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5

Environmental Consequences of Long-Term Repository Performance

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5. ENVIRONMENTAL CONSEQUENCES OF LONG-TERM REPOSITORY PERFORMANCE

This chapter describes potential human health impacts from radioactive and nonradioactive materials released to the environment during the first 10,000 years after closure of a repository at Yucca Mountain. The impact calculations assumed that the current population in the Yucca Mountain region would remain constant, as discussed in Section 5.2.4.1. The chapter also describes the peak radiation dose during the first 1 million years after closure. Closure of a repository would include the following events, which are analyzed in Chapter 4:

- Sealing of the underground emplacement drifts
- Backfilling and sealing of other underground openings
- Removal of the surface facilities
- Construction of surface monuments to discourage human intrusion
- Creation of institutional controls, including land records and monuments, to identify the location of the repository

In addition, this chapter discusses estimates of potential biological impacts from radiological and chemical groundwater contamination; potential environmental impacts of such contamination and potential biological impacts from the long-term production of heat by decay of the radioactive materials that would be disposed of in a repository at Yucca Mountain; and potential environmental justice impacts. These would be the only other potential impacts likely from the long-term postclosure system. There would be no repository activities; no changes in land use, employment of workers, water use or water quality other than from the transport of radionuclides; and no use of energy or other resources, or generation or handling of waste after closure of a repository. Therefore, analysis of impacts to land use, noise, socioeconomics, cultural resources, surface-water resources, aesthetics, utilities, or services after closure is not required. As part of closure activities, the U.S. Department of Energy (DOE) would return the land to its original contour and erect appropriate monuments marking the repository, which would result in some minor impacts on aesthetics depending on the exact design of the monuments (currently undetermined). Impacts from closure are discussed in Chapter 4. After the completion of closure, risk of sabotage or intruder access would be highly unlikely. Chapter 4 (Section 4.1.8.3) discusses the potential for sabotage prior to closure. Section 5.7.1 discusses potential impacts from an intruder after closure.

DOE performed this analysis of potential impacts after repository closure for three thermal load scenarios. The selected thermal load would be attained by varying the spacing between emplacement drifts and between waste packages in the drifts. The high thermal load of 85 metric tons of heavy metal (MTHM) per acre would emplace radioactive materials over the smallest repository area. The intermediate thermal load of 60 MTHM per acre would emplace radioactive materials over a larger repository area. The low thermal load of 25 MTHM per acre would emplace the radioactive materials over the largest repository area.

This assessment considered the following three transport pathways (means by which contamination could reach the biosphere) from spent nuclear fuel and high-level radioactive waste to reach human populations and cause health consequences:

- Groundwater
- Surface water
- Atmosphere

The principal pathway would result from rainwater migrating down through the unsaturated zone into the repository, dissolving some of the material in the repository, and carrying contaminants from the dissolved material downward through the unsaturated zone and through the groundwater system to locations where human exposure could occur. A surface-water pathway would arise only from groundwater that reached the surface at a discharge location, so the assessment considered surface-water consequences along with groundwater consequences. An airborne pathway could result from radioactive carbon-14 from spent nuclear fuel that migrated to the surface in the form of carbon dioxide gas that mixed with the atmosphere. Spent nuclear fuel contains other gases such as various xenon isotopes and krypton-85, but their very short half-lives would preclude their presence by the time of closure. Radon generated by uranium decay would not be a problem in the Yucca Mountain vicinity because closed residential structures would be unlikely on Yucca Mountain (see Section 5.2.4.1).

The assessment estimated potential human health impacts from the groundwater transport pathway at four locations in the Yucca Mountain groundwater hydrology region of influence: water wells 5, 20, and 30 kilometers (3, 12, and 19 miles) from the repository and the nearest surface-water discharge point [about 80 kilometers (50 miles) from the repository]. These consequences are in terms of radiological dose and the probability of a resulting latent cancer fatality. A latent cancer fatality is a death from cancer resulting from, and occurring sometime after, exposure to ionizing radiation or other carcinogens.

DOE assessed the processes by which waste could be released from a repository at Yucca Mountain and transported to the environment. The analysis used computer programs developed to assess the release and movement of radionuclides and hazardous materials in the environment. Some of the programs analyzed the behavior of engineered components such as the waste package, while others analyzed natural processes such as the movement of groundwater. The programs are based on the best available geologic, topographic, and hydrologic data and current knowledge of the behavior of the materials proposed for the system. The assessment used data from the Yucca Mountain site characterization activities, material tests, and expert opinions as input parameters to estimate human health consequences. Many parameters used in the analysis cannot be exactly measured or known; only a range of values can be known. The analysis accounted for this type of uncertainty; thus, the results are ranges of health consequences.

The long-term performance assessment considered human health impacts during the first 10,000 years after repository closure and the peak dose during the first 1 million years after repository closure. Estimates of potential human health impacts from the undisturbed evolution of a repository included the effects of such natural processes as corrosion of waste packages, dissolution of waste forms, and changing climate. In addition, the assessment examined the effects of such disturbances as exploratory drilling, seismicity, or volcanic events.

DOE has developed the information about the potential environmental impacts that could result from either the Proposed Action or the No-Action Alternative to inform the Secretary of Energy's determination whether to recommend Yucca Mountain as the site of this Nation's first monitored geologic repository for spent nuclear fuel and high-level radioactive waste.

5.1 Inventory for Performance Assessment Calculations

DOE proposes to dispose of between 10,000 and 11,000 waste packages containing as much as 70,000 MTHM of spent nuclear fuel and high-level radioactive waste in a repository at Yucca Mountain. There are several different types of disposal containers for commercial spent nuclear fuel and different container designs for DOE spent nuclear fuel and high-level radioactive waste. The exact number of waste packages, therefore, would depend on various options in the proposed design. This long-term consequence assessment identified the inventory by the source categories of waste material to be disposed of (commercial spent nuclear fuel, DOE spent nuclear fuel, weapons-usable plutonium, and high-level radioactive waste). For purposes of modeling, the inventory for each of the categories was averaged into an appropriate number of packages, each with identical contents. The average of the modeled inventories resulted in a total of nearly 12,000 idealized packages (slightly higher than the actual number of waste packages that would be emplaced) in three basic types, as described in the sections below. Figure 5-1 shows the averaging process.

INVENTORY OF RADIOACTIVE MATERIALS

There are more than 200 radionuclides in the waste inventory (see Appendix A). To perform impact calculations efficiently, this evaluation used a reduced number of radionuclides (see Appendix I). Those radionuclides eliminated from further consideration had at least one of the following characteristics:

- Radionuclides with short half-lives (generally less than several hundred years) that are not decay products of long-lived radionuclides (for example, krypton-85, xenon isotopes, and cesium-137)
- Radionuclides with high chemical sorption or low solubility that will decay before arriving at a human exposure point (for example, americium-241 and nickel-59)
- Radionuclides with low biosphere dose conversion factors that convert concentration to dose [relatively high radionuclide concentrations in groundwater would be required to produce a given dose compared to other radionuclides (for example, zirconium-93)]

TERMS RELATED TO RADIOACTIVE MATERIALS

A **curie** is a unit of radioactivity equal to the amount of a radioactive isotope that decays at a rate of 37 trillion disintegrations per second.

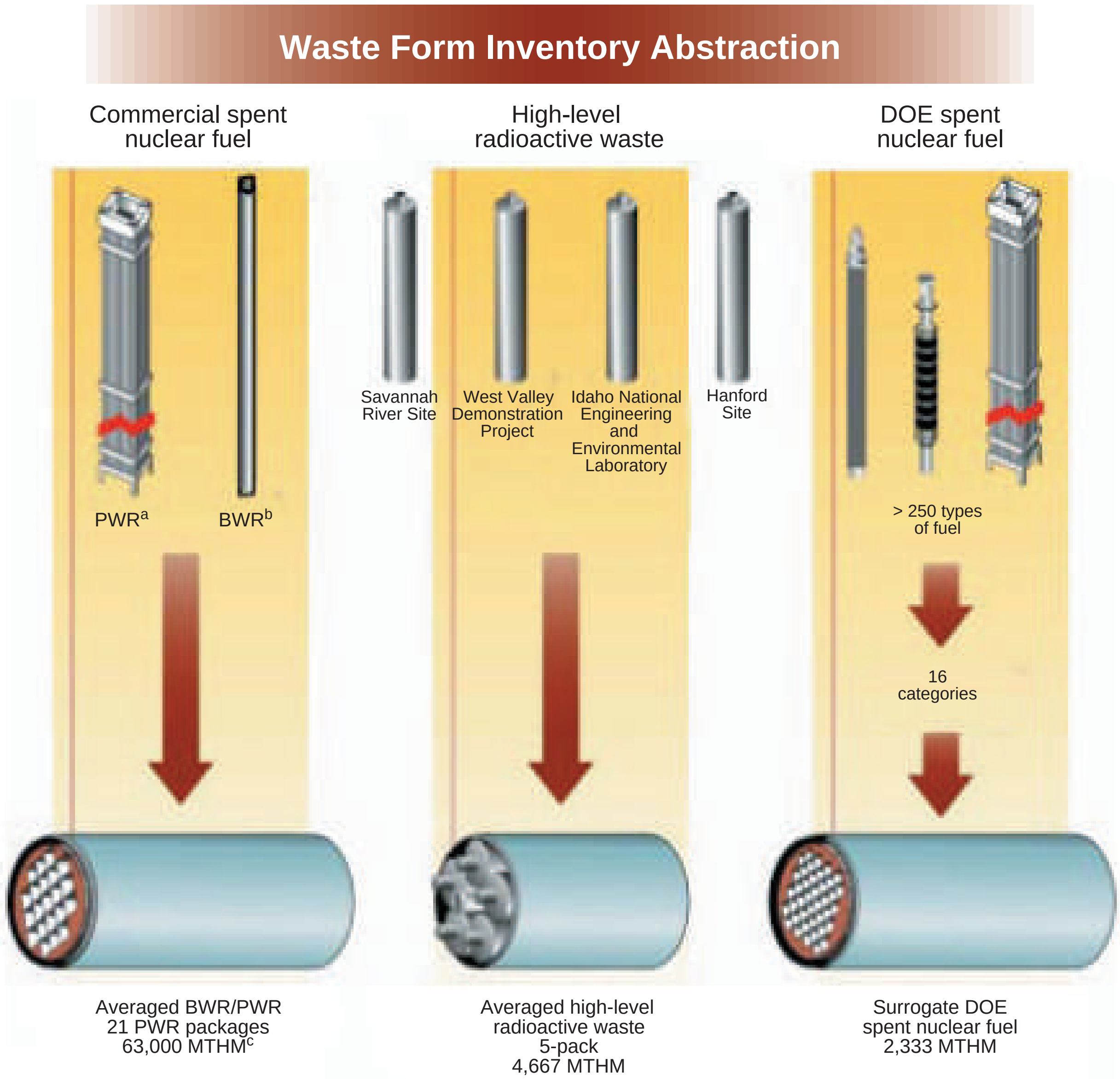
A **half-life** is the period during which radioactive decay causes half a given amount of a radionuclide to change to some other radionuclide or stable element.

During **decay**, the atom loses particles such as neutrons, electrons, or protons, and transforms to a different atomic mass or, in some cases, to a different atomic number and, ultimately, to a different element possessing different properties.

The large amounts of uranium in the repository would produce large quantities of radon as a decay product. The longest-lived radon isotope is radon-222, with a half-life of 4 days (CRC 1997, page 4-24); however, the large amount of uranium would result in a steady level of radon over time. The only potential transport and exposure pathway for radon would be the atmosphere because radon would not travel far enough in water to reach a receptor before decaying. The analysis did not consider radon for a gas pathway because it is a health problem only when trapped in closed structures (that is, it decays rapidly to nongaseous elements), and there should be no closed structures at the top of the mountain (see Section 5.2.4.1). Based on these considerations and previous performance analysis results at Yucca Mountain (TRW 1995b, all), DOE selected nine dominant radionuclides for analysis. Appendix I and previous performance analysis results at Yucca Mountain (Barnard et al. 1992, all; TRW 1995b, all) and the Viability Assessment (DOE 1998a, Volume 3, pages 3-95 to 3-99) contain more details on the inventory selection for the long-term performance models.

Table 5-1 lists the averaged radionuclide inventory in a waste package at the time of emplacement for the nine selected radionuclides for the following three sources:

- Commercial spent nuclear fuel
- DOE spent nuclear fuel
- High-level radioactive waste (including weapons-usable plutonium)



a. PWR = pressurized-water reactor.
b. BWR = boiling-water reactor.
c. MTHM = metric tons of heavy metal.

Note: For purposes of illustration, waste packages are shown without lids.

Source: Modified from DOE (1998a, Volume 3, page 3-98).

Figure 5-1. Inventory averaging (abstraction) process.

Table 5-1. Average radionuclide inventory (curies unless otherwise noted) per waste package for performance assessment calculations.[a]

Isotope	Half-life (years)	Commercial SNF[b] (7,760 idealized packages)	DOE SNF (2,546 idealized packages)	HLW[c] (1,663 idealized packages)
Carbon-14	5.7×10^{3}	12	0.31	0
Iodine-129	1.6×10^{7}	0.29	0.0057	0.000042
Neptunium-237	2.1×10^{6}	11	0.15	0.74
Protactinium-231	3.3×10^{4}	5.1[d]	0.66[d]	0.036[d]
Plutonium-239	2.4×10^{4}	3,100	160	24
Plutonium-242	3.9×10^{5}	17	0.11	0.02
Selenium-79	6.5×10^{4}	3.7	0.089	0.29
Technetium-99	2.1×10^{5}	120	2.6	30
Uranium-234	2.5×10^{5}	21	0.54	0.9

a. Source: DOE (1998a, Volume 3, Table 3-14, page 3-96).
b. SNF = spent nuclear fuel.
c. HLW = high-level radioactive waste.
d. Grams per waste package.

Some of the values in Table 5-1 are adjusted for ingrowth of radionuclides as products of decay of other radionuclides and are not an exact match with the inventory data in Appendix A. For example, americium-241, with a half-life of about 432 years, decays to neptunium-237. Because the waste packages are designed to last much longer than this (thousands of years), most of the americium-241 would decay to neptunium-237 before a waste package could fail. The analysis increased the inventory of neptunium-237 in the commercial spent nuclear fuel waste packages by 58 percent to account for this radioactive decay. A total of 11,969 idealized packages was used in the analysis.

DOE used a screening analysis to identify those chemically toxic materials that would require more detailed analysis (see Appendix I). The analysis started with a proposed inventory of all materials in the repository at the time of closure. This inventory included construction materials, waste package materials, and the contents of the waste packages. For each material, the screening process considered total inventory, solubility of the material in water, and chemical toxicity. The analysis found that earthen and concrete materials had no potential toxicity. The only known organic materials would be additives to the concrete (binders and conditioners) that either are inherently nontoxic or could break down completely in response to exposure to high radiation fields (TRW 1999b, pages 4-56 to 4-65) for 100 years or more before closure.

The first step in the screening process was to eliminate all nontoxic materials. In the second step, more materials were eliminated because their total quantity would be very low and dilution in the repository environment would reduce their concentration to below toxic levels before they entered the saturated groundwater system. Other materials would have low concentrations because of their very low solubilities. Low quantities or low concentrations accounted for the elimination of most hazardous materials in the spent nuclear fuel and high-level radioactive waste. The final step in the screening process was to eliminate materials that would not be transported to a surface drainage point or well in sufficient concentrations to pose a human health hazard.

Based on the screening analysis, DOE selected chromium, molybdenum, and uranium for detailed assessments of their potential human health impacts. Sections 5.6.1 through 5.6.3 describe these impacts. Chromium and molybdenum were retained for further analysis because they would be present in large quantities and remain in very soluble toxic forms. Uranium was retained because it would be present in very large quantities, is quite soluble, and is toxic as a heavy metal. The nickel-chromium alloy (Alloy-22) portion of the disposal container nominally would be 21.25 percent chromium (ASTM 1994, all). In addition, there would be approximately 4.3 kilograms (9.5 pounds) of chromium in a pressurized-water reactor fuel assembly and 1.9 kilograms (4.2 pounds) in a boiling-water reactor fuel assembly (see Appendix A). About 70 percent of the chromium in the repository would be in Alloy-22 disposal containers; the remainder would be in the fuel assemblies. All of the molybdenum would be in the Alloy-22, which nominally is about 13.5 percent molybdenum. DOE estimated the uranium inventory by using the repository capacity (in MTHM) to consider chemical toxicity. This is a very conservative approach because some of the heavy metal in spent nuclear fuel is plutonium and thorium, and the high-level radioactive waste has very small quantities of uranium because it is the byproduct of uranium and plutonium separations. The MTHM basis of high-level radioactive waste is the heavy metal content of the fuel from which the material was derived during the separation process. Plutonium was not included in the assessment of chemical toxicity because (in contrast to uranium) its radiotoxicity exceeds its chemical toxicity. Table 5-2 lists the total potential inventory of chromium, molybdenum, and uranium in the repository.

Table 5-2. Total inventory of chemically toxic materials in the repository.[a]

Element	Metric tons[b]
Chromium	14,000
Molybdenum	6,200
Uranium	70,000

a. Source: Appendix I, Table I-10.
b. To convert metric tons to tons, multiply by 1.1023; numbers are rounded to two significant figures.

5.2 System Overview

Radioactive materials in the repository would be placed about 300 meters (980 feet) beneath the surface (DOE 1998a, Volume 3, page 3-3). In physical form, the emplaced materials would be almost entirely in the form of solids with a very small fraction of the total radioactive inventory in the form of trapped gases (see Section 5.5). With the exception of a small amount of radioactive gas in the fuel rods, the primary means for the radioactive and chemically toxic materials to contact the biosphere would be along groundwater pathways. The materials could pose a threat to humans if the following sequence of events occurred:

- The waste packages and their contents were exposed to water
- Radionuclides or chemically toxic materials in the package materials or wastes became dissolved or mobilized in the water
- The radionuclides or chemically toxic materials were transported in water to an aquifer, and the water carrying radionuclides or chemically toxic materials was withdrawn from the aquifer through a well or at a surface-water discharge point and used directly by humans for drinking or in the human food chain (such as through irrigation or watering livestock)

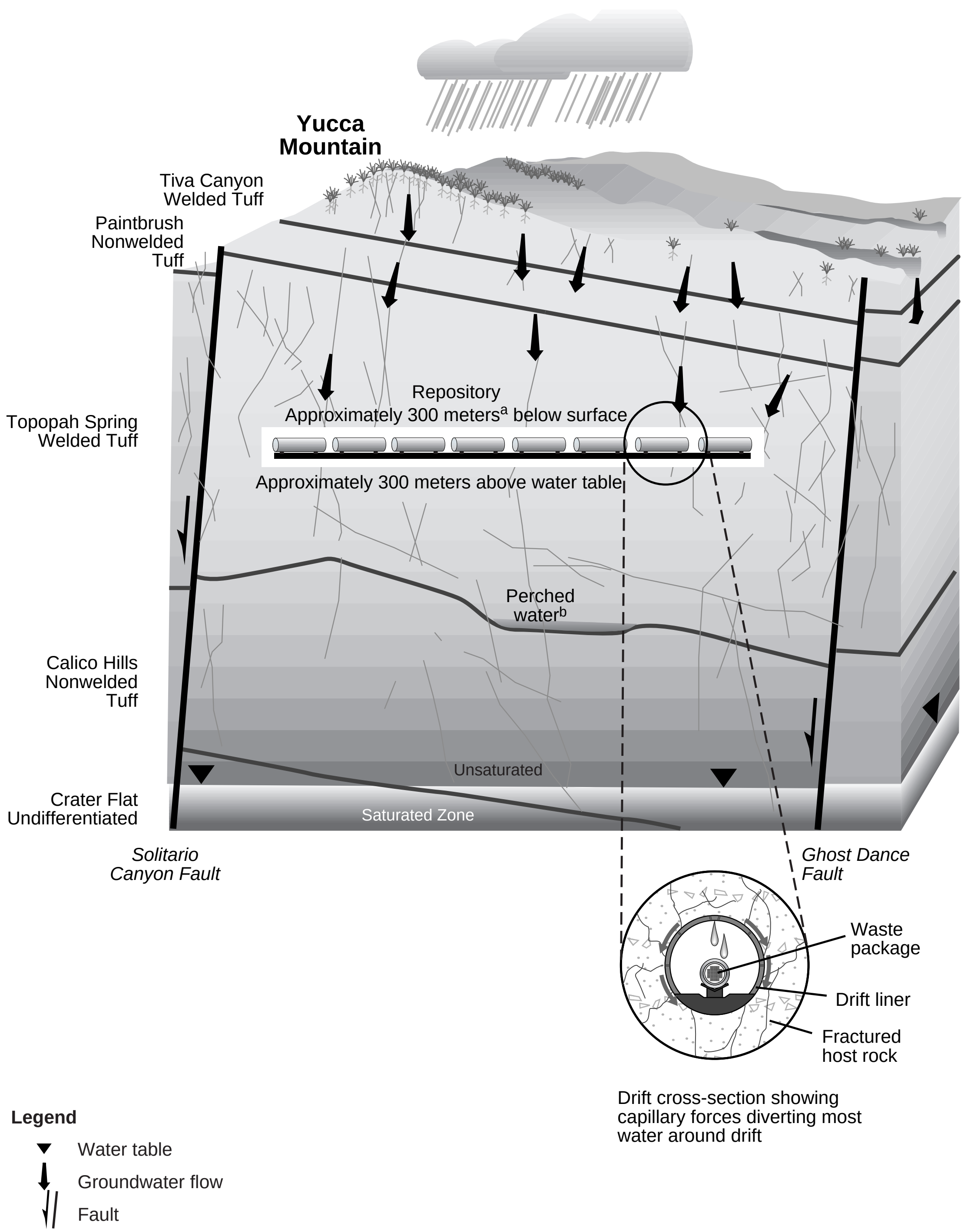
WASTE PACKAGE

A *waste package* consists of the waste form and any containers (disposal container, barriers, and other canisters), spacing structure or baskets, shielding integral to the container, packing in the container, and other absorbent materials immediately surrounding an individual disposal container, placed inside the container, or attached to its outer surface. The waste package begins its existence when the outer lid welds are complete and accepted and the welded unit is ready for emplacement in the repository.

