0	0.0	0.0
100,000	3.18×10^{-6}	0.0	3.41×10^{-5}	6.23×10^{-7}	1.41×10^{-3}	3.30×10^{-7}
500,000	2.72×10^{-5}	0.0	1.38×10^{-4}	2.41×10^{-6}	5.92×10^{-3}	1.75×10^{-6}
1,000,000	5.48×10^{-5}	7.23×10^{-12}	3.60×10^{-4}	2.70×10^{-6}	1.58×10^{-2}	4.03×10^{-6}
Wetter Climate						
10,000	0.0	0.0	1.78×10^{-14}	1.18×10^{-16}	7.38×10^{-13}	1.74×10^{-16}
100,000	4.36×10^{-6}	0.0	1.80×10^{-5}	1.19×10^{-7}	7.45×10^{-4}	2.09×10^{-7}
500,000	1.75×10^{-5}	2.25×10^{-6}	8.34×10^{-5}	4.78×10^{-7}	3.43×10^{-3}	9.33×10^{-7}
1,000,000	3.90×10^{-5}	1.04×10^{-5}	2.18×10^{-4}	5.23×10^{-7}	9.45×10^{-3}	2.43×10^{-6}

Table B-14. Soil concentrations of nonradiological contaminants at the Amargosa Farms area.

Time (year)	Soil concentration (grams per square meter)			
	Molybdenum	Nickel	Vanadium	Uranium
Present climate				
10,000	3.06×10^{-3}	0.0	0.0	0.0
100,000	3.06×10^{-3}	1.80×10^{-14}	1.76×10^{-5}	1.16×10^{-3}
500,000	3.06×10^{-3}	2.48	6.20×10^{-4}	5.27×10^{-3}
1,000,000	5.24×10^{-3}	5.05	6.32×10^{-4}	1.33×10^{-2}
Wetter climate				
10,000	3.06×10^{-3}	0.0	0.0	5.26×10^{-9}
100,000	3.06×10^{-3}	2.01	5.45×10^{-4}	6.13×10^{-4}
500,000	3.06×10^{-3}	2.81	6.20×10^{-4}	2.84×10^{-3}
1,000,000	5.24×10^{-3}	5.05	6.32×10^{-4}	7.77×10^{-3}

B.4.4 SOIL CONCENTRATIONS AT MIDDLE BASIN

At Middle Basin on the floor of Death Valley, concentrations of radiological and nonradiological contaminants were developed as an input to dose and daily intake estimates. Table B-15 presents these concentrations in terms of mass of contaminant per mass of evaporite, and they are reported as "soil concentrations." Note that the actual soil concentrations would be smaller because the evaporites would be mixed with clastic rock soils; however, the actual concentration cannot be readily determined. Because these soil concentrations were used to estimate dose and daily intake, the results shown in Section B.4.1.2.1 are conservatively high. The contaminants included in Table B-15 represent the radionuclides that contribute to dose and the only nonradiological contaminant that appears at Middle Basin during the 1-million-year period after closure of the repository.

The concentrations in Table B-15 are reported as grams of contaminant per gram of solid rather than grams per square meter as in Tables B-13 and B-14 in the previous section. The grams-per-square-meter values at Middle Basin are indeterminate because the characteristic depth is not known. To compare the values in Tables B-13 and B-14 with those given in Table B-15, divide the values in Tables B-13 and B-14 by 0.25 meter and then by the estimated bulk density of the soil (1.5×10^6 grams per cubic meter). As an example, the molybdenum concentration at the Amargosa Farms area for the present climate

scenario (Table B-14) at 1 million years is 5.24×10^{-3} grams per cubic meter, which converts to 1.39×10^{-3} gram per gram of soil compared with a value of 4.76×10^{-4} gram per gram of soil in Table B-15.

Table B-15. Soil concentrations of selected contaminants at Middle Basin.