Thus, the access to and flow of contaminated water are the most important considerations in determining potential health hazards.

5.2.1 COMPONENTS OF THE NATURAL SYSTEM

Figure 5-2 is a simplified schematic of a repository at Yucca Mountain. It shows the principal features of the natural system that could affect the long-term performance of the repository. Yucca Mountain is in a



a. To convert a meters to feet, multiply by 3.2808.
b. Perched water is a localized pocket of groundwater.

Source: Modified from DOE (1998a, Volume 3, page 3-3).

Figure 5-2. Components of the natural system.

semiarid desert environment where the average annual precipitation is between 100 and 250 millimeters (4 and 10 inches), varying by specific location over the immediate region (DOE 1998a, Volume 1, page 2-29). The water table is an average of 600 meters (2,000 feet) below the surface of the mountain. The proposed repository would be in unsaturated rock approximately midway between the desert environment and the water table.

> **HYDROGEOLOGIC TERMS**
>
> **Saturated zone:** The area below the water table where all spaces (fractures and rock pores) are completely filled with water.
>
> **Unsaturated zone:** The area between the surface and the water table where only some of the spaces (fractures and rock pores) are filled with water.
>
> **Matrix:** The solid, but porous, portion of the rock.

The water table is the boundary between the unsaturated zone above and the saturated zone below. In the subsurface region above the water table, the rock contains water but the water does not fill all the open spaces in the rock. Because the open spaces are only partially filled, this region is called *the unsaturated zone.* Water in the unsaturated zone tends to move generally downward in response to capillary action and gravity. In contrast, water fills all the open spaces in the rock below the water table, so this region is called the *saturated zone*. Water in the saturated zone tends to flow laterally from higher to lower pressures. Both zones contain several different rock types, as shown in Figure 5-2. The layers of major rock types in the unsaturated zone at the Yucca Mountain site are the Tiva Canyon welded, Paintbrush nonwelded, Topopah Spring welded, Calico Hills nonwelded, and Crater Flat undifferentiated tuffs. Figure 5-2 shows two of the faults at the proposed site—the Ghost Dance fault that occurs within the repository block and the Solitario Canyon Fault that forms the western boundary of the repository block. Faults are slip zones where rock units have become displaced either vertically, laterally, or diagonally, resulting in the rock layers being discontinuous. These slip zones tend to form a thin plane in which there is more open space that acts as a channel for water. Some faults tend to fill with broken rock formed as they slip, so they take on a very different flow property from that of the surrounding rock. The proposed repository would be in the Topopah Spring welded tuff in the unsaturated zone, about 300 meters (980 feet) below the surface and approximately 300 meters above the water table (DOE 1998a, Volume 3, page 3-3).

When it rains in the Yucca Mountain vicinity, most of the water runs off and a very limited amount infiltrates the rock on the surface of the mountain. Some of the water that remains on the surface or infiltrates the rock evaporates back into the atmosphere (directly or through plant uptake and evapotranspiration). The very small amount of water that infiltrates the rock and does not evaporate percolates down through the mountain to the saturated zone. Water that flowed through the unsaturated zone into the proposed repository could dissolve some of the waste material, if there was a breach in the package containment, and could carry it through the groundwater system to the accessible environment, where exposure to humans could occur.

5.2.2 COMPONENTS OF THE WASTE PACKAGE

Under the Proposed Action, spent nuclear fuel and high-level radioactive waste would be placed in cylindrical metal *disposal containers*. After being sealed, a disposal container would be called a *waste package*. Each waste package would have a 10-centimeter (4-inch)-thick carbon-steel outer shell, and an inner shell of a 2-centimeter (0.8-inch)-thick nickel-chromium alloy (called *Alloy-22*). The Alloy-22 would corrode 100 to 1,000 times slower than the carbon steel. Commercial spent nuclear fuel, which would comprise 98 percent of the radioactivity in the repository, would be additionally protected by a thin cladding of a zirconium alloy. Approximately 1 percent (by volume) of the commercial spent nuclear fuel would have cladding made of stainless steel rather than zirconium alloy. Commercial spent nuclear fuel would account for 75 percent of the total number of waste packages. Zirconium alloy has a corrosion rate much lower than that of Alloy-22. Water would not reach the fuel until there were openings in the carbon steel, the Alloy-22, and the cladding material. About 3.3 percent of the proposed repository inventory would be DOE spent nuclear fuel that would have a variety of cladding. Cladding was not considered to be a transport barrier for DOE spent nuclear fuel. The high-level radioactive waste form would not have cladding; this material would be in stainless-steel canisters, which for conservatism were not given any value as barriers.

5.2.3 VISUALIZATION OF THE REPOSITORY SYSTEM FOR ANALYSIS OF LONG-TERM PERFORMANCE

In general, the repository system was modeled as a series of processes linked together, one after the other, spatially from top to bottom in the mountain. From a computer modeling standpoint, it is important to break the system into smaller portions that relate to the way information is collected. In reality, an operating repository system would be completely interconnected, and virtually no process would be independent of other processes. However, the complexity of such a system demands some idealization of the system for an analysis to be performed.

In the following presentation, the processes are discussed in relation to the key attributes of the repository safety strategy. The four key attributes are:

- Limited water contacting waste package
- Long waste package lifetime
- Slow release of radionuclides from the waste
- Reduction in the concentration of radionuclides and chemically toxic material during transport from the waste to a point of human exposure

Along with the processes, this chapter discusses the models used to analyze them. The analysis included models associated with abnormal or disruptive events like volcanism, seismicity, and human intrusion. These events, if they occurred, would affect the undisturbed repository. The *Viability Assessment of a Repository at Yucca Mountain* contains details of the model construction and the input and output parameters (DOE 1998a, Volume 3, pages 3-1 to 3-162), and Appendix I, Section I-4 discusses the changes made for this EIS. The following sections summarize the expected behavior of the major components.

5.2.3.1 Limited Water Contacting Waste Package

Changes in climate over time provide a range of conditions that determine how much water could fall onto and infiltrate the ground surface. Based on current scientific understanding, the current climate is estimated to be the driest that the Yucca Mountain vicinity will ever experience. All future climates were assumed to be similar to or wetter than current conditions. The *climate* model provides a forecast of future climates based on information about past patterns of climates (DOE 1998a, Volume 3, pages 3-8 and 3-9). The model represents future climate shifts as a series of instant changes between the current dry climate, a long-term average climate with about twice the precipitation of the dry climate, and a very wet climate with about three times the precipitation of the dry climate. The water from precipitation that is not lost back to the atmosphere by evaporation or transpiration enters the unsaturated zone flow system. Water infiltration is affected by a number of factors related to climate, such as an increase or decrease in vegetation on the ground surface, total precipitation, air temperature, and runoff. The *infiltration* model uses data collected from studies of surface infiltration in the Yucca Mountain region (DOE 1998a, Volume 1, page 2-41). It treats infiltration as variable in the region, with more occurring along the crest of Yucca Mountain than along its base. The results of the climate model affect assumed infiltration rates.

Water generally moves downward in the rock matrix and in rock fractures. The rock mass at Yucca Mountain is composed of volcanic rock that is fractured to varying degrees as a result of contraction during cooling of the original, nearly molten rock and as a result of extensive faulting in the area. Water flowing in the fractures moves much more rapidly than the water moving through the matrix. In some locations, some of the water collects into locally saturated zones in the rock or is diverted laterally by differences in the rock properties. The overall unsaturated flow system is very heterogeneous, and the locations of flow paths, velocities, and volumes of groundwater flowing along these paths are likely to change many times over the life of the repository system. The *unsaturated zone flow* model assumes constant flow over a specific time period (taken from the infiltration model) and generates three-dimensional flow fields for three different infiltration boundary conditions, the three different climates described above, and several values of rock properties (DOE 1998a, Volume 3, pages 3-2 to 3-23). Because this model can assess the movement of materials leached from failed waste packages, the analysis used it to analyze the period after which most of the heat effects would have subsided and assumed there would be no further influence of heat on unsaturated zone flow fields.

The heat generated by the decay of nuclear materials in the repository would cause the temperature of the surrounding rock to rise from the time of emplacement until approximately 15 to 25 years after repository closure (DOE 1998a, Volume 3, page 3-37). The water and gas in the heated rock would be driven away from the proposed repository during this period, referred to in this document as the *thermal pulse*. This would occur under all thermal load scenarios discussed in this EIS. The thermal output of the materials would decrease with time; eventually, the rock would return to its original temperature, and the water and gas would flow back toward the proposed repository. The *mountain-scale thermal hydrology* model uses two-dimensional cross-sections taken from the three-dimensional, site-scale unsaturated zone flow model (see Appendix I, Section I.4). It provides the air mass-fraction and gas-flux near the repository drift to the near-field geochemical process models.

Some conceptual uncertainty exists regarding the influence of heat on water movement in the unsaturated zone. Some analysts (DOE 1998o, all) have suggested there could be a large thermal influence on the movement and chemistry of water after the repository cooled. Specifically, differences in temperature could focus water flow back toward the repository, resulting in much higher seepage rates than this analysis considered in the period after the thermal pulse. Therefore, this view would yield different results than the current drift-seepage models. Such a focus could have a large effect on the movement of radionuclides in the unsaturated zone. DOE is planning to conduct studies to measure the influence of temperature differences on water movement (DOE 1998a, Volume 4, page 3-17).

In addition, there is uncertainty concerning the influence of high temperatures on rock properties. The high temperatures might cause mineral alterations and produce long-term alteration in unsaturated zone water chemistry. However, some sensitivity studies on alternative chemistry scenarios suggest this would not have a large effect on the results (DOE 1998a, Volume 3, pages 4-85 to 4-86). Specifically, the effect of loss of sorptive capacity in the unsaturated zone was examined and would not have a large effect on biosphere dose. DOE is planning to conduct studies of the influence of heat on the chemical environment (DOE 1998a, Volume 4, page 3-22).

After the water returned to the repository walls, it would drip into the repository but only in a relatively few places. The number of seeps that could occur and the amount of water that would be available to drip would be restricted by the low rate at which water flows through Yucca Mountain, which is in a semiarid area. Drips could occur only if the hydrologic properties of the rock mass caused the water to concentrate enough to feed a seep. Over time, the number and locations of seeps would increase or decrease, corresponding to increased or decreased infiltration based on changing climate conditions. The *seepage flow* model calculates the amount of seepage that could occur based on input from the unsaturated zone flow model (DOE 1998a, Volume 3, pages 3-11 and 3-12). The basic conceptual model for seepage suggests that openings in unsaturated rock act as capillary barriers and divert water around them. For seepage to occur in the conceptual model, the rock pores at the drift wall would have to be locally saturated. Drift walls could become locally saturated by either disturbance to the flow field caused by the drift opening or variability in the permeability field that creates channeled flow and local ponding. Of the two reasons, the variability effect is more important. Drift-scale flow calculations made with uniform hydrologic properties suggest that seepage would not occur at expected percolation fluxes. However, calculations that include permeability variations do estimate seepage, with the amount depending on the hydrologic properties and the incoming percolation flux. Ongoing studies suggest that water travels through the unsaturated zone at highly variable rates from less than 100 years to thousands of years (see Chapter 3, Section 3.1.4.2.2).

5.2.3.2 Long Waste Package Lifetime

Because a repository at Yucca Mountain would be located above the water table in the unsaturated zone, the most important process controlling waste package lifetime is whether water would drip from the seeps on the package.

The location of the seeps would depend to some extent on the natural conditions of the rock but also on the alterations caused by construction of a repository. Alterations such as increased fracturing might be caused by mechanical processes related to drilling the drifts or by thermal heating and expansion of the drift wall. The alterations in the seepage could also be caused by chemical alterations occurring as the engineered materials dissolved in water and reprecipitated in the surrounding rock, closing the pores and fractures. The chemistry in the drift would change continually because of the complex interactions among the incoming water, circulating gas, and materials in the drift (for example, concrete from the liner or metals in the waste package). The changes in chemistry would be strongly influenced by heat during the thermal pulse.

The *drift-scale thermal hydrology* model calculates waste package surface temperature and relative humidity in the drift for different waste package types in several regions of the repository and provides these values to the waste package degradation model (DOE 1998a, Volume 3, pages 3-29 to 3-33). This model also calculates average waste form temperature and liquid saturation in the invert in the regions of the repository and provides these values to the waste form degradation and unsaturated zone transport models. Finally, it calculates average drift wall temperature, relative humidity, and liquid saturation for the invert, and provides these values to the near-field geochemistry models.

In the reference design, the radioactive waste placed in the proposed repository would be enclosed in a two-layer waste package. The layers would be of two different materials that would fail at different rates and from different mechanisms as they were exposed to various repository conditions. As described in Section 5.2.2, the outer layer would be carbon steel and the inner layer a high-nickel alloy metal. Where water dripped on the waste packages, the packages would corrode over time. The breaches probably would occur as deep, narrow pits or as broader areas called *patches*. The changing thermal, hydrologic, and chemical conditions in the repository would influence the corrosion rate of the waste packages.

The *near-field geochemistry* model calculates the interaction of water flowing through the drift with the material in the drift (DOE 1998a, Volume 3, pages 3-39 to 3-73). Equilibrium calculations generate a set of chemical composition parameters that the *waste-package degradation* model uses. In addition, the waste-package degradation model uses information from the drift-scale thermal hydrology model and the near-field geochemistry model to determine a corrosion rate that would vary at different areas on a given waste package (patch to patch and pit to pit) and from waste package to waste package. The surface of a conceptual waste package would have 400 separate areas called patches (DOE 1998a, Volume 3, pages 3-73 to 3-90). This model calculates the cumulative number of package failures as a function of time (a *failure* would be the first pit penetration or first patch penetration), the average size of failed patches over time, and the average pit area per package over time. The final calculations include assumed failures (to be conservative) that could be caused by manufacturing defects or mishandling.

The analysis assessed the possible effect of chemically toxic materials. The analysis did not identify any organic materials as being present in enough quantities to be toxic. A screening process eliminated most other materials because they were not of concern for human health effects (see Appendix I, Section I.3.2). Some of the components of the high-nickel alloy (such as chromium and molybdenum) were of sufficient quantity and possible toxicity to warrant an assessment of their transport into the biosphere. The rate of release of these materials was taken directly from the waste-package degradation modeling. These contaminants were modeled in the same way as the radionuclides in the models discussed below.

5.2.3.3 Slow Release of Radionuclides from Waste Package

If seepage water eventually entered a waste package through holes caused by corrosion, it could contact the radioactive material inside. Most of the material would be from commercial reactors, but some would be defense high-level radioactive waste, immobilized waste form incorporating formerly weapons-usable plutonium, and DOE spent nuclear fuel. Because most of the material would be commercial spent nuclear fuel, the long-term performance of the repository system would depend primarily on that material. The next two paragraphs discuss important considerations about commercial spent nuclear fuel.

The water would first contact the very thin layer [about 570 micrometers (0.022 inch) thick] of a zirconium alloy that would cover the surface of most of the fuel elements. This layer, called cladding, would have to be breached by mechanical or chemical processes before the radioactive fuel pellets could be exposed. *Cladding degradation* by chemical or physical processes such as corrosion or creep rupture is specified directly as a fraction of failed cladding over time (DOE 1998a, Volume 3, pages 3-100 to 3-103). This model includes other cladding degradation modes such as mechanical failure. It provides the cladding failure rate to the waste-form degradation and engineered-barrier system transport models.

After the cladding failed, individual fuel elements would start to degrade, making the radionuclides available for transport. The degradation process could involve several stages because the waste forms would sometimes be altered to different chemical phases before they reached a phase that would allow the nuclides to be released from the waste. Also, different radionuclides have different chemical properties, so the reaction rates of the individual nuclides with water would vary greatly. In general, however, modeling results show that once the waste form began to alter, it would take about 1,000 years for the commercial spent nuclear fuel to degrade completely in the case of the reference design repository. The result would be that certain nuclides would be released much earlier than others. The results of the long-term performance analysis show this effect, as different nuclides become the key contributors to dose rate over different time periods.

The *waste-form degradation* model uses degradation-rate formulas developed from experiments for the three different waste forms discussed in Section 5.1. This model provides values for the mass of the waste form exposed and the volume of water in contact with this waste form over time. These outputs are used to calculate the radionuclide release rate to the water inside the waste package. The rate at which a particular radionuclide would be released from the waste form would depend on the solubility of the radionuclide in the seepage water. Low-solubility radionuclides would tend to reach their solubility limit quickly, so the waste form could release them at the rate at which the water carried them away. High-solubility radionuclides would be released at a rate that would depend on the rate at which the water reacted with the waste form. The Viability Assessment (DOE 1998a, Volume 3, page 3-99) contains a more detailed discussion of the waste degradation model. The solubilities and assumed mechanisms in the waste degradation models are based on the best available information, but there are differing opinions, particularly about mechanisms of release and solubility of specific radionuclides such as neptunium-237. These differing opinions deal with:

- The appropriate solubility for neptunium (DOE 1998o, all)
- Mobilization of radionuclides from the spent nuclear fuel through a vapor-phase release mechanism (DOE 1998o, page 7) (the current model assumes only a liquid-phase release mechanism)

The long-term performance modeling results show that neptunium-237 would be an important contributor to long-term health effects.

Either of these variations could result in a different rate of release than the current analysis estimated. Higher neptunium solubility could result in higher release rates because solubility determines the release rate of neptunium in the current model. However, the long package life in the current system (modeling results show only a few packages would fail before 10,000 years) would tend to reduce any effect of differences in release rates prior to 10,000 years after closure, should any of these alternative interpretations prove to be accurate. In the model results, package failure rates versus time dominate the dose rates such that the release rate after package failure would play a minor role in determining total dose over time. In the 1-million-year period after closure, there could be some change in dose rates. The addition of vapor processes to aqueous transport processes could increase estimated dose rates by an undetermined amount. DOE is planning additional studies that will help deal with these issues (DOE 1998a, Volume 4, page 3-19).

To move out of the waste package, the radionuclides either would be carried away from the waste form in flowing water or would move in a thin film of water by diffusion. To escape, the radionuclides would have to exit through a pit or patch in the waste package and move out into the waste emplacement drift. The *radionuclide-mobilization and engineered-barrier system transport* model uses the seepage flux and radionuclide solubility in the groundwater to calculate the amount of each radionuclide that would move into the unsaturated zone (DOE 1998a, Volume 3, pages 3-90 to 3-109). It passes the amount of each radionuclides released directly to the unsaturated zone transport model.

5.2.3.4 Reduction in Concentration of Radionuclides and Chemically Toxic Materials During Transport

After escaping from the waste package, the radionuclides and other nonradioactive materials could advance through materials on the drift floor, which would be mainly concrete, and the corrosion products from the waste package. At this point, the radionuclides could either adhere to some of the materials on the drift floor, continue moving in the water, or become attached to extremely small particles of clay, silica, or iron called "colloids." Because of their molecular charge and physical size, these colloidal particles would move through the rock mass under the proposed repository somewhat differently than noncolloidal particles.

The radionuclides and chemically toxic materials would move down beneath the proposed repository at different rates based on (1) the chemical characteristics of the contaminants and of the rock they would be passing through and (2) the velocity of the water in which they were contained. The rock underlying the repository is unsaturated, and the water movement behaves as described above. Some water moves rapidly in fractures and some much more slowly in the rock. The transport rate would also depend on the tendency of the individual radionuclide or chemical to interact with the rock through which it would move. Some radionuclides would adhere to some minerals in a process called *sorption* and would be bound in the rock for long periods. Sorption can be irreversible in some instances, leaving the nuclide bound permanently in the rock. In other cases, the radionuclides could desorb at a future time and move through the rock. Other types of radionuclides would move more quickly through the rock with little or no interaction that delayed their transport. The analysis assumed that the nonradioactive toxic chemicals would not sorb and would move at the same rate as the water. This conservative assumption was based on a lack of reliable data on the sorption of these materials on tuff. The three-dimensional *unsaturated zone transport* model calculated the amount of each radionuclide and nonradioactive chemical species that would move from the unsaturated zone into the saturated zone and passed this value to the saturated zone transport model (DOE 1998a, Volume 3, pages 3-109 to 3-129).

When the radionuclides reached the water table, they would be caught in the saturated zone flow system. Beneath Yucca Mountain, the water in the saturated zone flows in a generally southerly direction toward the Amargosa Valley. Nuclide sorption would also occur in the rocks and alluvium along the flow paths in the saturated zone. Because of the differences in chemistry between the unsaturated and saturated zone rock and water, the transportation rates of nuclides involved in sorption would be different for the two zones. As the radionuclides moved in the saturated zone along different paths and through different materials, they would gradually become more dispersed and the concentration of the nuclides in any volume of water would decrease.

The *saturated zone transport* model calculates the movement of radionuclides from the unsaturated zone through an aquifer to a groundwater well or surface discharge location. This model is based on the assumption that water in the saturated zone travels along six paths or stream tubes between Yucca Mountain and the well (DOE 1998a, Volume 3, pages 3-130 to 3-143). This six-stream-tube model does not model dilution in the saturated zone; rather, a dilution factor recommended in an expert elicitation exercise (DOE 1998a, Volume 3, page 3-138) was applied to the results for 20 kilometers (12 miles). The basic recommended dilution factor was supplemented by additional empirical calculations for the distances and repository layouts in this EIS. Appendix I, Section I.4.5.4, of this EIS discusses these additional dilution factors. The model performs these flow and transport simulations for nine radionuclides and three chemically toxic materials using multiple simulations of uncertain saturated zone model parameters.

If the radionuclides were removed from the saturated zone by water pumped from wells, the radioactive material could cause doses to humans in several ways. For example, the well water could irrigate crops that persons or livestock consumed, water stock animals that provided milk or meat products, or provide drinking water. In addition, if the water pumped from irrigation wells evaporated on the ground surface, the nuclides could be left as fine particulate matter that could be picked up by the wind and inhaled by humans. The *biosphere* pathway model (DOE 1998a, Volume 3, pages 3-145 to 3-162) addresses what would happen to radionuclides between the time they were pumped from a well and the time they were ingested by a human being. The model uses a biosphere dose-conversion factor that converts saturated zone radionuclide concentrations to individual radiation dose rates. The dose factor was developed by analyzing the multiple pathways through the biosphere by which radionuclides can affect a person. The biosphere scenario assumed a reference person living in the Amargosa Valley region at various distances from the proposed repository at Yucca Mountain. People living in the community of Amargosa Valley would be the group most likely to be affected by radioactive releases (the critical group) because of their proximity to the proposed repository, and because the Amargosa Valley region is hydraulically downgradient from the proposed repository (Luckey et al. 1996, page 14). The reference person is representative of this group: an adult who lives year-round at this location, uses a well as the primary water source, and otherwise has habits (such as the consumption of local foods) similar to those of the inhabitants of the region. Because changes in human activities over millennia are unpredictable, the analysis assumed that the present-day reference person described future inhabitants.

The chemically toxic materials are not evaluated in the biosphere model because there are no usable dose comparison values. Instead, the concentrations of these materials in the groundwater are reported at the same distances where the radionuclide doses were evaluated. The concentrations are then compared to available regulatory standards such as the Maximum Contaminant Level Goal.

The groundwater analysis described above does not consider an alternative view of possible important groundwater migration mechanisms. In 1989, J. S. Szymanski (then a DOE staff scientist) raised the possibility of inundation of the proposed repository as an issue in a report to DOE (Szymanski 1989, all). This view is discussed in detail in Chapter 3, Section 3.1.4.2.2, and DOE does not agree with the inundation scenario for the reasons discussed in Chapter 3. There has been no analysis to determine the effects; however, if such an event occurred, the long-term impacts would probably increase greatly.

The groundwater path doses are based on specific paths of groundwater flow derived from regional data. There are differing opinions about these flow paths, which are derived from regional hydraulic head data and other measurements (Lehman and Brown 1996, all). This alternative concept of flow interprets local high pressure to be due to features such as faults and concludes with a largely different flow pattern in the 20-kilometer (about 12-mile) radius around the proposed repository. These alternative paths could produce somewhat different results in the saturated zone groundwater travel rates, direction, and dilution factors. Such changes could have some effect on the dose estimates. DOE does not know whether adaptation of the alternative paths would increase or decrease dose or how large an effect there would be. The current design of the proposed repository relies very heavily on the delay of release by providing long-lived waste packages, such that package failures would occur periodically over hundreds of thousands of years. The long lives of the packages tend to control the dose results, especially because the saturated zone delay and mixing has a small effect on the concentrations exiting the proposed repository. Therefore, alternative flow paths would not be likely to have a large effect on doses.

5.2.3.5 Disruptive Events

The key attributes of the system, given in the previous sections, describe the continually ongoing processes expected to occur in and around the proposed repository system. The term used to denote the sequence of anticipated conditions is the "nominal case." In contrast, the "disturbed case" refers to discrete, unanticipated events that disrupt the nominal case system. The disruptive events include the following (with impacts discussed in Section 5.7):

- Formation of a volcano in or near the proposed repository
- Earthquake
- Human intrusion into the proposed repository

Yucca Mountain is in a terrain that has experienced volcanic activity in the geologic past. The rocks in which the repository would be constructed are volcanic in origin. However, scientific studies of

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Features are physical parts of the system important to how the system could perform. Examples include the Ghost Dance Fault and the Topopah Spring stratigraphic unit.

Events are occurrences in time that can affect the performance or behavior of the system. Events tend to happen in short periods in comparison to the period of concern, and they tend to occur at unpredictable times. Examples include a volcanic intrusion or a human intrusion by drilling.

Processes are physical and chemical changes that occur over long periods, tend to be 100-percent likely to occur, and are predictable. Examples include corrosion of the metals in the waste package and dissolving of waste form materials after exposure to water.

the timing, volume, and other aspects of volcanism have concluded that volcanic activity in this area has been waning in the recent geologic past and that the probability of volcanic activity as a repository-disturbing event is low. For completeness, part of the long-term performance analysis is an assessment of the consequences of a small cinder cone formed by a dike (a lava flow) that flowed up through or close to the proposed repository drifts.

In contrast, earthquakes have occurred in the Yucca Mountain geologic region of influence, and are likely to occur in the future. The effects of an earthquake that would be important to postclosure repository performance primarily would result from ground motions rather than from direct offset along a fault, because the waste emplacement areas would be away from block-bounding faults, which are the most likely sites for fault offsets. The primary effect of ground shaking would be to hasten rock fall into the drift. Such rock fall would have the potential to damage the waste package and hasten water intrusion into the waste form.

The analysis treated human intrusion as an event in which part of the contents of a waste package would be released to the water table through the borehole of a well drilled directly through the proposed repository. Providing a verifiable forecast of future human activity is very difficult, if not impossible. The impact of such human intrusion was not included directly in the final presentation of results but was compared to the long-term performance results to determine the potential level of influence. In other words, the probability of human intrusion occurring was not modeled; however, the possible consequences were qualitatively evaluated for a few intrusion scenarios.

5.2.3.6 Nuclear Criticality

A nuclear criticality occurs when sufficient quantities of fissionable materials come together in a precise manner and the required conditions exist to start and sustain a nuclear chain reaction. The waste packages would be designed to prevent a criticality from occurring in one of them. In addition, it is very unlikely that a sufficient quantity of fissionable materials could accumulate outside the waste packages in the precise configuration and with the required conditions to create a criticality. If, somehow, an external criticality were to occur, analyses indicate that it would have only minor effects on repository performance. An explosive criticality is not credible (DOE 1998a, Volume 3, pages 4-92 to 4-99).

5.2.3.7 Atmospheric Radiological Consequences

In addition to the groundwater pathway, the long-term performance analysis evaluated the potential consequences of the release of radioactive gases into the environment. An analysis separate from the groundwater modeling described in the previous sections was used to forecast such consequences. The model used results from the waste-package degradation models to evaluate when packages and fuel cladding would fail and therefore release contained radioactive gases. This model provided input to release and transport estimates for the atmospheric pathway. Section 5.5 contains details of this analysis.

5.2.4 UNCERTAINTY

As with any impact estimate, there is a level of uncertainty associated with the forecast, especially when estimating impacts over thousands of years. *Uncertainty* can be defined as the measure of confidence in the forecast related to determining how a system will operate or respond. The amount of uncertainty associated with an impact estimate is a reflection of several factors, including the following four:

- An understanding of the components of a system (such as human and societal, hydrogeologic, or engineered) and how those components interact. The greater the number of components, the more complex the system, or the lesser capability to measure or understand the system or components produces a greater potential for uncertainty. Similarly, fewer studies or more assumptions produce greater potential for uncertainty.

- The time scale over which estimates are made. Longer time scales for forecasts produce greater potential for uncertainty.
- The available computation and modeling tools. More general computation tools or more assumptions produce greater potential for uncertainty.
- The stability and uniformity (or variability) of the components and system being evaluated. Less stability and uniformity (that is, greater variability) produces a greater potential for uncertainty.

DOE recognizes that uncertainties exist from the onset of an analysis; however, forecasts are valuable in the decisionmaking process because they provide insight based on the best information and scientific judgments available. The following section discusses uncertainties in the context of possible effects on the impact estimates reported in this chapter. The discussion is divided to address:

- Uncertainty associated with societal changes and climate
- Uncertainty associated with currently unavailable data
- Uncertainty associated with models and model parameters

5.2.4.1 Uncertainty Associated with Societal Changes, Climate, and Other Long-Term Phenomena

General guidance on predicting the evolution of society has been provided by the National Academy of Sciences. In its report, *Technical Bases for Yucca Mountain Standards* (National Research Council 1995, all), the Committee on Technical Bases for Yucca Mountain Standards concluded that there is no scientific basis for predicting future human behavior. The study recommends policy decisions that specify the use of default (or reference) scenarios to incorporate future human behaviors in compliance assessment calculations. The analysis in this chapter follows the recommended approach, using as defaults societal conditions as they exist today; as such, it is based on the assumption that populations would remain at their present locations and population densities would remain at their current levels. However, this assumption, while appropriate for estimating impacts for comparison with other proposed actions, is not realistic because it is likely that populations will move and change in size. For example, if populations were to move closer to or increase in size in the Yucca Mountain groundwater hydrology region of influence, the radiation dose and resultant impacts could increase. DOE does not have the means to predict such changes quantitatively with great accuracy; therefore, the analysis does not attempt to quantify the resultant effects on overall impacts. In addition, the analysis does not address the potential benefits from future human activities including improved technology for removing radioactive materials from drinking water or the environment or medical advances such as cures for cancer.

Estimates of future climatic conditions are based on what is known about the past, with consideration given to climate impacts caused by human activities. Calcite in Devils Hole, a fissure in the ground approximately 40 kilometers (25 miles) southeast of Yucca Mountain, provides the best dated record of climate changes over the past 500,000 years. The record shows continual variation, often with very rapid jumps, between cold glacial climates (for the Great Basin, these are called pluvial periods) and warm interglacial climates similar to the present. Fluctuations average 100,000 years in length. Because this basic time scale has been corroborated by other measurements (for example, oxygen-isotope variations in marine sediments), it has been selected as the average climate cycle (DOE 1998a, Volume 3, page 3-8). The past climate cycles were then idealized into a regular cycle of pulses, which were repeated throughout the period of the forecast. This method inherently assumes that the future will repeat the past.

However, while current understanding of the causes of climate change allows some confidence in this approach, a considerable amount of conservatism was built into the models to account for possible climate uncertainties. For example, a large range of water fluxes were used to reflect the wide rainfall variations that could occur over thousands and hundreds of thousands of years. The analysis assumed that the current climate is the driest it will ever be at Yucca Mountain.

5.2.4.2 Uncertainty Associated with Currently Unavailable Data

DOE is planning additional work to help reduce the amount of uncertainty associated with currently unavailable data. The supporting models will be updated to address the principal factors that have been made a high priority in the DOE plan (DOE 1998a, Volume 4, page 2-29). These factors include:

- Drift seepage and percolation to depth
- Effects of heat and excavation on flow
- Dripping onto waste packages
- Chemistry of water on the waste packages
- Integrity of the inner corrosion-resistant waste package barrier
- Integrity of the spent nuclear fuel cladding
- Formation and transport of radionuclide-bearing colloids
- Transport in the unsaturated zone

The planned work in these areas is summarized below. More detailed information about this work and other planned work to address principal factors with lower priority is provided in the technical work plan (DOE 1998a, Volume 4, page 3-1 to 3-58).

Data on percolation and seepage at the drift scale will continue to provide insights on the processes that will control the amount of water that might contact waste packages. Planned work will examine percolation over that part of the proposed repository layout accessed by the cross drift and in geologic layers that will include more of the repository horizon. Plans include the following testing and modeling activities:

- *Excavation of two additional niches and preparation of two fracture/matrix test beds in the cross drift.* Seepage and fracture/matrix interaction tests will be performed in the lower Topopah Spring units that comprise the majority of the potential repository horizon. Planned tests include liquid release tests and long-term tracer injection tests.

- *Perform additional geochemical and isotopic analyses to determine where water has flowed in the past.* Concentrations of chemical components in the rock such as chloride, bromide, and sulfate will be measured, and the results will be used to identify fast paths and travel times. Ongoing analyses of the isotopic ages of fracture-lining minerals will provide information on the history of water movement. These studies show how and when water has moved through the unsaturated zone and reveal characteristics of the water, such as the chemical composition and temperature.

- *Perform a controlled study of percolation from the cross drift to the underlying Exploratory Studies Facility main drift.* The cross drift infiltration experiment in the crossover alcove will provide data on percolation rates through fractured welded tuffs under controlled boundary conditions.

- *Monitor moisture conditions in the Exploratory Studies Facility, including the cross drift.* Moisture monitoring activities in Alcoves 1 and 7 of the Exploratory Studies Facility will continue and monitoring in the cross drift will be established, for the study of moisture balance, ventilation effects, and the movement of water used in construction.

- *Update percolation and seepage models.* Percolation processes have been modeled at two scales: mountain and drift. These models will be updated so the modeled hydrostratigraphy is consistent with recent laboratory and field test data. Models for seepage into drifts will also be updated to encompass field test data and the effects of thermally driven-coupled processes.

The effects of heating on seepage are being investigated in a drift-scale thermal test currently being conducted and by laboratory experiments that will support models for predicting the effects of coupled processes over much longer periods.

5.2.4.3 Uncertainty Associated with Models and Model Parameters

The total system performance model used to assess the impacts from groundwater migration includes a very large number of submodels and requires a large amount of input data to estimate the performance of the system. The model must account for important features of the system, likely events, and processes that would contribute to the release and migration of materials. Because of the long periods simulated, the complexity and variability of a natural system, and several other factors, the performance modeling must deal with a large degree of uncertainty. This section discusses the nature of the uncertainties and how they were accounted for in the analysis and their implication to interpretation of impact results. The *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998a, Volume 3, pages 4-63 to 4-71) contains further details concerning this subject.

5.2.4.3.1 *Variability Versus Uncertainty*

A variable feature, event, or process is one that changes over space or time. Examples include the porosity of the rock mass, the temperature in the repository, and the geochemical environment in the repository drifts. If all information was available, such parameters would be best expressed as known mathematical functions of space and time. In contrast, uncertainty relates to a lack of knowledge regarding a feature, event, or process—one whose properties or future outcome cannot be predicted. Four types of uncertainty are typically considered: value uncertainty, conceptual model uncertainty, numerical model uncertainty, and uncertainty regarding future events. The treatment of a feature, event, or process as purely variable or purely uncertain can lead to different modeling results.

Uncertainty and variability are sometimes related. The exact nature of the variability in a natural system cannot be known because all parts of the system cannot be observed. For example, DOE cannot dig up all the rock in Yucca Mountain and determine that the positioning of the rock layers is exactly as suggested by core sample data. Therefore, there is uncertainty about the properties of the rock at specific locations in the mountain because properties change with distance and it is not known how much they change at any given location. If the variability can be appropriately quantified or measured, a model usually can be developed to include this variability. If the variability cannot be physically quantified or estimated, it should be treated as uncertainty (lack of knowledge). However, the ability to model some types of spatial variability can be limited not only by lack of data but also by the capacity of a computer to complete calculations (for example, if one simulation took weeks or months to complete). In these instances, variability must be simplified in such a way as to be conservative (that is, the simulation would overestimate the impact).

Two basic tools were used in the analysis to deal with uncertainty and variability: alternative conceptual models and probability theory. Alternative conceptual models were used to handle uncertainty in the understanding of a key physical-chemical process controlling system behavior. Probability theory was used to understand the impacts of uncertainty in specific model parameters (that is, would results change if the parameter value was different). In particular, uncertain processes often required different conceptual models. For example, different conceptual models of how water in fractures communicates with water in the smaller pores or the matrix of the rock in the unsaturated zone lead to different flow and transport models. Sometimes conceptual models are not mutually exclusive (for example, both matrix and fracture flow might occur), and sometimes they do not exhaustively cover all possibilities (apparently matrix and fracture flow do cover all possibilities). These examples indicate that the use of alternative conceptual models, while often necessary to characterize some types of uncertainty, is not always as exact as desired.

A process of weighting alternative conceptual models (as described below) was used in the long-term performance assessment to account for uncertainties in conceptual models. The *Monte Carlo* sampling technique was used for handling uncertainty in specific model parameters and for alternative conceptual models that were weighted beforehand with specific probabilities. The method involves random sampling of ranges of likely values, or *distributions*, for all uncertain input parameters. Distributions describe the probability of a particular value in the range. A common type of distribution is the familiar "bell-shaped" curve, also known as *normal distribution*. Parameters in the system performance analysis are described by many different types of distributions appropriate for how the values and their probabilities are understood. Numerous realizations of the repository system behavior were calculated, each based on one set of samples of all the inputs. Each total system realization had an associated probability so that there is some perspective on the likelihood of that set of circumstances occurring. The Monte Carlo method yields a range for any chosen performance measure (for example, peak dose rate to an individual in a given period at a given location) along with a probability for each value in the range. In other words, it gives an estimate of repository performance and determines the possible errors based on the estimate. In this chapter, the impact estimates are expressed as the mean of all the realizations and the 95th-percentile value (that is, the value for which 95 percent of the results were smaller).

5.2.4.3.2 *Weighting of Alternative Conceptual Models*

In some cases, modeling alternatives form a continuum, and sampling from the continuum of assumptions fits naturally in the Monte Carlo framework of sampling from probability distributions. In other cases, the assumptions or models are discrete choices. In particular, some processes are so highly uncertain that there are not enough data to justify developing continuous probability distributions over the postulated ranges of behavior. In such cases, a high degree of sampling is unwarranted, and an analysis often models two or three cases that it assumes to encompass (bound) the likely behavior.

There were two possible approaches to incorporating discrete alternative models in the performance assessment: weighting all models into one comprehensive Monte Carlo simulation (lumping), or keeping the discrete models separate and performing multiple Monte Carlo simulations for each discrete model (splitting). In this analysis, a combination of the two approaches was used. The main results in Section 5.4 were developed using the splitting approach because they were based on a limited range of uncertainty. Based on expert judgment (and to some extent the finite time and resources that could be applied to the analysis effort), the analysis used a best estimate of the more likely ranges of model behavior and parameter ranges. Some alternative models were not included in the analysis, and some parameter ranges of the included models were narrowed. The level of uncertainty included in the model was based on the current level of knowledge regarding the various processes controlling system behavior. In several instances, the range of uncertainty was set quite large, in a conservative manner. Because of this narrowed range of models and parameters, the results are *conditional*, meaning that they depend on certain models and parameters being held constant or having their variance restricted. One such condition is the specific design of the repository and the waste packages in the reference design of this EIS. Another important condition is that the cladding on the spent nuclear fuel can be depended on as a barrier.

Other conditional results were used to characterize the effect of certain assumptions. For example, results are given in this chapter for three thermal load scenarios; Section 5.4.4 describes the result when the fuel cladding was not considered as a barrier. Additional splitting was done to consider such events as human intrusion (Section 5.7.1), volcanic disturbances (Section 5.7.2), and seismic disturbances (Section 5.7.3). The consequences of these types of events are not part of results given in Section 5.4, rather they are reported as added impacts with certain probabilities of occurrence.

5.2.4.3.3 *Uncertainty and the Proposed Action*

The analysis for the Proposed Action encompassed many of the underlying uncertainties. It included some of all four types of uncertainty: value or parameter uncertainty, conceptual model uncertainty, numerical model uncertainty, and future-event uncertainty. Therefore, the results represent a “lumping” approach. Uncertainty not lumped into the modeling, which produced the central results in Section 5.4, was addressed discretely in alternative models, alternative features, and alternative events such as human intrusion. These alternatives were “split” from the nominal results, and their effects on performance are described separately.

5.2.4.3.4 *Uncertainty and Sensitivity*

In addition to accounting for the uncertainty, characteristics of the engineered and natural systems (such as the unsaturated and saturated zones of the groundwater system) that would have the most influence on repository performance also need to be understood. This information helps define *uncertainty* in the context of what would most influence the results. This concept is called *sensitivity analysis*. A number of methods are used to explain the results and quantify sensitivities. Total system performance is a function of sensitivity (if a parameter is varied, how much do the performance measures change) and uncertainty (how much variation of a parameter is reasonable). For example, the long-term performance results could be very sensitive to a certain parameter, but the value for the parameter is exactly known. In the uncertainty analysis techniques described below, that parameter would not be regarded as important. However, many parameters in the analyses do have an associated uncertainty and do become highly important to performance. On the other hand, the level of their ranking can depend on the width of the assigned uncertainty range.

Most of the important parameters with possibly limited uncertainty ranges in the model were examined in alternative models. The alternative models either expand the range of the parameters beyond the expected range of uncertainty or change the weighting of the parameter distribution. For example, this type of analysis was performed for alternative models of seepage (DOE 1998a, Volume 3, pages 5-1 to 5-9) and cladding degradation (DOE 1998a, Volume 3, pages 5-32 to 5-35).