	Soil concentration (grams per gram of soil)			
Time (year)	Clorine-36	Iodine-129	Technetium-99	Molybdenum
Present Climate				
10,000	0.0	0.0	0.0	0.0
100,000	7.21×10^{-11}	2.51×10^{-9}	1.48×10^{-8}	2.78×10^{-4}
500,000	9.06×10^{-12}	1.06×10^{-8}	8.72×10^{-9}	2.78×10^{-4}
1,000,000	5.42×10^{-12}	1.65×10^{-8}	3.62×10^{-9}	4.76×10^{-4}
Wetter Climate				
10,000	1.15×10^{-11}	4.75×10^{-10}	2.50×10^{-9}	4.00×10^{-5}
100,000	1.40×10^{-11}	6.44×10^{-10}	3.50×10^{-9}	7.13×10^{-5}
500,000	2.47×10^{-12}	2.73×10^{-9}	2.44×10^{-9}	7.13×10^{-5}
1,000,000	1.48×10^{-12}	4.25×10^{-9}	1.01×10^{-9}	1.22×10^{-4}

B.4.5 INFLUENCE OF AN ADDITIONAL DISCHARGE AREA

The regional flow modeling discussed in Section B.1 did not identify additional discharge areas during the wetter climate. This is due to the restrictions/simplifications of this modeling. The U.S. Geological Survey identified drains and discharge areas in the Death Valley regional groundwater flow system for a future wetter climate (DIRS 120425-D'Agnese et al. 1999, all). Chapter 2 of this Analysis of Postclosure Groundwater Impacts discusses these potential discharge areas along or north of the State Line Deposits. The remainder of this section discusses impacts resulting from one important discharge point that could be in the flow paths identified in the regional flow modeling.

In addition to the Death Valley floor, the Furnace Creek springs area, and Alkali Flat, there is another discharge area that radionuclides might reach during the wetter climate. This area lies a few kilometers northwest of the Amargosa Farms area near the Nevada-California state line (DIRS 120425-D'Agnese et al. 1999, Figure 14) and would be an area of groundwater discharge during a future climate, similar to the wetter climate analyzed in this document. It is not clear what discharge rate might occur at such a spring, but it is reasonable to assume that it might be a few thousand acre-feet per year during a wetter climate (the Furnace Creek springs currently discharge about 2,300 acre-feet annually). Nor is it clear what portion of the contaminants would discharge at this potential location; however, if some portion of the plume were to discharge at the surface in this area, estimates have the resultant doses somewhere between those presented for the Amargosa Farms area (pumping scenario with recycle) and those the Repository SEIS estimated for the Regulatory Compliance Point (assuming full discharge of all contaminants). Discharge of a portion of the plume in this area would reduce the doses somewhat at the Amargosa Farms area in the pumping scenario and Death Valley in the no-pumping scenario because the discharge would alter the original mass balance prepared for this analysis. In the pumping scenario, the water from the discharge site would contain concentrations of radionuclides less than those at the Regulatory Compliance Point and somewhat higher than those at the Amargosa Farms area and would flow down the Amargosa River in a generally southerly direction. Assuming this surface water might be used for subsistence farming, the doses resulting from its use would be estimated to fall somewhere between those estimated for the Amargosa Farms area and those estimated in the Repository SEIS for the Regulatory Compliance

Point. In the no-pumping scenario, this water discharging from the additional site would result in doses somewhere between those for the Regulatory Compliance Point and those calculated for the Furnace Creek springs area.

B.5 Sensitivity Test

As mentioned earlier in this appendix, there is some uncertainty in the flow paths of the contaminants and in the transport properties of the water-bearing structures through which the contaminants may or may not pass. The transport properties are the key properties in the analysis of how the contaminants could move in the environment beyond the Regulatory Compliance Point. Because the Analysis of Postclosure Groundwater Impacts is a deterministic, single-point analysis, it not only is appropriate to characterize uncertainties, it is necessary to understand their importance. To this end, DOE has conducted a sensitivity analysis.

In this sensitivity analysis, DOE considered the transport to Amargosa Farms in the no-pumping, wetter climate scenario. The bulk density and porosity were set at the mean values for alluvium. The partition coefficients were set at their 0 percentile or lower limit values (DIRS 185814-DOE 2008, Table 2.3.9-14) Table B-16 shows a comparison of the parameters used to the base case. Figure B-24 shows the results. As can be seen, the results only show a 15-percent difference. This indicates a relatively mild sensitivity of the results to the key transport parameter. Thus, it is not critical to pinpoint exact transport parameters to give an adequate result.

Table B-16. Comparison of sensitivity case and base case parameters.