System performance could be sensitive to repository design options, but models and parameters for these various options do not have an assigned uncertainty. Therefore, although they can be important, they do not show up as key parameters based on uncertainty analysis. The determination of the parameters or components that are most important depends on the particular performance measure being used. This point was demonstrated in the 1993 Total System Performance Assessment (Andrews, Dale, and McNeish 1994, all; Wilson et al. 1994, all) and the *Total System Performance Assessment–1995* (TRW 1995b, all). For example, these two analyses showed that the important parameters would be different for 10,000-year peak doses than for 1-million-year peak doses.

There are several techniques for analyzing uncertainties, including the use of qualitative scatter plots where the results (for example, dose rate) are plotted against the input parameters and visually inspected for trends. In addition, performance measures can be plotted against various subsystem outputs or surrogate performance measures (for example, waste package lifetime) to determine if that subsystem or performance surrogate would be important to performance. There are several formal mathematical techniques for analyzing the sets of realizations from a Monte Carlo analysis to extract information about the effects of parameters. Such an analysis determined the principal factors affecting the performance of the reference design.

5.2.4.3.5 *Confidence in the Long-Term Performance Estimates*

As described above, the analysis accounted for the many uncertainties involved. Further, an understanding of the sensitivities of principal factors in the system performance was developed. Table 5-3 lists the principal factors as they relate to repository performance, and relates the factors to model confidence and significance of uncertainty (sensitivity). If there is low confidence in the model (high uncertainty) and high significance, planned research will further refine the model and data (DOE 1998a, Volume 4, Section 3). For example, ongoing research emphasizes transport through the unsaturated zone and the integrity of the inner corrosion-resistant waste package barrier.

Table 5-3. Confidence in the long-term performance of the repository system in relation to groundwater contamination.[a]

Desired attributes of the repository and principal factors associated with the reference design	Confidence in the models to reasonably represent the impacts and processes	Significance of uncertainty to the estimate of performance
Limited water contacting waste package		
Precipitation and infiltration of water into the mountain	High	Medium
Percolation to depth	Medium	Medium
Seepage into drifts	Low	High
Effects of heat and excavation on flow	Low	Medium
Dripping onto waste package	Low	Medium
Humidity and temperature at waste package	Very High	Low
Long waste package lifetime		
Chemistry at waste package	Medium	Medium
Integrity of outer waste package barrier	High	Medium
Integrity of inner waste package barrier	Medium	High
Low rate of release of radionuclides from breached waste package		
Seepage into waste package	Medium	Medium
Integrity of spent fuel cladding	Medium	High
Dissolution of uranium oxide and glass waste form	High	Medium
Solubility of neptunium-237	High	Medium
Formation of radionuclide- bearing colloids	Low	Medium
Transport of radionuclides within and out of waste package	Medium	Medium
Radionuclide concentration reduction during transport between the waste package and the environment		
Transport of radionuclides through the unsaturated zone	Low	High
Transport of radionuclides through the saturated zone	Low	Medium
Dilution from pumping in water supply	Very High	Medium
Biosphere transport and uptake	Very High	Low

a. Source: Adapted from DOE (1998a, Volume 4, Table 2-2, page 2-20).

The general approach to long-term performance analysis in this EIS conforms with international practices, as assured through continued participation in the Performance Assessment Advisory Group of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development in Paris. The Performance Assessment Advisory Group has had the Yucca Mountain Site Characterization Project as a contributing and participating member for many years, and the group has fostered the open discussion of current performance assessment approaches across national boundaries and regulatory boundaries. This practice has allowed the critical evaluation of member nations' performance assessment approaches. A document produced by this group compared more than 10 recent performance assessments, in terms of approach and scope, and made recommendations for the general content of a safety evaluation (OECD 1997, all). This information is being considered in the planning, production, and documentation of ongoing performance assessment work.

In addition, the long-term performance analysis approach in this EIS is generally accepted by the external oversight and internal review groups, including the Nuclear Waste Technical Review Board and the Total System Performance Assessment Peer Review Panel. Nevertheless, these two groups have criticized specific elements of the performance assessment work represented in this EIS, and they have made recommendations in several reports for additional work to support the modeling.

For example, the most recent report of the Total System Performance Assessment Peer Review Panel states that "the overall performance assessment framework and the approach used in developing the TSPA-VA were sound and followed accepted methods," but also includes approximately 145 pages of observations and suggestions for improvements. All of the suggestions are being addressed in the overall planning for the Site Recommendation of 2001 and, if the site is approved, the License Application of 2002. Volume 4 of the Viability Assessment (DOE 1998a, Volume 4, pages 3-1 to 3-68) discusses this planning. The Panel was particularly critical when stating that the report failed to provide a statement of the "probable behavior of the repository" as requested by Congress. The Panel interpreted that requirement to be an impossibly exacting test. The Panel suggested that the Department should move away from seeking predictive certainty and show safety through bounding arguments and conservative designs, as is done in this EIS. The Department, in the context of preparing a performance evaluation that provides for a "reasonable assurance" of safety, generally agrees with the Panel's advice.

The EIS performance assessment represents a "snapshot in time" and ongoing work will help refine that snapshot. In the meantime, DOE believes the performance results of this EIS are conservative estimates, and that work currently in progress or planned will increase confidence in the overall modeling approach.

5.3 Locations for Impact Estimates

Yucca Mountain is in southern Nevada, in the transition area between the Mojave Desert and the Great Basin. It is a semiarid region with linear mountain ranges and intervening valleys, with current rainfall averaging between about 100 and 250 millimeters (4 and 10 inches) a year, sparse vegetation, and a low population. Although there is low infiltration of water through the mountain and no people currently live in the analyzed land withdrawal area, radioactive and chemically toxic materials released from the repository could affect persons living closer to the proposed repository in the distant future. This section describes the regions where possible human health impacts could occur.

Figure 5-3 is a map with arrows showing the general direction of groundwater movement from Yucca Mountain. Shading indicates major areas of groundwater discharge through a combination of springs and evapotranspiration by plants. The general path of water that infiltrates through Yucca Mountain is south toward Lathrop Wells, into and through the area around Death Valley Junction in the lower Amargosa Valley. Natural discharge of groundwater from beneath Yucca Mountain probably occurs farther south at Franklin Lake Playa (Czarnecki 1990, pages 1 to 12), and spring discharge in Death Valley is a possibility (D'Agnese et al. 1997, pages 64 and 69). Although groundwater from the Yucca Mountain vicinity flows near or under Ash Meadows in the volcanic tuff or alluvial aquifers, the surface discharge areas at Ash Meadows and Devils Hole are fed from the carbonate aquifer. While these two aquifers are connected, the carbonate aquifer has a hydraulic head that is 36 meters (120 feet) higher than that of the volcanic or alluvial aquifers. Because of this pressure difference, water from the volcanic aquifer does not flow into the carbonate aquifer; rather, the reverse occurs. Therefore, no contamination from Yucca Mountain could discharge to the surface at Ash Meadows or Devils Hole (TRW 1999h, all). Therefore, radionuclides released from a repository at Yucca Mountain would not appear in the surface discharge at

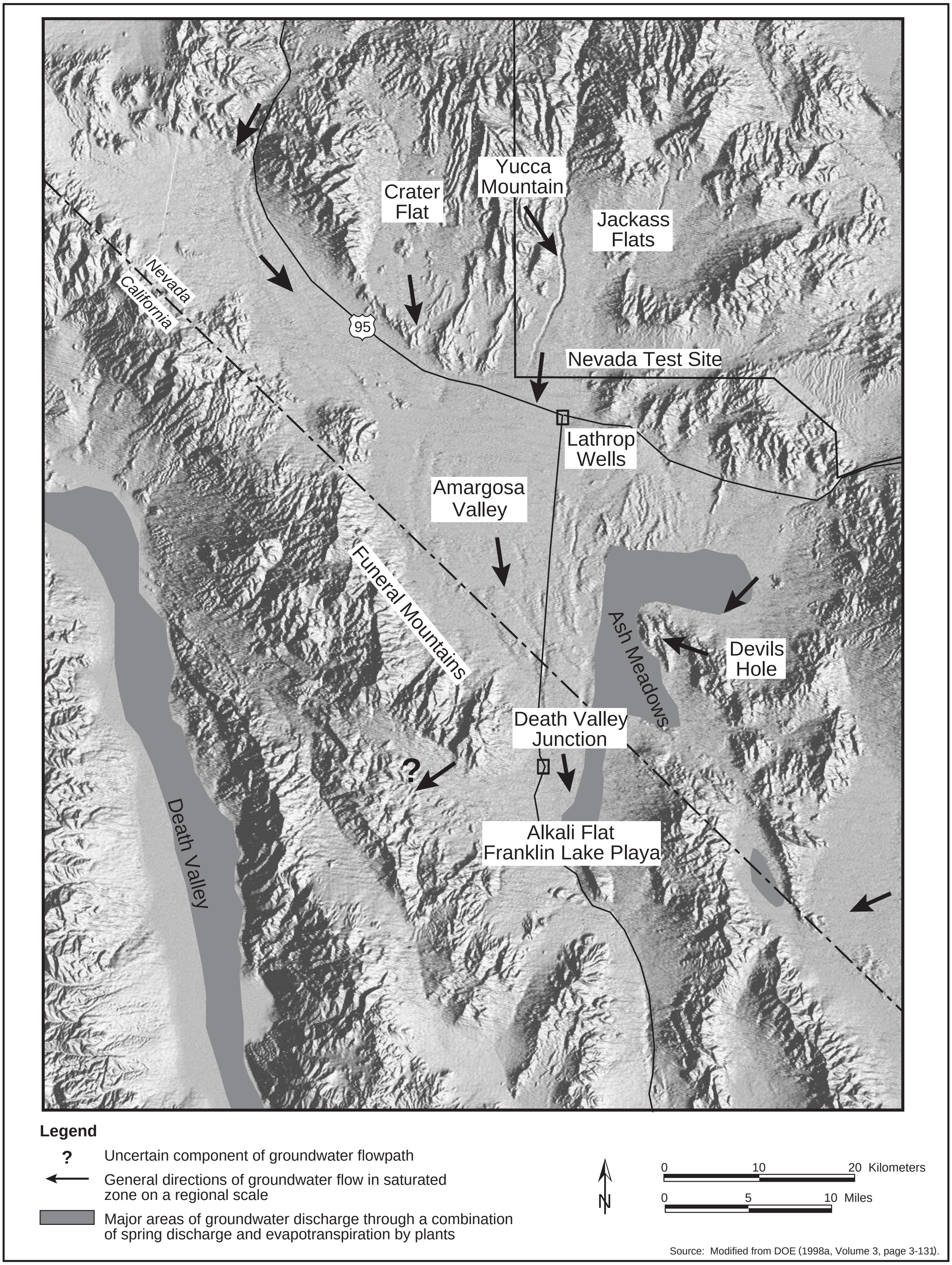

Figure 5-3. Map of the saturated groundwater flow system.

Ash Meadows or Devils Hole. Because there would be no contamination of this discharge water, there would be no human health impacts. Furthermore, there would be no consequences to the endangered Ash Meadows Amargosa pupfish (*Cyprinodon nevadensis mionectes*) or Devils Hole pupfish (*Cyprinodon diabolis*) at those locations.

POPULATION DOSE AND FUTURE POPULATION SIZE

Population dose is a summation of the dose received by individuals in an exposed population (unit of measure is *person-rem*). The population dose depends on the number of people at different locations. If the number of people increases in the future, the population dose estimate would also increase.

Figure 3-21 in Chapter 3 shows the estimated population of 28,000 permanent residents within 80 kilometers (50 miles) of Yucca Mountain in 2000. This map provides the information used to estimate population doses from radionuclides released to the atmosphere from the repository. The atmosphere analysis used an 84-kilometer radius rather than the 80-kilometer (50-mile) radius described in Chapter 3 to include the population of Pahrump.

People who could be exposed in the future to groundwater-borne contaminants would live to the south of Yucca Mountain in the direction of groundwater flow. At present, there are no permanent residences within 5 kilometers (3 miles) to the south of the proposed repository. Groundwater depth is approximately 100 meters (330 feet) at 5 kilometers from Yucca Mountain. Closer to Yucca Mountain, groundwater is at depths greater than 200 meters (660 feet), which imposes economic constraints on agricultural uses of land (DOE 1998a, Volume 3, page 3-150). Population projections for 2000 indicate that the area within 5 kilometers of the proposed repository would remain unpopulated (see Chapter 3, Figure 3-21) (for further discussion on why 2000 population was used, see Section 5.2.4.1). However, because there are sources of potable groundwater, the analysis performed human health impact calculations for a hypothetical person living 5 kilometers south of the proposed repository who uses well water.

At present, very few people live within 20 kilometers (12 miles) to the south of the repository, but there is some land suitable for farming in that region. For example, about eight permanent residents live in the Lathrop Wells community. Therefore, the analysis performed human health impact calculations, based on human ingestion of groundwater from wells in the area, for a person living 20 kilometers south of the proposed repository. The nearest private property in the direction of groundwater flow from the repository site is at the Nevada Test Site boundary approximately 18 kilometers (11 miles) to the south. Environmental consequences at 18 kilometers would not be expected to differ substantially (about 10 percent) from those estimated at 20 kilometers. The closest population center in the Amargosa Valley is about 30 kilometers (19 miles) away. The analysis calculated human health impacts from well water contamination to persons living at that location. Groundwater carrying dissolved radionuclides from the Yucca Mountain Repository could emerge as surface water at Franklin Lake Playa. The analysis also calculated human health impacts from surface-water discharge to a hypothetical person living near Franklin Lake Playa and identified them as impacts at the 80-kilometer (50-mile) or discharge location.

5.4 Waterborne Radiological Consequences

The following sections report potential radiation dose rates, expressed in millirem per year, to an individual living south of Yucca Mountain and using groundwater (characterized as the maximally exposed individual). The analysis converted the dose rate to the probability of contracting a fatal cancer (referred to as a latent cancer fatality) due to exposure to radioactive materials in the water. In addition, the analysis calculated population doses in person-rem for two different periods: for the 70-year lifetime at the time of the peak dose during the first 10,000 years after repository closure, and integrated over the first 10,000 years after repository closure. The analysis also converted the population dose to the expected number of latent cancer fatalities in the population. DOE based the analysis on the inventories discussed in Section 5.1. However, the analysis included the entire carbon-14 inventory of the commercial spent nuclear fuel as a solid in the groundwater release models. Actually, 2 percent of the carbon-14 exists as a gas in the fuel (see Section 5.5). Thus, the groundwater models slightly overestimate (by 2 percent) the potential impacts from carbon-14.

MAXIMALLY EXPOSED INDIVIDUAL

DOE has used *maximally exposed individual* in environmental impact statements to help describe potential radiological impacts to an individual member of the public. Its use follows established DOE National Environmental Policy Act guidance and precedents.

The broad definition of a maximally exposed individual is a hypothetical person who is exposed to environmental contaminants (for example, radiation) in such a way—by a combination of factors including location, lifestyle, dietary habits, and so on—that this individual would be the most highly exposed member of the public. The definition of maximally exposed individual for evaluating postclosure exposures from the groundwater pathway in this EIS is a subset of this broad definition, defined for a narrower set of exposure conditions. In this EIS, the maximally exposed individual is a hypothetical member of the group of adults that would live in the Amargosa Valley after repository closure (no earlier than 2118), with a characteristic range of lifestyle, food consumption, and groundwater usage patterns. More specifically, this individual would grow half of the foods that the individual would consume on the property, irrigate crops and water livestock using groundwater, and would also use groundwater as a drinking water source and to bathe and wash clothes. The EIS analyzed four maximally exposed individuals to represent impacts from use of groundwater at four distances from the repository: 5, 20, 30, and 80 kilometers (3, 12, 19, and 50 miles). The 80-kilometer distance is Franklin Lake Playa.

5.4.1 CONSEQUENCES FROM THE GROUNDWATER EXPOSURE PATHWAY FOR THE HIGH THERMAL LOAD SCENARIO

Four sets of 100 model simulations were run for the high thermal load scenario, one set for each of the four distances from Yucca Mountain. Each simulation used separate sets of sampled uncertainty parameters and generated a dose-rate profile for the 10,000 years following repository closure. Each simulation produced the maximum dose rate (in millirem per year) over the 10,000 years. Table 5-4 lists the mean and the 95th-percentile values of the set of 100 peak dose rates. The table lists the dose rate to the maximally exposed individual and the resultant probability of a latent cancer fatality for that individual. The distance of the receptor from the repository would have a large influence on the dose and the number of latent cancer fatalities.

RADIATION MEASURES

The **millirem** is the unit of radiological dose reported in this analysis. *Milli* means one one-thousandth. A *rem* (Roentgen Equivalent in Man) is the amount of ionizing radiation required to produce the same biological effect in a person as 1 roentgen of high-penetration X-rays. A **roentgen** is a unit of measure of X-ray or gamma-ray radiation exposure discussed in terms of the amount of energy transferred to a unit mass of air. One roentgen corresponds to the absorption of 87.7 ergs (6.5×10^{-6} foot-pound) per gram of air.

Ninety-five percent of the calculated dose rates for the maximally exposed individual at 5 kilometers (3 miles) would be below 1.3 millirem per year and would have an associated lifetime probability of a latent fatal cancer of 0.000044. For comparison purposes, the background radiation level from environmental sources in the United States is approximately 300 millirem per year (NCRP 1987, page 14), corresponding to an individual lifetime probability of contracting a latent cancer fatality of about 0.001.

Population doses were calculated based on the dose rates in Table 5-4. The population size was based on the population numbers in Figure 3-21 in Chapter 3 of this EIS. For these calculations, the analysis assumed that no one would be exposed at 5 kilometers (3 miles); eight people would be exposed at about 20 kilometers (12 miles); 1,126 people would be exposed at about 30 kilometers (19 miles); and 13 people would be exposed at about 80 kilometers (50 miles). Thus, approximately 1,150 people would be exposed to contaminated groundwater. This stylized population dose analysis assumes that people would continue to live in the locations being used at present. This assumption is consistent with the recommendation made by the National Academy of Sciences (National Research Council 1995, all) because it is impossible to make accurate predictions of future lifestyles and residence locations.

Table 5-4. Consequences for a maximally exposed individual from groundwater releases of radionuclides during 10,000 years after repository closure for the high thermal load scenario.

	Mean consequence[b]		95th-percentile consequence[c]	
MEI[a]	Peak dose rate (millirem/year)[d]	Probability of an LCF[e]	Peak dose rate (millirem/year)[d]	Probability of an LCF
At 5 kilometers[f]	3.2×10^{-1}	1.1×10^{-5}	1.3	4.4×10^{-5}
At 20 kilometers	2.2×10^{-1}	7.6×10^{-6}	5.8×10^{-1}	2.0×10^{-5}
At 30 kilometers	1.2×10^{-1}	4.2×10^{-6}	2.8×10^{-1}	1.0×10^{-5}
At discharge location[g]	3.0×10^{-2}	1.1×10^{-6}	2.9×10^{-3}	1.0×10^{-7}

a. MEI = maximally exposed individual.
b. Based on four sets, one for each distance of 100 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. All peaks occur at or near 10,000 years, indicating that the dose rate would still be rising at the end of the simulation period.
e. LCF = latent cancer fatality; incremental lifetime (70 years) risk of contracting a fatal cancer for individuals, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).
f. To convert kilometers to miles, multiply by 0.62137.
g. 80 kilometers at Franklin Lake Playa.

Table 5-5 lists the population consequences associated with the results given in Table 5-4. The values in Table 5-5 include a scaling factor for water use. The performance assessment transport model calculated the dose rates for the maximally exposed individual assuming dissolved radionuclides would mix only in water that flowed through the unsaturated zone of Yucca Mountain with no further mixing in the saturated zone aquifer. Infiltration through the Yucca Mountain Repository accounts for only about 27,000 cubic meters (22 acre-feet) of water per year (see Appendix I, Section I.4.5.3). This compares to an annual water use in the Amargosa Valley of about 17.3 million cubic meters (14,000 acre-feet) (see Table 3-11). The analysis diluted the concentration of the nuclides in the 27,000 cubic meters of water throughout the 17.3 million cubic meters of water prior to calculating the population dose.

Table 5-5. Population consequences from groundwater releases of radionuclides during 10,000 years after repository closure for the high thermal load scenario.

	Mean consequence[a]		95th-percentile consequence[b]	
Case	Population dose (person-rem)	Population LCF[c]	Population dose (person-rem)	Population LCF
Peak 70-year lifetime	1.5×10^{-2}	7.5×10^{-6}	3.5×10^{-2}	1.8×10^{-5}
Integrated over 10,000 years	3.7×10^{-1}	1.8×10^{-4}	1.2	5.8×10^{-4}

a. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
c. LCF = latent cancer fatality; expected number of cancer fatalities for populations, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).

The consequences listed in Table 5-4 are small because the analysis computed that most of the waste packages would last longer than 10,000 years. The inner layer of the waste package would have a very low corrosion rate, but there is a high degree of uncertainty in the value of the average corrosion rate. Model simulations estimated that some of the waste packages would fail within 10,000 years but some would last for more than 1 million years after repository closure. The analysis accounted for premature failures due to manufacturing defects or mishandling during emplacement. It assumed that these failures (called *juvenile failures*) would occur exactly 1,000 years after repository closure. Based on a study of industrial experience of manufacturing and handling (DOE 1998a, Volume 3, page 3-81), the estimated rate of juvenile failures would be very low. If juvenile failures did not occur, the mean consequences listed in Table 5-4 would decrease by about 2 percent, while the 95th-percentile consequences would be unchanged.

The radionuclides that would contribute the most to individual dose in 10,000 years would be iodine-129, technetium-99, and carbon-14 dissolved in groundwater. For example, the mean consequence at 30 kilometers (19 miles) has iodine-129 contributing 59 percent of the dose rate, technetium-99 contributing 36 percent, and carbon-14 contributing 4 percent. This analysis assumed that 2 percent of the carbon-14 migrated as gas in the form of carbon dioxide (see Section 5.5 for more details). The groundwater modeling conservatively ensures that all of the carbon-14 migrates into the water part.

The times that the peak dose rates listed in Table 5-4 would occur are close to 10,000 years and still would be less than 1.0 millirem per year (Figure 5-4). This indicates that the dose rate would be rising at the end of the 10,000-year simulation period. The peak doses before 10,000 years would be due to the relatively quick dissolution and transport of technetium-99, iodine-129, and carbon-14 from failed waste packages. Table 5-6 lists the same type of results as those in Table 5-4, but the timeframe is 1 million years after repository closure. A small fraction of the model simulations for the 80-kilometer (50-mile) distance have an increasing dose rate at the 1-million-year mark. The dose rates that would be increasing after 1 million years were usually among the smallest of the entire set of 100 results. The simulations were ended after 1 million years largely because further radioactive decay would decrease dose rates even for very long-lived radionuclides. The peak dose rate usually coincided with the occurrence of a wetter climate period.

Table 5-6. Maximally exposed individual doses from groundwater releases of radionuclides during 1 million years after repository closure for the high thermal load scenario.

	Mean[b]		95th-percentile[c]	
MEI[a]	Peak dose rate (millirem/year)	Time of peak (years)	Peak dose rate (millirem/year)	Time of peak (years)
At 5 kilometers[d]	1,400	792,000	9,100	320,000
At 20 kilometers	260	336,000	1,400	364,000
At 30 kilometers	150	418,000	820	416,000
At discharge location[e]	50	818,000	190	716,000

a. MEI = maximally exposed individual.
b. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. To convert kilometers to miles, multiply by 0.62137.
e. 80 kilometers at Franklin Lake Playa.

The radionuclides that would contribute the most to the peak dose rate in 1 million years would be neptunium-237 and plutonium-242. The mean dose at 30 kilometers (19 miles) showed neptunium-237 contributing 92 percent of the dose rate, plutonium-242 contributing 5 percent, plutonium-239 contributing 1 percent, and uranium-234 contributing 1 percent. The plutonium isotopes contributing to dose were due to colloidal transport of plutonium, not transport of plutonium as a dissolved element in

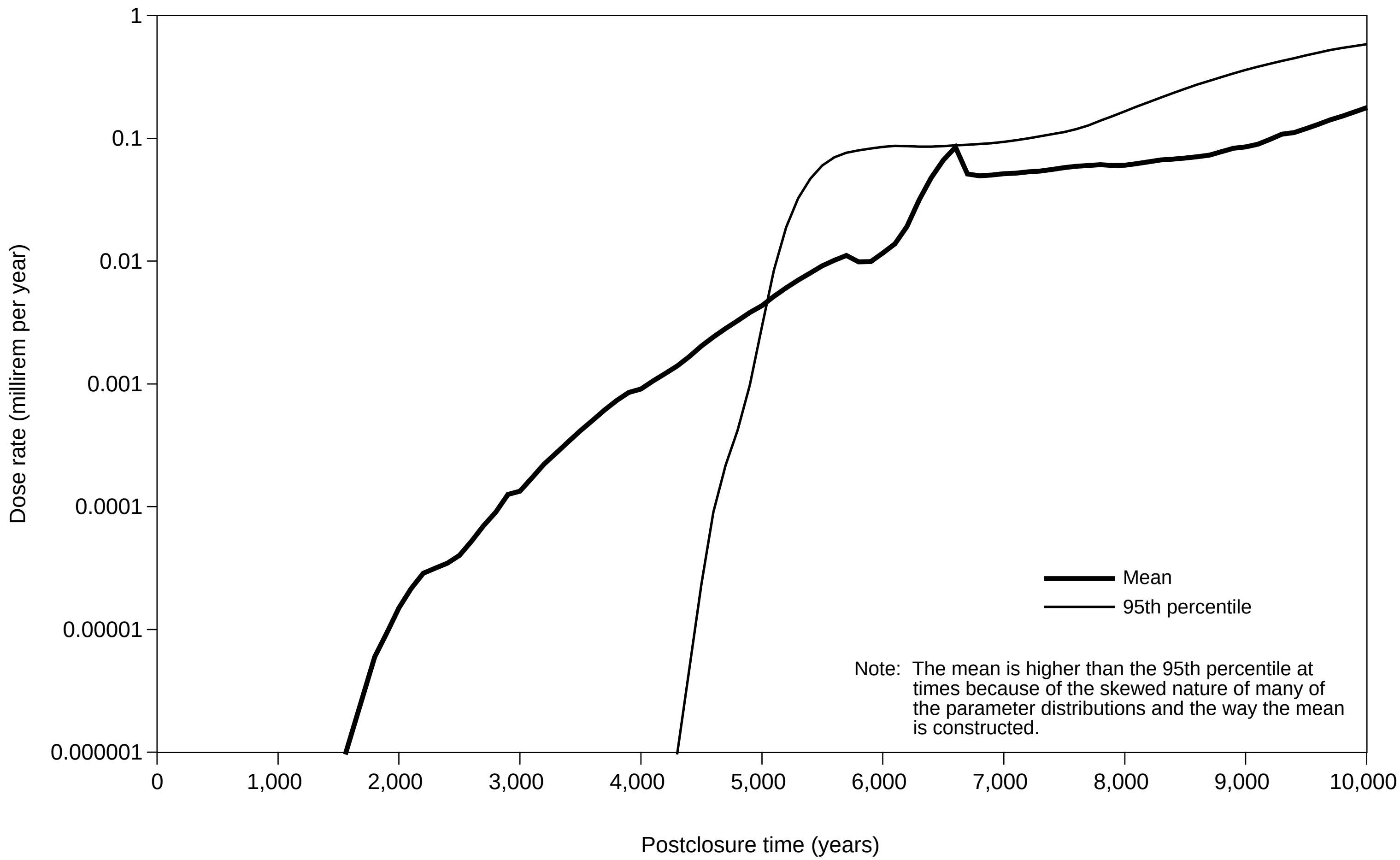

Figure 5-4. 10,000-year history of dose at 20 kilometers (12 miles) from the repository for the high thermal load scenario.

groundwater. In the construct of the mean, the time of occurrence of the peak dose can be very sensitive and might change abruptly to different times. This occurs because the time plot of the mean curve is relatively flat with occasional sudden peaks. Thus, the times of the peaks might not seem to be following a pattern. Since the mean does not represent any actual trial in the 100 simulations, the times of occurrence might not have much meaning. Similar effects will be noted in some of the results for the other thermal loads.

Table 5-7 lists peak radionuclide concentrations (amount of radionuclide in a volume of water) at four human exposure locations for the high thermal load scenario for the first 10,000 years after repository closure. It also lists the gross alpha-particle activity and the drinking water dose (the dose resulting from direct ingestion of the water at the given concentration). The gross alpha concentration is an analytical measurement used in monitoring the radiological quality of drinking water contamination levels. It represents the total amount of radioactivity from radionuclides with radioactivity due to the emission of alpha particles. (An alpha particle is a positively charged particle emitted by certain radioactive material, made up of two neutrons and two protons or the equivalent of a helium nuclei.) The consequences at each distance come from a different set of 100 simulations. As a result, some model predictions show fluctuations in the relative concentration of specific nuclides can occur at different distances. For example, the modeled concentration of carbon-14 for the 95th-percentile consequence would be higher at 30 kilometers (19 miles) than at 20 kilometers (12 miles), although the total modeled dose is about 2 times higher at 20 kilometers than at 30 kilometers (see Table 5-4).

Table 5-7. Peak radionuclide concentrations (picocuries per liter) in water and associated annual drinking water dose at human exposure distances for 10,000 years after repository closure for the high thermal load scenario.

	Mean consequence[a,b]				95th-percentile consequence[c]			
	Distance (kilometers)[d]				Distance (kilometers)			
Radionuclide	5	20	30	80	5	20	30	80
Carbon-14	2.1	1.1	6.4×10^{-1}	1.8×10^{-3}	8.2	1.8	3.1	2.7×10^{-2}
Iodine-129	1.3×10^{-1}	7.0×10^{-2}	4.1×10^{-2}	1.0×10^{-4}	5.7×10^{-1}	1.2×10^{-1}	2.0×10^{-1}	2.0×10^{-3}
Neptunium-237	6.4×10^{-4}	2.3×10^{-8}	6.1×10^{-15}	5.6×10^{-24}	6.5×10^{-4}	1.3×10^{-17}	1.3×10^{-23}	4.2×10^{-24}
Protactinium-231	2.9×10^{-12}	4.7×10^{-26}	4.7×10^{-26}	2.4×10^{-26}	2.0×10^{-24}	2.0×10^{-24}	1.3×10^{-26}	1.3×10^{-26}
Plutonium-239	5.7×10^{-5}	5.6×10^{-9}	4.8×10^{-10}	1.3×10^{-13}	1.8×10^{-9}	2.4×10^{-11}	8.1×10^{-10}	2.1×10^{-17}
Plutonium-242	3.5×10^{-7}	2.9×10^{-11}	3.1×10^{-12}	8.9×10^{-16}	1.0×10^{-11}	7.8×10^{-14}	4.5×10^{-12}	1.5×10^{-19}
Selenium-79	3.8×10^{-1}	8.2×10^{-4}	2.4×10^{-6}	1.4×10^{-21}	1.7×10^{0}	1.4×10^{-18}	6.8×10^{-19}	3.2×10^{-21}
Technetium-99	4.5×10^{1}	3.0×10^{1}	1.0×10^{1}	3.3×10^{-2}	3.9×10^{2}	8.4×10^{1}	1.3×10^{2}	8.3×10^{-1}
Uranium-234	8.8×10^{-5}	9.0×10^{-10}	1.2×10^{-16}	2.9×10^{-23}	8.3×10^{-5}	4.4×10^{-23}	3.7×10^{-23}	3.7×10^{-23}
Gross alpha[e]	7.0×10^{-4}	2.9×10^{-8}	4.8×10^{-10}	1.3×10^{-13}	6.5×10^{-4}	2.4×10^{-11}	8.1×10^{-10}	2.1×10^{-17}
Annual drinking water dose (millirem)	8.1×10^{-2}	4.8×10^{-2}	2.0×10^{-2}	5.9×10^{-5}	5.4×10^{-1}	1.2×10^{-1}	1.8×10^{-1}	1.3×10^{-3}

a. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. The concentrations for the mean and 95th-percentile consequences are the concentrations that yielded the mean and 95th-percentile doses reported in Table 5-4.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. To convert kilometers to miles, multiply by 0.62137.
e. By regulatory convention, the gross alpha-particle radiation does not include uranium.

The annual drinking water doses in Table 5-7 (and below in Tables 5-11 and 5-15) are based on the assumption that an individual drinks exactly 2 liters (about 0.5 gallon) of water each day. Ingestion dose conversion factors were taken from Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion and Ingestion (Eckerman, Wolbarst, and Richardson 1988, pages 155 to 179). The full-pathway dose rates calculated in this chapter using biosphere dose conversion factors were based on food and water intake values for a reference adult derived from an extensive survey of residents of the Amargosa Valley (DOE 1998a, Volume 3, pages 3-151 to 3-155).

Thus, the drinking water dose reported in Table 5-7 might be different from the portion of the total dose reported in Table 5-4 that is due to water consumption. For both the mean and 95th-percentile consequences, the gross alpha activity would be much lower than the 15 picocuries per liter specified as the attainment limit for drinking water for community water systems [40 CFR Part 141, Subpart B, Section 141.15(b)]. The dose rates from drinking liters (0.5 gallon) of water a day would also be below the 4-millirem-per-year limit for community water systems [40 CFR Part 141, Subpart B, Section 141.16(a)].

5.4.2 CONSEQUENCES FROM THE GROUNDWATER EXPOSURE PATHWAY FOR THE INTERMEDIATE THERMAL LOAD SCENARIO

Under the intermediate thermal load scenario, DOE would place the same inventory of materials in the repository as under the high thermal load scenario. This scenario would differ from the high thermal load scenario by increased spacing between the emplacement drifts. Thus, the radioactive and chemically hazardous material would be spread out over about 4.3 square kilometers (1,100 acres) rather than the approximately 3 square kilometers (740 acres) for the high thermal load scenario.

Table 5-8 lists the mean and 95th-percentile consequences of the set of 100 peak dose rates computed for this scenario. It also lists the dose to the maximally exposed individual and the resultant probability of a latent cancer fatality. The radionuclides contributing the most to the individual dose in 10,000 years would be technetium-99, iodine-129, and carbon-14. Figure 5-5 shows how peak dose increases over the first 10,000 years at the 20-kilometer (12-mile) distance and would remain below 1 millirem per year during this period.

Table 5-8. Consequences for a maximally exposed individual from groundwater releases of radionuclides during 10,000 years after repository closure for the intermediate thermal load scenario.

	Mean consequence[b]		95th-percentile consequence[c]	
MEI[a]	Peak dose rate (millirem/year)[d]	Probability of an LCF[e]	Peak dose rate (millirem/year)[d]	Probability of an LCF
At 5 kilometers[f]	1.4×10^{-1}	4.9×10^{-6}	1.1	3.9×10^{-5}
At 20 kilometers	1.3×10^{-1}	4.5×10^{-6}	5.8×10^{-1}	2.0×10^{-5}
At 30 kilometers	4.6×10^{-2}	1.6×10^{-6}	1.1×10^{-1}	3.9×10^{-6}
At discharge location[g]	2.9×10^{-3}	1.0×10^{-7}	1.9×10^{-3}	6.6×10^{-8}

a. MEI = maximally exposed individual.
b. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. All peaks occur at or near 10,000 years, indicating that the dose rate would still be rising at the end of the simulation period.
e. LCF = latent cancer fatality; incremental lifetime (70 years) risk of contracting a fatal cancer for individuals, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).
f. To convert kilometers to miles, multiply by 0.62137.
g. 80 kilometers at Franklin Lake Playa.

Table 5-9 lists the population consequences for the intermediate thermal load scenario. The scaling factor for changing the dose rate for the maximally exposed individual into a dose rate for a member of the population was computed by diluting the approximately 31,000 cubic meters (25 acre-feet) of water infiltrating through the Yucca Mountain Repository (see Appendix I, Section I.4.5.3) by the annual water use in the Amargosa Valley of about 17.3 million cubic meters (14,000 acre-feet).

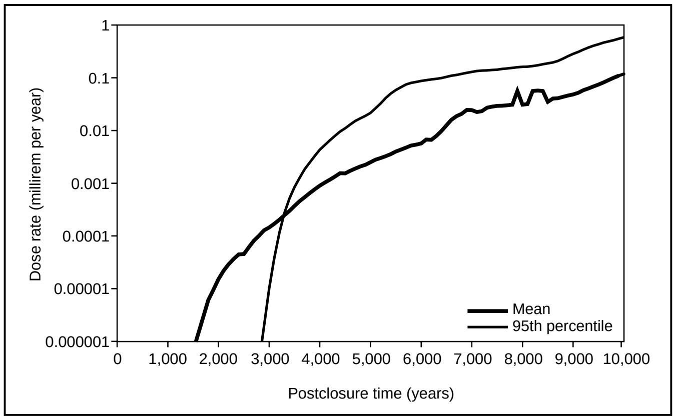

Figure 5-5. 10,000-year history of dose at 20 kilometers (12 miles) from the repository for the intermediate thermal load scenario.

Table 5-9. Population consequences from groundwater releases of radionuclides during 10,000 years after repository closure for the intermediate thermal load scenario.

	Mean consequence[a]		95th-percentile consequence[b]	
Case	Population dose (person-rem)	Population LCF[c]	Population dose (person-rem)	Population LCF
Peak 70-year lifetime	6.6×10^{-3}	3.3×10^{-6}	1.7×10^{-2}	8.3×10^{-6}
Integrated over 10,000 years	1.3×10^{-1}	6.7×10^{-5}	3.6×10^{-1}	1.8×10^{-4}

a. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
c. LCF = latent cancer fatality; expected number of cancer fatalities for populations, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).

Table 5-10 lists results for peak consequences for the 1-million-year period. The radionuclides that would contribute the most to the peak dose rate would be neptunium-237 and plutonium-242. As with the 10,000-year case, there would be no meaningful trend due to thermal load in a comparison of this table to the similar table for higher thermal load scenarios.

Table 5-10. Maximally exposed individual doses from groundwater releases of radionuclides during 1 million years after repository closure for the intermediate thermal load scenario.

	Mean[b]		95th-percentile[c]	
MEI[a]	Peak dose rate (millirem/year)	Time of peak (years)	Peak dose rate (millirem/year)	Time of peak (years)
At 5 kilometers[d]	470	296,000	2,800	320,000
At 20 kilometers	170	804,000	900	712,000
At 30 kilometers	90	418,000	500	932,000
At discharge location[e]	30	872,000	120	702,000

a. MEI = maximally exposed individual.
b. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. To convert kilometers to miles, multiply by 0.62137.
e. 80 kilometers at Franklin Lake Playa

Table 5-11 lists peak radionuclide concentrations in water at four human exposure locations for the intermediate thermal load scenario. The peak concentrations would be from the first 10,000 years after

Table 5-11. Peak radionuclide concentrations (picocuries per liter) in water and associated annual drinking water dose at human exposure distances for 10,000 years after repository closure for the intermediate thermal load scenario.

	Mean consequence[a,b]				95th-percentile consequence[c]			
	Distance (kilometers)[d]				Distance (kilometers)			
Radionuclide	5	20	30	80	5	20	30	80
Carbon-14	1.2	1.1	4.4×10^{-1}	1.6×10^{-2}	9.6	5.9	6.7×10^{-1}	4.1×10^{-2}
Iodine-129	8.0×10^{-2}	5.5×10^{-2}	2.9×10^{-2}	1.1×10^{-3}	7.2×10^{-1}	4.3×10^{-1}	4.8×10^{-2}	2.8×10^{-3}
Neptunium-237	9.1×10^{-5}	8.0×10^{-9}	7.5×10^{-16}	2.2×10^{-23}	1.3×10^{-6}	4.2×10^{-14}	5.1×10^{-22}	2.4×10^{-24}
Protactinium-231	1.5×10^{-14}	5.0×10^{-26}	3.8×10^{-26}	3.8×10^{-26}	1.2×10^{-26}	1.6×10^{-24}	1.6×10^{-24}	7.6×10^{-27}
Plutonium-239	6.9×10^{-6}	3.2×10^{-9}	2.4×10^{-10}	7.0×10^{-13}	6.3×10^{-10}	3.0×10^{-10}	2.7×10^{-12}	2.5×10^{-11}
Plutonium-242	4.8×10^{-8}	2.2×10^{-11}	1.4×10^{-12}	4.8×10^{-15}	3.5×10^{-12}	1.8×10^{-12}	9.3×10^{-15}	1.7×10^{-13}
Selenium-79	9.4×10^{-2}	4.3×10^{-4}	2.6×10^{-6}	2.0×10^{-21}	5.0×10^{-1}	1.8×10^{-18}	1.3×10^{-18}	3.1×10^{-21}
Technetium-99	2.1×10^{1}	1.7×10^{1}	4.5	3.7×10^{-1}	4.3×10^{2}	1.8×10^{2}	1.7×10^{1}	1.1
Uranium-234	1.9×10^{-5}	4.0×10^{-11}	7.8×10^{-17}	2.9×10^{-23}	1.3×10^{-7}	6.3×10^{-16}	2.9×10^{-23}	2.1×10^{-23}
Gross alpha[e]	9.8×10^{-5}	1.1×10^{-8}	2.4×10^{-10}	7.0×10^{-13}	1.3×10^{-6}	3.1×10^{-10}	2.7×10^{-12}	2.5×10^{-11}
Annual drinking water dose (millirem)	4.1×10^{-2}	3.1×10^{-2}	1.1×10^{-2}	6.5×10^{-4}	6.2×10^{-1}	2.9×10^{-1}	2.9×10^{-2}	1.8×10^{-3}

a. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. The concentrations for the mean and 95th-percentile consequences are the concentrations that yielded the mean and 95th-percentile doses listed in Table 5-8.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. To convert kilometers to miles, multiply by 0.62137.
e. By regulatory convention, the gross alpha does not include uranium.

repository closure. The table also lists the gross alpha-particle activity (excluding uranium). The drinking water dose is associated with drinking exactly 2 liters (approximately 0.5 gallon) of water each day. For both the mean and 95th-percentile consequences, the gross alpha activity would be much lower than the 15 picocuries per liter specified as the attainment limit for drinking water for community water systems [40 CFR Part 141 Subpart 15(a)]. The dose rates from drinking 2 liters (0.5 gallon) of water a day would also be below the 4-millirem-per-year limit for community water systems [40 CFR Part 141 Subpart 16(a)].