Transport property	Sensitivity case[a]	Base case[b]
Porosity (no units; fraction of solid volume occupied by voids)	0.16	0.16
Bulk Density (grams per milliliter)	2.00	2.00
Dispersion Coefficient (meters)	100	100
Specific Discharge wetter climate (meters per day)	0.024	0.024
K_d for uranium (milliliters per gram)	1.7	4.2
K_d for neptunium (milliliters per gram)	1.8	6
K_d for plutonium (milliliters per gram)	50	93
K_d for cesium (milliliters per gram)	100	728
K_d for americium, thorium, protactinium, and actinium (milliliters per gram)	1000	4762
K_d for strontium (milliliters per gram)	20	210
K_d for radium (milliliters per gram)	100	550
K_d for selenium (milliliters per gram)	1	14
K_d for tin (milliliters per gram)	100	1,916
K_d for carbon, technetium, iodine, and chlorine (milliliters per gram)	0	0

a. Source: DIRS 185814-DOE 2008, Table 2.3.9-14.
b. Source: Table B-1, Pumping flow path column, from this appendix.
K_d = partition coefficient.

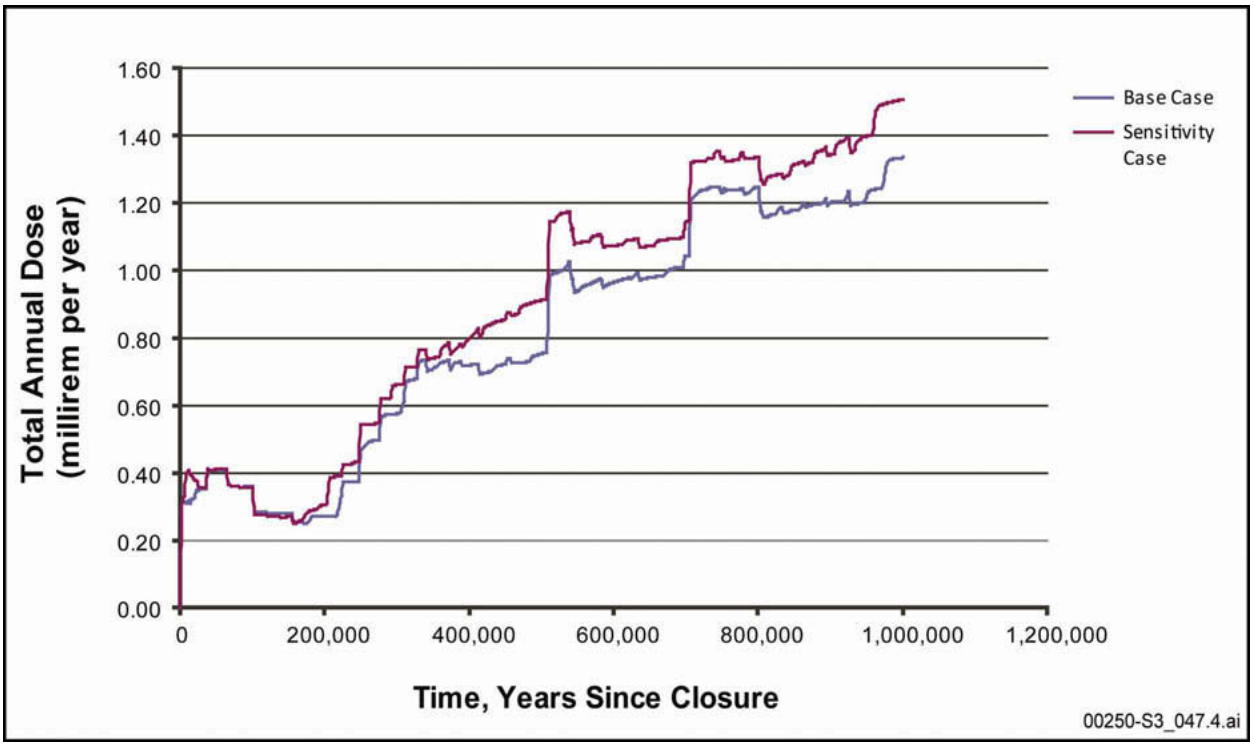

Figure B-24. Sensitivity case for the Amargosa Farms area, pumping, wetter climate.

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