5.4.3 CONSEQUENCES FROM THE GROUNDWATER EXPOSURE PATHWAY FOR THE LOW THERMAL LOAD SCENARIO

Under the low thermal load scenario, the same inventory of materials would be placed in the repository as under the high thermal load scenario. This scenario would differ from the high thermal load scenario by increased spacing between the emplacement drifts and increased spacing between waste packages in the drifts. Thus, the radioactive and chemically hazardous contamination would be spread over about 10 square kilometers (2,500 acres) rather than the approximately 3 square kilometers (740 acres) used for the high thermal load scenario.

Table 5-12 lists the mean and 95th-percentile consequences of the set of 100 peak dose rates computed for the low thermal load scenario. It also lists the dose to the maximally exposed individual and the resultant probability of a latent cancer fatality. The radionuclides contributing the most to the individual dose in 10,000 years would be iodine-129, technetium-99, and carbon-14. Figure 5-6 shows how peak dose increases over the first 10,000 years at the 20-kilometer (12-mile) distance and would remain at or below 0.1 millirem per year during that time.

Table 5-12. Consequences for a maximally exposed individual from groundwater releases of radionuclides during 10,000 years after repository closure for the low thermal load scenario.

	Mean consequence[b]		95th-percentile consequence[c]	
MEI[a]	Peak dose rate (millirem/year)[d]	Probability of an LCF[e]	Peak dose rate (millirem/year)[d]	Probability of an LCF
At 5 kilometers[f]	1.3×10^{-1}	4.7×10^{-6}	1.6×10^{-1}	5.6×10^{-6}
At 20 kilometers	5.9×10^{-2}	2.1×10^{-6}	6.1×10^{-2}	2.1×10^{-6}
At 30 kilometers	4.0×10^{-2}	1.4×10^{-6}	2.3×10^{-2}	8.1×10^{-7}
At discharge location[g]	5.3×10^{-4}	1.9×10^{-8}	1.9×10^{-3}	6.6×10^{-8}

a. MEI = maximally exposed individual.
b. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. All peaks occur at or near 10,000 years, indicating that the dose rate would still be rising at the end of the simulation period.
e. LCF = latent cancer fatality; incremental lifetime (70 years) risk of contracting a fatal cancer for individuals, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).
f. To convert kilometers to miles, multiply by 0.62137.
g. 80 kilometers at Franklin Lake Playa.

Table 5-13 lists the population doses associated with the low thermal load scenario. The scaling factor for changing the dose rate for the maximally exposed individual into a dose rate for a member of the population was computed by diluting 57,000 cubic meters (46 acre-feet) of water infiltrating through the repository (see Section I.4.5.3) by the annual water use in the Amargosa Valley of about 17.3 million cubic meters (14,000 acre-feet). The repository infiltration rate would not increase in proportion to the decreased thermal load because, as the repository expanded, DOE would use additional areas where the infiltration rates would be different than those for the repository areas under the high thermal load scenario.

Table 5-13. Population consequences from groundwater releases of radionuclides during 10,000 years after repository closure for the low thermal load scenario.

	Mean consequence[a]		95th-percentile consequence[b]	
Case	Population dose (person-rem)	Population LCF[c]	Population dose (person-rem)	Population LCF
Peak 70-year lifetime	1.1×10^{-2}	5.3×10^{-6}	6.2×10^{-3}	3.1×10^{-6}
Integrated over 10,000 years	2.7×10^{-1}	1.3×10^{-4}	1.2×10^{-1}	6.0×10^{-5}

a. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
c. LCF = latent cancer fatality; expected number of cancer fatalities for populations, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).

Table 5-14 lists the same type of results as those in Table 5-12, but the interval is 1 million years after repository closure. The radionuclides that would contribute the most to the peak dose rate would be neptunium-237, plutonium-242, and plutonium-239. As with the 10,000-year case, this table indicates no meaningful trend due to thermal load in comparison to the similar table for higher thermal load scenarios.

Table 5-15 lists peak radionuclide concentrations in water at four human exposure locations for the low thermal load scenario for the 10,000-year period. It also lists the gross alpha particle activity (excluding uranium). For the mean and 95th-percentile consequences, the gross alpha activity would be much lower than 15 picocuries per liter at all distances. The dose rates associated with drinking exactly 2 liters (0.5 gallon) of water each day are provided. As with the other results in this section, this table indicates no meaningful trend due to thermal load in comparison to the similar table for higher thermal load scenarios (Table 5-7).

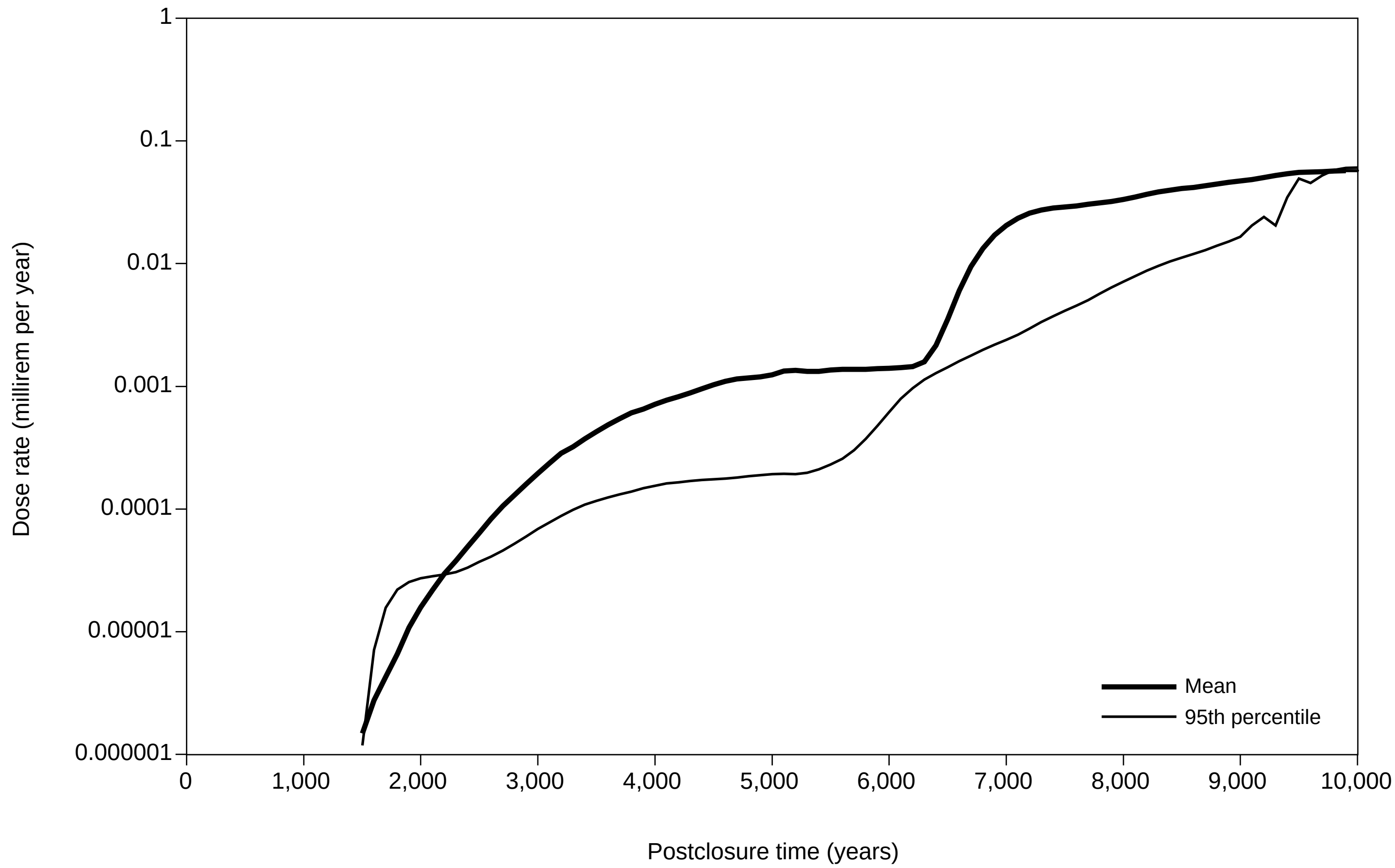

Figure 5-6. Peak dose increases over the first 10,000 years at 20 kilometers (12 miles) from the repository.

Table 5-14. Maximally exposed individual doses from groundwater releases of radionuclides during 1 million years after repository closure for the low thermal load scenario.

	Mean[b]		95th-percentile[c]	
MEI[a]	Peak dose rate (millirem/year)	Time of peak (years)	Peak dose rate (millirem/year)	Time of peak (years)
At 5 kilometers[d]	630	296,000	3,600	320,000
At 20 kilometers	160	804,000	860	334,000
At 30 kilometers	70	400,000	360	308,000
At discharge location[e]	40	824,000	160	726,000

a. MEI = maximally exposed individual.
b. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. To convert kilometers to miles, multiply by 0.62137.
e. 80 kilometers at Franklin Lake Playa.

Table 5-15. Peak radionuclide concentrations (picocuries per liter) in water and associated annual drinking water dose at human exposure distances for 10,000 years after repository closure for the low thermal load scenario.

	Mean consequence[a,b]				95th-percentile consequence[c]			
	Distance (kilometers)[d]				Distance (kilometers)			
Radionuclide	5	20	30	80	5	20	30	80
Carbon-14	1.6	7.9×10^{-1}	4.0×10^{-1}	6.7×10^{-3}	5.6	5.9	2.1×10^{-1}	3.1×10^{-2}
Iodine-129	1.0×10^{-1}	5.0×10^{-2}	2.3×10^{-2}	4.8×10^{-4}	4.0×10^{-1}	1.5×10^{-1}	1.8×10^{-25}	2.4×10^{-3}
Neptunium-237	7.3×10^{-4}	9.3×10^{-12}	2.2×10^{-16}	9.1×10^{-23}	1.4×10^{-6}	4.0×10^{-12}	7.1×10^{-25}	7.1×10^{-25}
Protactinium-231	1.4×10^{-16}	2.6×10^{-24}	7.8×10^{-26}	7.9×10^{-26}	1.6×10^{-16}	7.7×10^{-27}	2.2×10^{-27}	2.2×10^{-27}
Plutonium-239	9.4×10^{-5}	2.4×10^{-9}	1.1×10^{-9}	6.5×10^{-13}	2.5×10^{-13}	7.7×10^{-16}	4.0×10^{-14}	7.7×10^{-13}
Plutonium-242	6.9×10^{-7}	1.6×10^{-11}	5.5×10^{-12}	4.5×10^{-15}	3.2×10^{-16}	4.3×10^{-18}	2.8×10^{-16}	5.5×10^{-15}
Selenium-79	2.7×10^{-1}	4.4×10^{-6}	8.9×10^{-12}	7.8×10^{-22}	3.2	1.8×10^{-7}	1.7×10^{-21}	1.6×10^{-20}
Technetium-99	1.7×10^{1}	7.3	4.5	7.2×10^{-2}	1.9	1.4×10^{1}	6.3	3.4×10^{-1}
Uranium-234	3.1×10^{-6}	1.5×10^{-12}	4.1×10^{-16}	1.5×10^{-23}	2.0×10^{-7}	6.7×10^{-11}	6.2×10^{-24}	6.2×10^{-24}
Gross alpha[e]	8.2×10^{-4}	2.4×10^{-9}	1.1×10^{-9}	6.6×10^{-13}	1.4×10^{-6}	4.0×10^{-12}	4.0×10^{-14}	7.7×10^{-13}
Annual drinking water dose (millirem)	4.4×10^{-2}	1.9×10^{-2}	1.0×10^{-2}	1.8×10^{-4}	9.5×10^{-2}	5.3×10^{-2}	7.0×10^{-3}	9.1×10^{-4}

a. Based on four sets, one for each distance, of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. The concentrations for the mean and 95th-percentile consequences would be the concentrations that yielded the mean and 95th-percentile doses reported in Table 5-12.
c. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
d. To convert kilometers to miles, multiply by 0.62137.
e. By regulatory convention, the gross alpha does not include uranium.

5.4.4 SENSITIVITY STUDY ON THE FUEL CLADDING MODEL

The analysis assumed that the zirconium alloy cladding on about 0.1 percent of the fuel rods in commercial spent nuclear fuel would fail before the fuel was placed in the repository. This failure rate is two times higher than that reflected in data reported by the Electric Power Research Institute (TRW 1998k, pages 6-25 to 6-27). A modeling assumption underlying the groundwater-based consequences described in Sections 5.4.1 through 5.4.3 is that the intact cladding on the spent fuel rods would be very resistant to corrosion. Rothman (1984, all) compared the oxidation rates assessed by six different authors and estimated that corrosion amounts would vary from 4 to 53 micrometers (0.00016 to 0.0021 inch) for cladding exposed for 10,000 years at 180° C (356° F) in a wide variety of chemical conditions at lower and higher pHs than those estimated for the repository. The six corrosion models used a temperature dependency that estimated near-zero corrosion rates for long-term repository temperatures. A recent paper confirmed the ability of zirconium alloy cladding to resist corrosion in the Yucca Mountain environment (Hillner, Franklin, and Smee 1998, all). The typical cladding for fuel rods would be 570 micrometers (0.022 inch) thick. The cladding model used for this analysis estimated that between 0.3 and 40 percent of the zirconium alloy fuel rod cladding would fail after 1 million years (DOE 1998a, Volume 3, page 4-12).

Because zirconium alloy has been used as a cladding on fuel rods for a little over 40 years, there are different opinions about its ability to provide long-term protection (over thousands of years) of fuel rod contents. There is some uncertainty about whether the radioactive and thermal environment inside the waste packages would alter the zirconium alloy enough that it would not provide much protection against waste mobilization after the waste package failed. DOE performed a sensitivity analysis to assess the importance of cladding protection on dose impacts. Additional stochastic (random) runs for 10,000 and 1 million years after repository closure were performed under the assumption that the zirconium alloy cladding would provide no resistance to water or radionuclide movement after the waste package failed. Table 5-16 compares the peak dose rate from groundwater transport of radionuclides for the two different cladding models. The analysis used data representing the high thermal load scenario to calculate individual exposures for a 20-kilometer (12-mile) distance.

Table 5-16. Comparison of consequences for a maximally exposed individual from groundwater releases of radionuclides using different fuel rod cladding models under the high thermal load scenario.

	Mean consequence[a]		95th-percentile consequence[b]	
Maximally exposed individual	Dose rate (millirem/year)	Probability of an LCF[c]	Dose rate (millirem/year)	Probability of an LCF
Peak at 20 kilometers[d] within 10,000 years after repository closure with cladding credit	0.22	7.6×10^{-6}	0.58	2.0×10^{-5}
Peak at 20 kilometers within 10,000 years after repository closure without cladding credit	5.4	1.9×10^{-4}	15	5.3×10^{-4}
Peak at 20 kilometers within 1 million years after repository closure with cladding credit	260	9.0×10^{-3}	1,400	5.0×10^{-2}
Peak at 20 kilometers within 1 million years after repository closure without cladding credit	3,000	1.1×10^{-1}	10,800	3.8×10^{-1}

a. Based on sets of 100 simulations of total system performance, each using random samples of uncertain parameters.
b. Represents a value for which 95 out of the 100 simulations yielded a smaller value.
c. LCF = latent cancer fatality; incremental lifetime (70 years) risk of contracting a fatal cancer for individuals, assuming a risk of 0.0005 latent cancer per rem for members of the public (NCRP 1993a, page 31).
d. To convert kilometers to miles, multiply by 0.62137.

A comparison of the peak dose rates for the 10,000-year analysis showed that the estimated human health effects would increase if credit for the zirconium alloy cladding were eliminated. The estimated consequences would be approximately 25 times larger for both the mean and 95th-percentile consequences. A comparison of the peak dose rates for the 1-million-year analysis showed that the estimated human health effects would increase by a smaller amount if the zirconium alloy cladding were eliminated. The increase was about 12 times the mean consequence and 8 times the 95th-percentile consequence. Similar impacts would occur to drinking water concentrations.

The no-cladding analysis assumed that the zirconium alloy cladding would not provide any barrier to water movement and radionuclide mobilization after the waste package failed. However, DOE expects that the zirconium alloy would provide some impediment to radionuclide mobilization if the waste package was breached (DOE 1998a, Volume 3, page O-8). Therefore, the results for no cladding credit listed in Table 5-16 could be viewed as upper bounds on dose and health effects.

5.5 Atmospheric Radiological Consequences

After DOE closed the repository, there would be limited potential for releases to the atmosphere because the waste would be isolated far below the ground surface. Still, the rock is porous and does allow gas to flow, so the analysis must consider possible airborne releases. The only radionuclide in the analysis after screening (see Table 5-1) with a potential for gas transport is carbon-14 in the form of carbon dioxide. Iodine-129 can exist in a gas phase, but DOE expects it would dissolve in the groundwater rather than migrate as a gas. The solubility of iodine-129 is a great deal higher than that of carbon dioxide, and the water is already saturated in carbon dioxide because of interaction with carbonate rocks. After the carbon-14 escaped as carbon dioxide from the waste package, it would flow through the rock. About 2 percent of the carbon-14 in commercial spent nuclear fuel is in a gas phase in the space (or gap) between the fuel and the cladding around the fuel (Oversby 1987, page 92). The atmospheric model used a gas-phase inventory of 0.234 curie of carbon-14 per waste package of commercial spent nuclear fuel at the time of emplacement. The atmospheric model estimated human health impacts for the population in the 84-kilometer (52-mile) region surrounding the repository and for the global population.

5.5.1 CARBON-14 SOURCE TERM

The calculation of regional doses used an estimate of the annual release rate of carbon-14. The analysis based the carbon-14 release rate on the estimated time line of container failures for the high thermal load scenario, using average values for the stochastic (random) parameters that were input. The expected number of spent nuclear fuel waste package failures as a function of time was used to estimate the carbon-14 release rate after repository closure. The amount of material released from each package as a function of time was reduced to account for radioactive decay. As for the waterborne releases described in Section 5.4, some credit was taken for the intact zirconium alloy cladding (on approximately 99 percent of the spent nuclear fuel by volume) delaying the release of gas-phase carbon-14. The zirconium alloy cladding on 0.1 percent of the fuel was assumed to have failed in the reactor environment (DOE 1998a, Volume 3, page 3-97), and the stainless-steel cladding on approximately 1.2 percent of the total spent fuel inventory was also assumed to have failed before it was placed in the waste package. Thus, gas-phase releases from this fuel would have occurred before it was shipped to the repository. Appendix I contains more details on the release model and reports a sensitivity study that assumed some of the stainless-steel cladding was intact when placed in the waste package. The maximum annual-release rate would occur about 19,000 years after repository closure. The estimated maximum release rate is 9.8×10^{-8} curies per year.

5.5.2 ATMOSPHERIC CONSEQUENCES TO THE LOCAL POPULATION

DOE used the GENII program (Napier et al. 1997, all) to model the atmospheric transport and human uptake of the released carbon-14 for the 84-kilometer (52-mile) population dose calculation. Doses to the regional population around Yucca Mountain from carbon-14 releases were estimated using the population distribution shown in Chapter 3, Figure 3-21, which indicates that 28,000 people would live in the region surrounding Yucca Mountain in 2000. The computation also used current (1993 to 1996) annual average meteorology (see Appendix I, Table I-5). GENII calculated a dose factor of 2.2×10^{-9} person-rem per microcurie per year of release. For a 0.098-microcurie-per-year release, this corresponds to a 7.8×10^{-15} rem-per-year average dose to individuals in the population. Thus, a maximum 84-kilometer population dose rate is 2.2×10^{-10} person-rem per year. This dose rate corresponds to 1.1×10^{-13} latent cancer fatality in the regional population of 28,000 persons during each year at the maximum carbon-14 release rate. This annual dose yields an average lifetime dose of 1.5×10^{-8} rem over a 70-year lifetime, corresponding to 7.6×10^{-12} latent cancer fatality during the 70-year period of the maximum release rate.

5.6 Consequences from Chemically Toxic Materials

A number of materials that DOE would place in the repository are hazardous to human health at sufficient concentrations in water. This section examines the consequences to individuals in the Amargosa Valley from releases of nonradioactive materials. Appendix I, Section I.3.2 describes the screening analysis DOE used to select constituents for detailed analysis.

5.6.1 HUMAN HEALTH IMPACTS FROM CHROMIUM

There would be about 14,000 metric tons (15,000 tons) of chromium in the repository under the Proposed Action (see Table 5-2). About 70 percent of the chromium would be in the Alloy-22 used for the corrosion-resistant layer of the waste packages, and the remainder would be in stainless-steel components inside the waste packages (for example, brackets, fixtures, separators, some cladding, and additional interior canisters). Chemical modeling studies of the corroding waste packages showed that the hexavalent form of chromium would dominate, primarily because the environment at the point of corrosion would have a very low pH and because there would be enough oxygen to support the complete oxidation of chromium. The hexavalent form is highly soluble and toxic to humans.

There are two measures for comparing the human health effects for chromium. When the Environmental Protection Agency established its Maximum Contaminant Level Goals, it considered safe levels of contaminants in drinking water and the ability to achieve these levels with the best available technology. The Maximum Contaminant Level Goal for chromium is 0.1 milligram per liter (0.0000062 pound per cubic foot) (40 CFR 141.51). The other measure for comparison is the reference dose factor for chromium, which is 0.005 milligram per kilogram (0.0004 ounce per pound) of body mass per day (EPA 1998a, all). The reference dose factor represents a level of intake that has no adverse effect on humans. It can be converted to a threshold concentration level for drinking water. The conversion yields essentially the same concentration for the reference dose factor as the Maximum Contaminant Level Goal.

One hundred simulations were run to model the release and transport of chromium for 10,000 years following repository closure. The consequences were computed at the distances used for waterborne radionuclide impacts [5, 20, 30, and 80 kilometers (3, 12, 19, and 50 miles) from the repository]. Results from a two-stage model accounting for both chromium from the inner shell of Alloy-22 and the interior stainless-steel components in some of the waste forms (spacers, grids, hardware, cladding, additional containment cans, etc.) demonstrated that the interior stainless steel mass could be neglected in estimating peak chromium concentrations in the accessible environment. Therefore, the calculation of the release rate of chromium from the repository used the inventory and corrosion rate of Alloy-22. Appendix I contains details on the chromium modeling runs. Table 5-17 lists the peak chromium concentrations computed for each model run.

Table 5-17. Peak chromium concentrations (milligrams per liter)[a] in water for 10,000 years after closure at four locations by thermal load scenario.[b]

	High thermal load		Intermediate thermal load		Low thermal load	
MEI[c]	Mean	95th-percentile	Mean	95th-percentile	Mean	95th-percentile
At 5 kilometers[d]	0.0085	0.037	0.0029	0.0096	0.0046	0.016
At 20 kilometers	0.0028	0.012	0.0023	0.010	0.0018	0.0083
At 30 kilometers	0.0018	0.0063	0.00080	0.0038	0.00067	0.0033
At 80 kilometers	0.00022	0.00061	0.000031	0.00015	0.000053	0.00034

a. To convert milligrams per liter to pounds per cubic foot, multiply by 0.0000624.
b. Based on 100 simulations of total system performance using random samples of uncertain parameters.
c. MEI = maximally exposed individual.
d. To convert kilometers to miles, multiply by 0.62137.

For the high thermal load scenario, the mean peak concentrations would range from a high of 8.5×10^{-3} milligram per liter (5.3×10^{-7} pound per cubic foot) at 5 kilometers (3 miles) down to 2.2×10^{-4} milligram per liter (1.4×10^{-8} pound per cubic foot) at 80 kilometers (50 miles). The 95th-percentile peak concentrations would range from a high at 5 kilometers of 0.037 milligram per liter (2.3×10^{-6} pound per cubic foot) down to 6.1×10^{-4} milligram per liter (3.8×10^{-8} pound per cubic foot) at 80 kilometers. Because none of the estimated concentrations exceed the Maximum Contaminant Level Goal or reference dose factor, DOE anticipates no detrimental impacts to water quality due to chromium contamination under the high thermal load scenario.

For the intermediate thermal load scenario, the mean peak concentrations would range from a high of 2.9×10^{-3} milligram per liter (1.8×10^{-7} pound per cubic foot) at 5 kilometers (3 miles) down to 3.1×10^{-5} milligram per liter (1.9×10^{-9} pound per cubic foot) at 80 kilometers (50 miles).

The 95th-percentile peak concentrations would range from a high at 5 kilometers (3 miles) of 0.01 milligram per liter (6.2×10^{-7} pound per cubic foot) down to 1.5×10^{-4} milligram per liter (9.4×10^{-9} pound per cubic foot) at 80 kilometers (50 miles). Because none of the estimated concentrations exceed the Maximum Contaminant Level Goal or reference dose factor, DOE anticipates no detrimental impacts to water quality due to chromium contamination under the intermediate thermal load scenario.

For the low thermal load scenario, the mean peak concentrations would range from a high of 4.6×10^{-3} milligram per liter (2.9×10^{-7} pound per cubic foot) at 5 kilometers (3 miles) down to 5.3×10^{-5} milligram per liter (3.3×10^{-9} pound per cubic foot) at 80 kilometers (50 miles). The 95th-percentile peak concentrations would range from a high at 5 kilometers of 0.016 milligram per liter (1.0×10^{-6} pound per cubic foot) down to 3.4×10^{-4} milligram per liter (2.1×10^{-8} pound per cubic foot) at 80 kilometers. In some instances (for example, 5 and 80 kilometers), the chromium concentrations are higher for the low thermal load than the intermediate thermal load. This is caused by the effect of the repository-area shape on the calculation of the dilution factors used for the saturated zone and the correlative differences in the percolation flux. Section I.5.2 in Appendix I discusses these factors with respect to waterborne radioactive materials (this discussion is also applicable to waterborne chemically toxic materials). Because none of the estimated concentrations exceed the Maximum Contaminant Level Goal or reference dose factor; DOE anticipates no detrimental impacts to water quality due to chromium contamination under the low thermal load scenario.

At present, the carcinogenicity of hexavalent chromium by the oral route of exposure cannot be determined because of a lack of sufficient epidemiological and toxicological data (EPA 1998a, page 48; EPA 1998b, all). Therefore, the groundwater concentrations reported in Table 5-17 cannot be expressed in terms of human health effects (latent cancer fatalities).

5.6.2 HUMAN HEALTH IMPACTS FROM MOLYBDENUM

The Alloy-22 to be used as a waste package inner-barrier would contain 13.5 percent molybdenum. During the corrosion of Alloy-22, molybdenum would mobilize almost in the same manner as chromium. Due to the corrosion conditions, molybdenum would dissolve in a highly soluble hexavalent form. Because the releases of both chromium and molybdenum would be constrained by the degradation rate of Alloy-22, the source term concentration for molybdenum would be approximately 0.64 (13.5/21.25) times the source term concentration for chromium. Detailed transport modeling of molybdenum would use the same mechanisms and parameters as those for chromium, so modeling is unnecessary. Molybdenum in the water at concentrations 0.64 times those reported above for chromium is a reasonable estimate. No regulatory standard for molybdenum has been established. Because the concentrations are very low, DOE anticipates no detrimental impacts to water quality due to molybdenum contamination under any of the thermal load scenarios.

5.6.3 HUMAN HEALTH IMPACTS FROM URANIUM (AS A CHEMICALLY TOXIC MATERIAL)

DOE ran 100 simulations to model the release and transport of uranium for the Proposed Action inventory. The Proposed Action inventory would contain approximately 70,000 MTHM (see Table 5-2). While a small percentage of the heavy metal in the spent fuel would not be uranium, assuming that all of it is uranium is reasonable because such an assumption would have a very small effect on the result. Furthermore, the analysis would tend to overestimate health effects because it assumed that the MTHM basis of high-level radioactive waste is uranium when there is very little uranium in that material. This introduces an approximate 7-percent increase into the result (see Table 5-2 and the accompanying discussion). The simulations were based on the high thermal load scenario, and the consequences were computed for exposures at 5 kilometers (3 miles) from the repository. In addition, the analysis assumed that uranium did not undergo radioactive decay. Appendix I contains more details of the modeling runs. The maximum uranium concentration over 10,000 years was calculated for each model simulation. The mean peak concentration of uranium would be 6.7×10^{-8} milligram per liter (5.2×10^{-9} pound per cubic foot) and the 95th-percentile peak concentration would be 2.2×10^{-8} milligram per liter (1.7×10^{-9} pound per cubic foot). The Environmental Protection Agency has proposed a Maximum Contaminant Level of 0.02 milligram per liter (0.02 part per million) (56 *FR* 33050, July 18, 1991). Because the concentrations would be very low (about 1 million times less than the proposed Maximum Contaminant Level), DOE anticipates no detrimental impacts to water quality due to uranium contamination under any of the thermal load scenarios.

The reference dose for elemental uranium is 0.003 milligram per kilogram of body mass per day (Eckerman and Ryman 1993, all). Assuming a maximum individual exposure from the drinking water pathway, the analysis used a 2-liter (0.52-gallon)-per-day intake rate and a 70-kilogram (153-pound) body weight to convert the reference dose to a threshold concentration, which would be 0.105 milligram per liter (0.0000063 pound per cubic foot). There is no Maximum Contaminant Level for elemental uranium.

Based on trends in waterborne radioactive material results, the concentrations of elemental uranium at more distant locations [20, 30, and 80 kilometers (12, 19, and 50 miles)] would be even lower. This observation also applies to the intermediate and low thermal load scenarios at all distances. Because of the extremely low concentrations calculated from these simulations, further simulations were not performed to evaluate other thermal loads under the Proposed Action. The calculated concentrations were many orders of magnitude below the threshold. Therefore, DOE believes elemental uranium would not present a health risk as a chemically toxic material under the Proposed Action for any thermal load scenario.

5.7 Consequences from Disruptive Events

The postclosure performance estimates discussed above include the possible effects of changing climate but do not address events that could physically disturb the repository. In general, disruptive events have identifiable starting and ending times, in contrast to continuous processes such as corrosion. The disruptive events examined in this section are an inadvertent intrusion into the repository by a drilling crew, seismic activity, and basaltic igneous (volcanic) activity. The choice of these three events is consistent with the analyses in the Viability Assessment (DOE 1998a, Volume 3, pages 4-80 to 4-102). The results in Section 5.7 are derived from that document, with no new model runs being performed for this EIS. The Viability Assessment used a model run, called the base case, as a reference case to determine the magnitude of impacts from the disruptive events. The base case is the same as the analysis for 85 MTHM per acre thermal load doses evaluated at a 20-kilometer (12-mile) distance in this EIS (the results are summarized in Table 5-4). The base case discussed in this section used the mean values of all the stochastic (random) parameters as inputs.

5.7.1 DRILLING INTRUSIONS

Human intrusion is generally interpreted to mean inadvertent penetration of the repository (such as by drilling operations) that would either release radionuclides at the surface or accelerate radionuclide transport to the dose-exposure location. The National Academy of Sciences has recommended that the direct impact of human intrusion not be considered in Total System Performance Assessment (National Research Council 1995, Chapter 4). The analysis reported here used the consequences of human intrusion, in terms of potential increases in long-term doses to the exposed public rather than impacts to the drilling crew, to measure the resilience of the repository to such disturbances. The Viability Assessment contains further details of the analysis and its basis (DOE 1998a, Volume 3, pages 4-99 to 4-102).

The analysis of human intrusion assumed that 10,000 years after closure, a drilling operation would penetrate the repository. The drilling event was modeled as occurring at 10,000 years after repository closure because waste packages probably would be degraded enough that a drill could penetrate them. The analysis also assumed that the intrusion would penetrate a waste package with a 21-centimeter (8.3-inch) drill bit. It assumed that the drilling proceeded through the waste package and down to the level of the water table. When the drill bit was removed, radioactive waste would fall down the drill hole to the saturated zone beneath the repository. There, flowing water would dissolve the waste and carry it to the accessible environment.

The analysis modeled a case in which 550 kilograms (1,200 pounds) of waste dropped down the hole and then dissolved at a slow rate (Figure 5-7) [considered a lower bounding situation (DOE 1998a, pages 4-99 to 4-102)]. The peak dose for this case in the first 10,000 years after the intrusion would be about 3.7 times that of the base case peak dose. Another case was modeled in which 2,700 kilograms (5,950 pounds) of waste fell down the hole and dissolved at a high rate [considered an upper bounding situation (DOE 1998a, pages 4-99 to 4-102)]. The peak dose for this case in the first 10,000 years after the intrusion (between 10,000 and 20,000 years after repository closure) would be about 145 times that of the base case peak dose about 2,000 years after the intrusion. By 10,000 years after the intrusion, there would be little difference between the doses for the base case and the doses from the intrusion cases. At 50,000 years after the intrusion, the doses from the intrusion cases would rise above that of the base case and stay elevated for approximately 100,000 years. The short-term increase in dose would be caused largely by rapid mobilization of technetium-99 and iodine-129. The long-term increase in dose would be caused largely by slower moving radionuclides such as plutonium.

In terms of the peak dose to a critical group over 100,000 years, the effects of human intrusion would be small (an increase approximately four times greater than the base case peak dose rate for about 50,000 years). Over 1 million years, the increase over the base case peak dose rate would be very small. At times close to the human intrusion event, the increased dose rates could be much larger than the corresponding base case rates.

If the drilling mud carried waste package contents to the surface, it would result in direct exposure of the drilling crew to those contents. The exposure to the drilling crew probably would result in lethal doses to those workers.

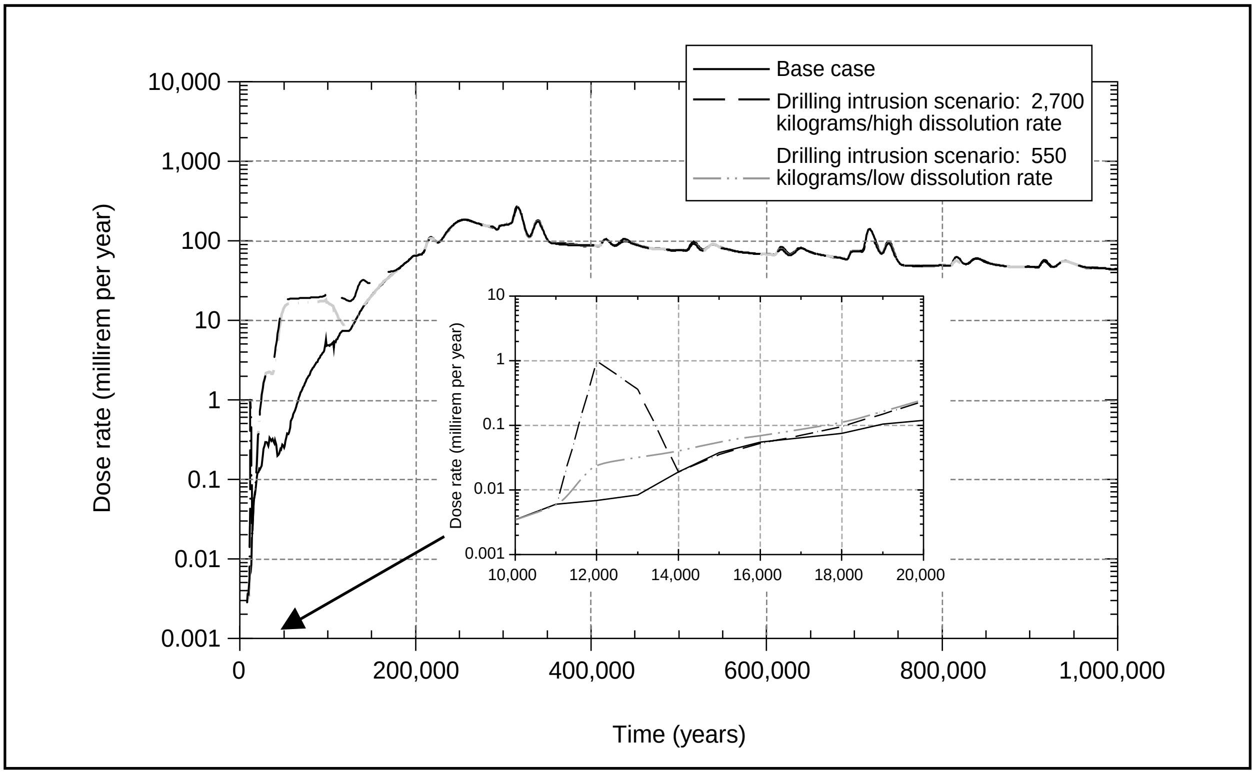

Figure 5-7. Comparison of time history of dose for the base case and under drilling intrusion scenarios 20 kilometers from the repository for the high thermal load scenario.

5.7.2 VOLCANIC DISTURBANCES

DOE has evaluated the probability of volcanic activity affecting the proposed repository (Geomatrix and TRW 1996, all). The primary criteria in defining the probability are the recurrence rate of future volcanic events and the spatial distribution of the events. The evaluation showed that it is unlikely that liquid magma or pyroclasts (hot gases that condense in air and form ash) from a volcano would intersect the repository. However, because there is a finite probability of such an occurrence, the analysis has evaluated it. The annual probability of this event occurring is 1.5×10^{-8} for the high thermal load scenario and 5.1×10^{-8} for the low thermal load.

DOE analyzed the effect on repository performance for three scenarios (DOE 1998a, Volume 3, pages 4-81 through 4-88):

- Direct release scenario: Radioactive material would be transported directly to the surface and atmosphere by a magma flow or pyroclastic flow.
- Enhanced source term scenario: Radioactive material would be entrained in magma that remained in the emplacement drift.
- Indirect igneous effects scenario: Magma would change the hydrologic flow in the saturated zone and alter the transport path of the radioactive material.

Direct Release Scenario

In this scenario the waste packages would be contacted by ascending magma or by pyroclastic flow. The Monte Carlo model determined when the volcanic event would occur, if a volcanic event would intersect an emplacement drift, if the event would intersect a container, if the waste package was breached how much material would be removed from a waste package, and if the ascending magma or pyroclasts could transport the waste. Because of its low velocity, the magma would not be removed from the waste package. Therefore, the dose to humans from this scenario was calculated based on the dispersal of radioactivity in volcanic ash. If the waste was not moved to the surface, it would collect somewhere underground and could contribute to the enhanced source term scenario. Less than 6 percent of all events would release contaminants into an ash cloud. Modeling of the direct release volcanism indicates that there would be very little impact from this scenario. The maximum dose rate from this scenario would be about 2 million times less than the maximum dose from the base case.

The calculation of radiation dose to humans from the air release scenario was based on the dispersal of contaminants in volcanic ash. The ash dispersal model (Jarzemba, LaPlante, and Poor 1997, all) uses information on eruption characteristics, wind direction and velocity, and ash and waste characteristics. Because the corrosion-resistant layers of the waste packages would maintain their structural integrity, few additional contaminant releases caused by eruptive events would be likely in the first 100,000 years after repository closure. The maximum dose from airborne ash caused by volcanism any time during the first 1 million years after repository closure would be about one million times less than the peak dose from the undisturbed groundwater transport of radionuclides.

Enhanced Source Term Scenario

The model for the enhanced source term scenario examined the interaction of the magma with waste packages in the emplacement drift and assumed that the magma would remain underground. The magma was predicted to contact between 0 and 170 packages, with an average of about 45. In this environment of high temperatures and aggressive gases, the waste package would fail. If the waste packages failed, the liquid magma could dissolve some of the uranium oxide in the spent fuel (Westrich 1982, all). When the basalt cooled [in about 10 years for a 2-meter (6.6-foot)-wide dike], groundwater would reenter the emplacement drifts. The basalt would crack as it cooled, allowing the groundwater to dissolve the uranium oxide and other radioactive materials in the contaminated basalt. The groundwater then would carry the contaminants through the geologic media to the accessible environment.

In one Monte Carlo calculation, the volcanic event would intersect waste packages at approximately 110,000 years after repository closure and would result in a peak dose four times the peak dose of the base case, with the peak occurring about 350,000 years after repository closure (DOE 1998a, Volume 3, pages 4-81 through 4-88). The other example assumed the event would occur about 740,000 years after repository closure and would result in a peak dose three times the base case peak dose. In both examples, the peak dose at the accessible environment would occur thousands of years after the event because of the time needed for groundwater to transport the radionuclides.

If an igneous event occurred in the first 100,000 years after repository closure, it would produce doses many times greater than the base case dose for the same period. The peak dose for the base case during the first 100,000 years after closure would range from 0 to 8 millirem per year. The corresponding peak dose if an igneous event occurred during the first 100,000 years after closure would range from 8 to about 64 millirem per year, which is much lower than the peak dose of about 200 millirem per year that would occur several hundred thousand years after closure. The increase in dose from an igneous event would be the result of the early rupture of a few waste packages. After doses from the waste released by interaction with the magma migrated in the groundwater to the accessible environment, the dose histories would coincide with the base case. The Viability Assessment (DOE 1998a, Volume 3, pages 4-81 to 4-88) provides detailed notes comparing results with and without volcanism.

Indirect Igneous Effects Scenario

Modeling of the indirect effects of nearby igneous events has shown that newly formed geologic structures (faults or dikes) upstream from the repository would have no effect on contaminant transport. To calibrate the flow model, it was necessary to make the hydraulic conductivity of existing structures very low (Wilson et al. 1994, Volume I, Table 11-1). Thus, making the structures even more of a barrier through igneous intrusion would cause no noticeable change in the groundwater flow patterns. When downgradient dikes are modeled as being more transmissive, there would be a small change in the groundwater flow pattern. Generally, flow would be directed more toward the east and could take longer to reach a water withdrawal well; thus, it would not be expected to increase the dose rates.

5.7.3 SEISMIC DISTURBANCES

The probability of earthquake occurrence in the Yucca Mountain vicinity is sufficiently high that DOE evaluated potential effects of seismic activity on repository performance (DOE 1998a, Volume 3, pages 4-88 to 4-92). The potential effects of seismic activity would be vibratory ground motion in the repository, causing falling rock to damage waste packages, and a nearby event causing changes in hydrologic properties. The *Probabilistic Seismic Hazard Analysis* (USGS 1998, all) estimated fault displacement and vibratory ground motion hazards in the Yucca Mountain vicinity. The results are in the form of annual frequencies that various levels of fault displacement and vibratory ground motion would exceed.

Seismic activity could cause rocks to fall from the ceilings or walls of the repository drifts. The size of falling rocks was correlated with vibratory ground motion. The distribution of the size of rocks available to fall was estimated from fracture spacing in the Exploratory Studies Facility at Yucca Mountain. Most rocks weigh less than 1,000 kilograms (2,200 pounds), with many weighing about 50 kilograms (110 pounds). There are very few rocks larger than 3,500 kilograms (7,700 pounds). Most waste package failures caused by seismic activity probably would occur when the waste package outer wall was completely corroded. After emplacement, rocks would have to be larger than any observed in the Exploratory Studies Facility to damage the waste packages. If the corrosion-allowance material and half of the corrosion-resistant material were corroded, a rock similar to the average-size rock in the Exploratory Studies Facility could damage a waste package. At times greater than 100,000 years after repository closure, damage from falling rocks would be more likely because the waste packages would be corroded. Because the waste packages would occupy about 40 percent of the space in a drift, a falling rock would have a 40-percent chance of hitting a waste package.

There is less than a 1 percent probability that a falling rock would breach a waste package during the first 10,000 years after repository closure because most waste package walls would still be thick enough to withstand such hits. Over 1 million years, falling rocks could breach about 30 percent of the waste packages in the repository. Such failures, when added to the normal failures from corrosion, would not change the overall probability of waste package failure much because they would occur mostly very late (more than 500,000 years) after emplacement. The calculations show that there would be almost no effect on repository performance from rockfall over a 1-million-year period after closure.

The Viability Assessment (DOE 1998a, Volume 3, pages 4-88 to 4-92) examined whether seismic activity in the Yucca Mountain vicinity would have the potential to affect repository performance, even if a new fault did not intersect the repository. Faulting in the saturated zone could potentially change water flow patterns and, therefore, repository performance. The saturated zone modeling assumed that most of the groundwater flow would occur in fractures, so the addition of a new fault would not be likely to alter repository performance.

5.8 Nuclear Criticality

Isolated nuclear criticality events could occur if the engineered control measures in the waste packages failed and other conditions (such as the presence of water) occurred. In addition, fissile material in the waste could form a critical configuration in the surrounding rock. Criticality has not been included in earlier total system performance analyses, but the DOE waste package design team performed an extensive investigation of this possibility (DOE 1998a, Volume 3, page 4-92). DOE found that the consequences of criticality would be relatively small in comparison to the measures for nominal repository performance.

An analysis of an in-package criticality scenario for commercial spent nuclear fuel used conditions and waste characteristics that potentially maximize the effects of the criticality (DOE 1998a, Volume 3, page 4-96). There are three possible ways that criticality could contribute to additional long-term impacts:

- Internal criticality of the package that would cause an increase of heat, the effect of which could change the properties affecting mobilization of waste
- Internal criticality that would cause an increase in the amount of radioactive material in the waste package
- External criticality resulting from a reaccumulation in the rock of fissile material that had leaked from the package

The analysis showed that the increase in heat from a highly unlikely internal criticality event would be only about 2 kilowatts per package, which is inconsequential in comparison to the overall repository heat load. The increase in radioactivity would be only 24 percent of the original radioactivity in the waste package for a 10,000-year criticality duration. Because of the small increases in radioactivity and heat output, there is no chance that a criticality would cause mechanical disruption of the waste package and engineered barrier system (DOE 1998a, Volume 3, page 4-98).

Criticalities outside the waste packages primarily would require some mechanism to accumulate the fissile material in a localized area. The estimated concentrations would be less than 0.01 percent by volume for plutonium, which is much too low to make criticality possible (DOE 1998a, Volume 3, page 4-98).

Based on these results, DOE concluded that an explosive nuclear criticality is not credible (could not occur). If a nuclear criticality event occurred (highly unlikely) it would not have a significant effect on long-term impacts from the repository.

5.9 Consequences to Biological Resources and Soils

DOE considered if the proposed repository would affect biological resources in the Yucca Mountain vicinity after closure through heating of the ground surface and through radiation exposure as the result of waste migration through groundwater to discharge points. After closure, heat from the radioactive decay of the waste would cause temperatures in the rock near the disposal containers to rise above the boiling point of water [100°C (212°F)] (DOE 1998a, Volume 3, page 3-36). The period the subsurface temperature would remain above the boiling point would vary from a few hundred years to a few thousand years, depending on the thermal load scenario. Conduction and the flow of heated air and water through the rock (advection) would carry the heat from the disposal containers through the rock to the surface and to the aquifer.

Although the atmosphere would remove excess heat when it reached the ground surface, the temperature of near-surface soils probably would increase slightly. Predicted increases in surface soil temperatures range from approximately 10°C (18°F) at the bedrock-soil interface (Bodvarsson, Bandurraga, and Wu 1997, page 510) to 6°C (10.8°F) for dry soil at a depth of 2 meters (6.6 feet) (Table 5-18). To address soil heterogeneity (differences in depth and water content), a recent study (TRW 1999r, all) modeled soil temperature increases at various depths under wet (saturated) and dry (no water at all) soil conditions for the high thermal load. They predicted that temperatures of near-surface soils would be unlikely to rise more than a few degrees (Table 5-18) but would increase with depth from the surface. Surface soil temperatures would start to increase after approximately 200 years and would peak after about 1,000 years. Later, the temperature would gradually decline and would approximate prerepository conditions after 10,000 years (TRW 1999r, Figure 4-13). The maximum change in temperature would occur directly above the repository, affecting approximately 3 square kilometers (740 acres) under the high thermal load scenario. The effects of repository heat on the surface soil temperatures would gradually decline with distance from the repository (TRW 1999r, page 49). Although not modeled, the increase in surface soil temperature would be lower under the intermediate and low thermal load scenarios, and the area that could be affected would be larger [as much as 10 square kilometers (2,500 acres) above the repository for the low thermal load scenario].

Table 5-18. Predicted temperature changes of near-surface soils under the high thermal load scenario.[a]

Soil depth (meters)[b]	Predicted temperature increase [a]	
	Dry soil	Wet soil
0.5	1.5°C (2.7°F)	0.2°C (0.36°F)
1.0	3.0°C (5.4°F)	0.4°C (0.72°F)
2.0	6.0°C (10.8°F)	0.8°C (1.4°F)

a. Source: TRW (1999r, page 45).
b. To convert meters to inches, multiply by 39.37.

There is considerable uncertainty in the estimates of soil temperature increases due to uncertainties in the thermal properties of the soil at Yucca Mountain, particularly thermal conductivity (the amount of heat that can be conducted through a unit of soil per unit time) (TRW 1999r, page 50).

The predicted temperature increase for dry soil provides a conservative estimate of the temperature increase that could occur because even partially saturated soil has a much greater thermal conductivity than dry soil. Soil moisture content recorded at a depth of 15 centimeters (6 inches) was as low as 3 percent on some study sites during some months, but the soil was never completely dry (TRW 1999s, page 14).

A depth of 1 meter (3.3 feet) is within the root zone for many desert shrubs. A temperature increase of 3°C (5.4°F) could affect root growth and other soil parameters such as the growth of microbes or nutrient availability. Studies at Yucca Mountain (TRW 1999s, pages 11 to 46) show that some plant species experienced a spatial range in soil temperatures of 4°C (7.2°F) at a depth of 0.45 meter (18 inches), which is comparable to the 0.5-meter (20-inch) depth used by TRW (1999r, all). Impacts to biological resources probably would consist of an increase of heat-tolerant species over the repository and a decrease of less tolerant species. In general, areas affected by repository heating could experience a loss of shrub species and an increase in annual species. A gradual (over 1,000 years) temperature increase of the magnitude predicted (TRW 1999r, all) probably would have less effect on the plant community than a more rapid change, such as that predicted for global warming.

The predicted increase in temperature would extend as far as 500 meters (1,600 feet) beyond the edge of the repository, with the greatest increase in temperature occurring in soils directly above the repository. A shift in the plant species composition, if any, would be limited to the area within 500 meters of the repository footprint [that is, as much as 8 square kilometers (2,000 acres)], with the greatest change within the central 3 square kilometers (740 acres) for the high thermal load scenario. Although a larger area could be affected under the intermediate and low thermal loads, the magnitude of the increase in soil temperature would be smaller and the associated effects on plant species composition would not be as pronounced as under the high thermal load.

A shift in the plant community probably would lead to localized changes in the animal community that depends on it for food and shelter. Specific plant and animal species and community changes cannot be predicted with certainty because changes in climate or seasonal episodic events (droughts, high rainfall) can substantially change species responses to single factors. However, the variation in surface soil temperatures at Yucca Mountain that are caused by elevation, slope, aspect, and other natural attributes suggest that soil temperature increases of the magnitude predicted (TRW 1999r, pages 44 to 48) are probably within the adaptive range of some plant species now at Yucca Mountain (TRW 1999s, pages 11 to 46).

Some reptiles, including the desert tortoise, exhibit temperature-dependent sex determination (Spotila et al. 1994, pages 103 to 116). Nest temperatures have a direct effect on sex determination, with lower temperatures resulting in predominately male hatchlings and higher temperatures resulting in predominately females. Although existing experimental data do not adequately represent the large fluctuations in nest temperatures in natural settings, an increase in soil temperature due to thermal load could influence the sex ratio and other aspects of the life history of the desert tortoise population residing over the repository footprint. However, depth to the top eggs of 23 nests at Yucca Mountain during 1994 averaged 11 centimeters (4.3 inches). Predicted temperature increases of clutches at that depth based on modeling results (TRW 1999r, pages 44 to 48) would be less than 0.5ºC (0.9°F). Given the ranges of critical temperatures reported by Spotila et al. (1994, all), an increase of this magnitude would be unlikely to cause adverse effects.

Changes in plant nutrient uptake, growth, and species composition, as a result of increases in soil temperature over long periods of time, could influence vegetation community dynamics and possibly alter desert tortoise habitat structure in areas immediately above the repository. However, little is known about the effects that minor alterations in habitat would have on desert tortoise population dynamics.

As discussed in Sections 5.4 and 5.6, in the distant future water at certain discharge points would be likely to carry concentrations of radionuclides and chemically toxic substances. DOE did not quantify impacts to biological resources from irrigation water discharged 5, 20, and 30 kilometers (3, 12, and 19 miles) from the repository, or from the evaporation of water at Franklin Lake Playa (where there is no surface water at present). The estimated doses to humans exposed to this water would be very small. In a similar manner, assumed doses to plants and animals would be small and the impacts from those doses would be unlikely to affect the population of any species because the doses would be much lower than the 100-millirad-per-day limit, at which there is no convincing evidence that chronic radiation exposure will harm plant or animal populations (IAEA 1992, page 54).

The desert tortoise is the only threatened or endangered species in the analyzed repository land withdrawal area (TRW 1999k, page 3-14). Desert tortoises are rare or absent on or around playas (Rautenstrauch and O'Farrell 1998, pages 407 to 411; Bury and Germano 1994, pages 64 and 65); therefore, DOE anticipates no impacts to this species from contaminated water resources at Franklin Lake Playa in the future.

Impacts to surface soils would be possible. Changes in the plant community as a result of the presence of the repository could lead to an increase in the amount of rainfall runoff and, therefore, an increase in the erosion of surface soils, thereby increasing the sediment load in surface water in the immediate Yucca Mountain vicinity.

5.10 Summary

Potential impacts to human health in the far future from a repository at Yucca Mountain would be dominated by impacts from radioactive materials in the waterborne pathway under all three thermal load scenarios of the Proposed Action. Although future disruptive events (human intrusion, volcanic activity, and seismic activity) would change radiation exposure rates, the effect of these on the reported impacts for the undisturbed case would be small under all thermal load scenarios. Large impacts from chemically toxic materials would be unlikely.

Tables 5-4, 5-8, and 5-12 list estimated radiation dose rates for a maximally exposed individual from the groundwater release pathway during the first 10,000 years after repository closure for the three thermal load scenarios. Table 5-19 summarizes the health effects based on the average peak-dose rates to the affected population (see Section 5.3) for these three scenarios. The fact that all of the numbers in Table 5-19 are much smaller than 1.0 means that it is most likely that no person would die due to groundwater contamination by radiological material in the 10,000-year period after repository closure. The number of cancer fatalities that would normally occur each year in the population in the Amargosa Valley (assuming a population of about 1,150 persons) would be about 2. This number is based on approximately 163 cancer fatalities per year per 100,000 population for males in the United States (NIH 1999, all). This comparison clearly indicates that the human health impacts associated with the Proposed Action would be very small for the population in general.

Table 5-19. Summary of health effects for the three thermal load scenarios for the Proposed Action.[a]

Thermal load	Peak 70-year lifetime LCFs[b]	10,000-year integrated LCFs
High	7.5×10^{-6}	1.8×10^{-4}
Intermediate	3.3×10^{-6}	6.7×10^{-5}
Low	5.3×10^{-6}	1.3×10^{-4}

a. Values based on the mean peak-dose rates from 100 simulations of total system performance using random samples of uncertain parameters.

b. LCFs = latent cancer fatalities.

It is appropriate to conclude that environmental justice impacts of long-term repository performance would not be disproportionately high and adverse because minority and low-income populations and Native Americans in the Amargosa Valley would experience a very small impact from radiological dose and there would be no other impacts relevant to environmental justice issues.

As discussed, overall human health impacts to Amargosa Valley residents would be small. The reference person studied to calculate human health impacts was defined as a person who lived year-round in the Valley, consumed locally produced foods, and ingested water from potentially contaminated sources. Estimated doses to plants and animals would also be small. The definition of the reference person and the dose rate to plants and animals address several issues of concern to environmental justice populations, such as relative immobility and dependence on local sources for food and water.

Figure 5-8 shows the mean peak dose rates from Tables 5-4, 5-8, and 5-12. The mean values were based on 100 simulations of total system performance, with each simulation using random samples of uncertainty parameters. Tables 5-6, 5-10, and 5-14 contain the corresponding radiation dose rates in the first 1 million years after repository closure for the three scenarios. Figure 5-9 shows the mean peak dose rates in the first 1 million years after repository closure. The doses shown in these figures do not include the effects of disruptive events.

The analysis indicates (as shown in Figures 5-8 and 5-9 and through a comparison of Tables 5-4, 5-8, and 5-12) that there would be no clear effect of thermal load on the doses, even though the impacts for the high thermal load scenario appear to be slightly larger than the impacts for the other scenarios. One

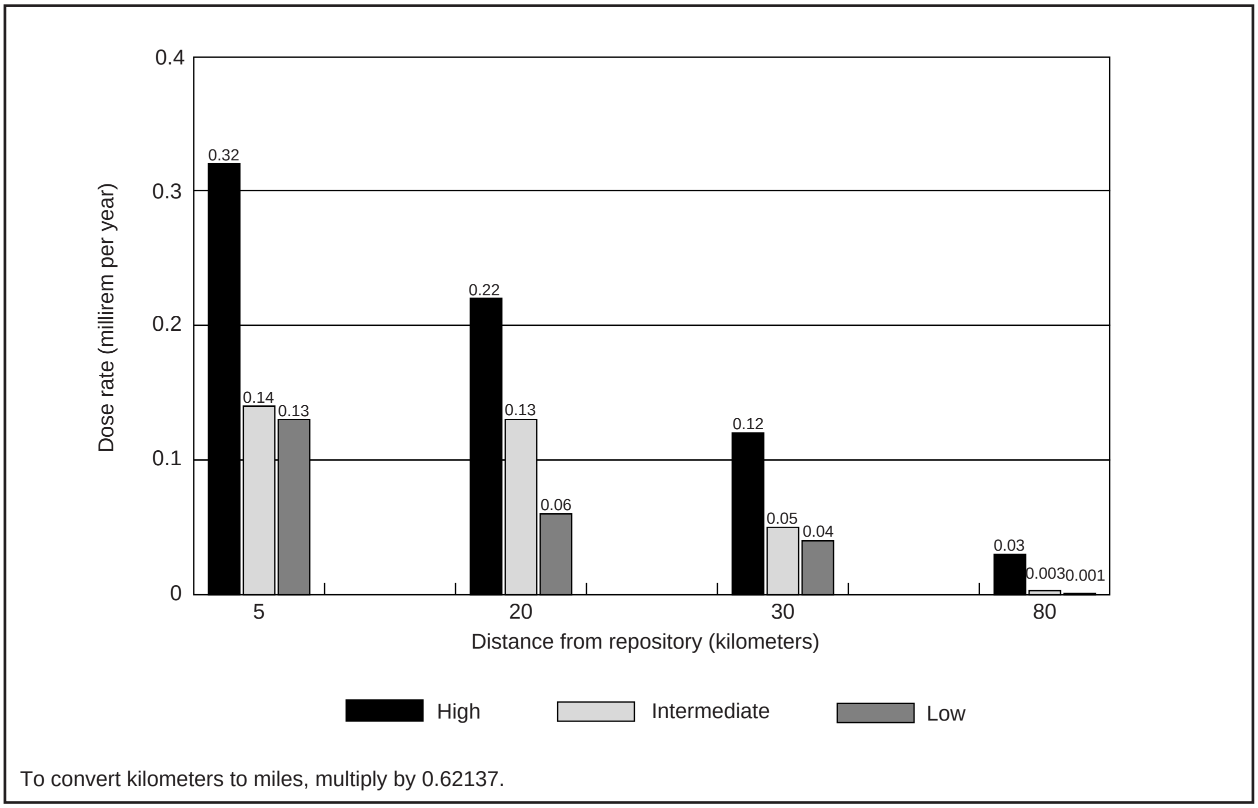

Figure 5-8. Comparison of the mean peak dose rates from contaminated groundwater in the first 10,000 years after repository closure for the three thermal load scenarios.

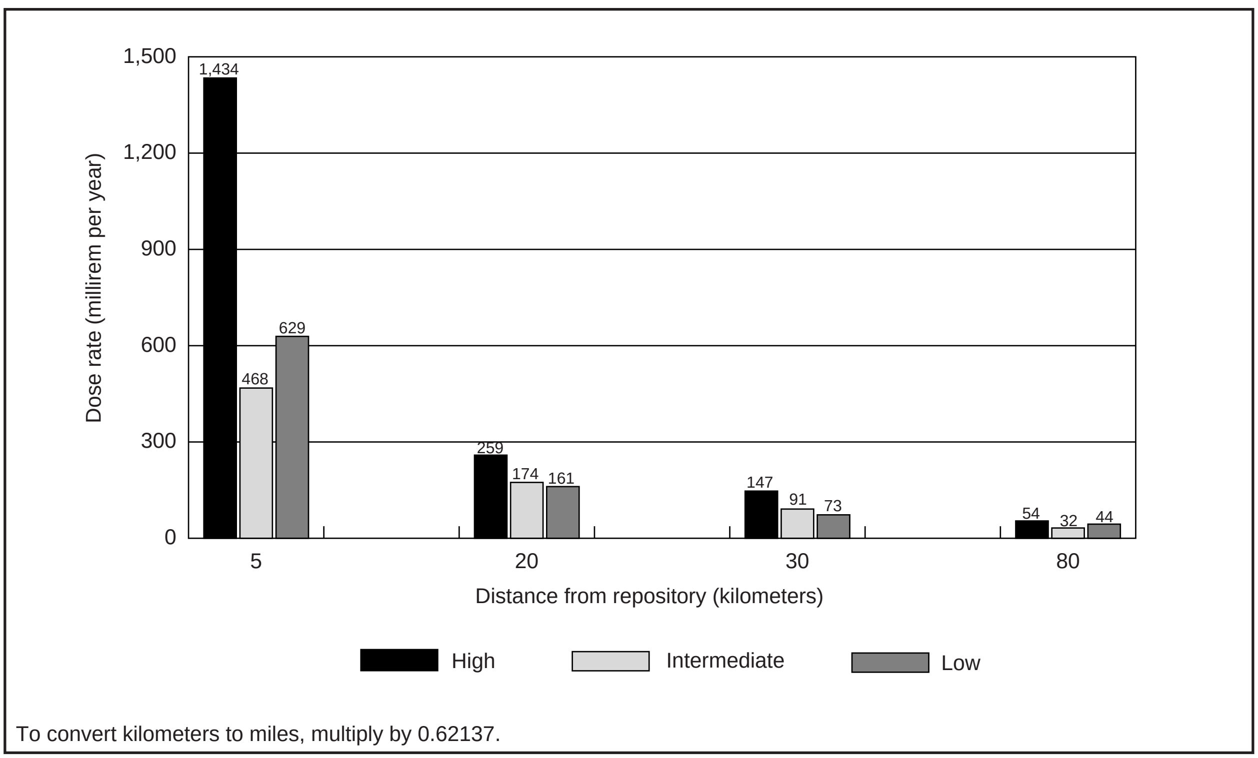

Figure 5-9. Comparison of the mean peak dose rates in the first 1 million years after repository closure for the three thermal load scenarios.

reason for the lack of difference in dose rates among thermal loads is that more than 99 percent of the waste packages would last beyond the time at which the repository temperature would be elevated much above ambient rock temperatures (DOE 1998a, Volume 3, pages 3-36 to 3-88). Thus, most radionuclides would not be released until long after the thermal effects had subsided and, therefore, thermal load would not have a large effect on the doses. The differences among thermal loads would be due to the placement of waste in different areas of the mountain, with different amounts of water infiltrating through the different areas. More details on the effect of spatially varying infiltration rates are provided in Appendix I.

The analysis also indicated that the dose to the maximally exposed individual would depend strongly on distance from the repository. The dose rates would be much higher at a 5-kilometer (3-mile) distance than at longer distances.